IMPROVING PREDICTABILITY OF TIME TO HARVEST AND YIELD OF FIELD GROWN TOMATO CROPS

By

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DECLARATION OF ORIGINALITY

The work contained in this thesis has not been previously submitted either in whole or in part for a degree at Central Queensland University (CQU) or any other tertiary institution. To the best of my knowledge and belief, the material presented in this thesis is original except where due reference is made in text.

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ABSTRACT

Accurate predictions of the timing of harvest and crop yield are of major benefit to large scale commercial tomato growers as they support efficient utilisation of resources and enable planting schedules to be managed so that there is a regular supply of product to the market. The predictive tools available to field tomato growers are limited as most tomato crop models have been developed for greenhouse conditions and indeterminate tomato cultivars. As the success of a crop yield forecasting system strongly depends on the crop simulation models ability to quantify the influence of weather and management practices on plant development, data describing effects of these factors on the key developmental events of flowering and fruit maturity are valuable.

In this study the effects of a range of management factors and planting times on flowering and fruit maturation were assessed in field trials and commercial crops. Analysis of commercial crop data from 217 crops grown over three production seasons in the Bundaberg region in Queensland, Australia demonstrated the dominant effect of temperature on crop development and also identified differences in developmental rate due to soil type. Replicated field trials revealed a small but significant effect of crop pruning strategies on flowering time and harvest date. Varying the fruit load on plants pruned to produce different branching patterns induced no significant changes in the photosynthesis rate of the plants, indicating that plasticity in source sink relations exist with new shoots from the axils of the leaves replacing fruit as the major sink in plants with reduced fruit load. It was also observed that varying the branching patterns in field grown tomato had a significant impact on assimilate partitioning and that this response resulted in a significant branching pattern effect on harvesting date of the crops. The fruit maturation rate and first harvesting time of commercial field grown tomato was influenced by pruning strategy, with the optimum strategy being that which maintained a desired source-sink ratio of vegetative and reproductive sink organs for optimum yield of the crops.

Base thermal time and seasonal pattern models for prediction of harvest date were developed that provided improved predictability over the current calendar date model used by industry. No adequate prediction of yield was achieved, and much more work is

needed in identification of the key factors causing the very large crop to crop differences in yield in commercial production in the study location

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ABBREVIATION

SP = Smith and Philip

CVS = Colour vision system

DSS = Decision support system

RUE = Radiation use efficiency

PPDF = Photosynthetic photon flux density

LAI = Leaf area index

APSIM = Agricultural production system simulator

CROSPAL = Crops simulator picking and assembling libraries

FSPM = Functional-structural plant models

SAM = Shoot apical meristem

IM = Inflorescences metamers

CV = Coefficient of variation

QY = Quantum yield

PAR = Photoactive radiation

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LIST OF PUBLICATIONS AND PRESENTATIONS

- **Modelling Tomato Harvesting:** Research Abstract (Poster) presented in Australian Society for Horticultural Science (ASHS) conference Lorne, Victoria, September 2011.
- **Modelling subtropical tomato crop production:** Conference paper presented in "High Value Vegetables in Southeast Asia: Production, Supply and Demand" 24-26 January 2012, Chiang Mai, Thailand.
- **Modelling of crops: field grown tomato yield forecasting:** Book chapter in Handbook of Vegetables: Volume II; Editor: K.V. Peter and P. Hazra.
- **Predicting field grown tomato crop performance:** Conference paper presented at international horticultural conference, Brisbane 2014.

CHAPTER 1

PROJECT OVERVIEW AND BACKGROUND

PROJECT OVERVIEW

This project was initiated by SP Exports, an agricultural company specialising in the production of field grown fresh tomatoes. In order to improve their capacity to provide year round supply of agreed volumes of fruit to major customers, the company was interested in developing systems to better predict and manage the timing of harvest and yield in field grown tomato production. This project examines aspects of tomato production under sub-tropical field conditions to generate the data needed to adapt existing tomato crop models or develop new models to predict harvest date and yield.

At the time the project commenced, SP Exports was the leading field grown fresh tomato producing company and the largest supplier of fresh tomatoes in Australia. The company had been a major fresh market tomato producer for over two decades and is based in the Bundaberg-Childers area in the Wide Bay region of Queensland, Australia. SP Exports has a long history in growing the tomato crop and has developed cultural practices suited to production in the sub-tropical environment of the Wide Bay region. The area producing tomato crops in the Bundaberg area by SP Exports is approximately 600 hectares, with crops grown at individual sites only once a year as part of a rotation with other vegetable crops and sugar cane. The company operates two separate pack houses in the region and has made significant investments in pack house technology. It has colour vision system (CVS) fruit grading machines for grading automatically and specialised packaging equipment for value added products required to meet the specifications of customers. The fruits are distributed all over the Australia and also exported to New Zealand through different market chains.

The Bundaberg region is the main field grown fresh tomato production area of SP Exports, but the company also extended its production to Bowen (Queensland) and Shepparton (Victoria) to better service year round supply contracts with supermarket chains. The field tomato production season in the Bundaberg district is from March to January, with the greatest production volumes in the late autumn period (May to July) and in spring/early summer (mid-October to December). The company grows Roma, Gourmet, Cherry and Grape tomatoes types to meet consumers demand in the market, and are also the sole Australian producer of gel-less tomato fruit which are marketed under the Intense- brand. Careful scheduling of crop production is required to manage the volume of production needed across multiple product lines and production locations. The threat of climate change and seasonal variability of production environment as well as the opportunities for increased domestic and export markets increase the complexity of management of the production schedule.

Decision support systems, incorporating crop models, are tools widely used in horticultural industries to assist growers to manage crop scheduling. The adoption by SP Exports of a crop model capable of predicting timing of harvest and yields from crops offers the potential to increase the efficiency of the company's production schedule. This project aims to provide data required for the development and adoption of a reliable field grown tomato crop model for the company.

BACKGROUND LITERATURE

THE TOMATO CROP

Tomato (*Solanum lycopersicum* L.; previously named *Lycopersicon esculentum* Mill.) is the world's second most important vegetable crop, and the tomato fruit is a valued component of the diet in most countries. Fruit is consumed in different ways as a raw, use in many dishes as an ingredient, salads, sauces and juice as a drink. The green and ripened fruit of tomato is also used for pickles. The fruit is good source of lycopene that has many beneficial effects for our health (Edward, 1999).

The wild species of tomatoes are considered to be originated from Ecuador south to northern Chile and the Galapagos Islands (Jenkins, 1948). The tomato fruit was spread around the Asian continent and Europe after the colonization by the Spanish in Americas. The fruit was distributed to Southeast Asia via Philippines by Spanish and later to the whole Asia. In Europe, the tomato was grown first in 15^{th} or early 16^{th} century as ornamental or curiosity plants and many people thought that it was poisonous to eat. The fruit was used as a vegetable in southern part of Europe only at the end of 16^{th} century. Although, it is originated in a sub-tropical climate (Jenkins, 1948), scientists have developed new cultivars through breeding program suitable to different climates from temperate to tropical zones.

Tomatoes are dicotyledonous plants and have many axially branches in the main shoot and other side shoots of the plant. The plants can be classified as determinate, semi-determinate and indeterminate based on the growth characteristics. The growth and development of the shoot in all types of tomato is sympodial. Some cultivars of tomato have simple leaves, but most of the cultivars have compound leaves. The leaves are 10-25 centimetres long, arranged in odd-pinnate and the petioles have up to nine leaflets. The leaflets of the flower are around eight centimetres long (Acquaah, 2002) and dense glandular hairs on the stem and leaves. The leaves are usually arranged around the stem in a spiral with a 2/5 phylotoxy (Varga & Bruinsma, 1986). The flower of the cultivated tomato plant is self-pollinated and the flowers are located 1-2 centimetres from each other and the corolla have five pointed lobes and yellowish colour.

Botanically, the tomato fruit is classified as a berry and is also called a true fruit but for culinary purposes, it is used as a vegetable. The fruit develops from the ovary of the flower after fertilization and the flesh is comprised of the peri carp walls. The fruit is filled with seeds and moisture in the hollow spaces called locular cavities. Most modern tomato varieties are smooth-surfaced and the fruits of hybrid varieties come in different sizes and shapes including round, flat, rectangular, ellipsoid, heart, long, obovoid and oxheart (Rodriguez et al., 2011). The colour of the fruits from the most common red form to yellow, orange, pink, and purple, but only red are widely available in markets.

GLOBAL TOMATO PRODUCTION

Globally, tomatoes are a very widely cultivated crop in open field and glasshouse production systems for fresh consumption and for processing. The crop is grown in both temperate and tropical regions, which together represent a total global production area of approximately 5.22 million hectares and a total estimated volume of production of 129.6 billion tonnes (FAO, 2011). China and Spain were the dominant countries for production and export of tomatoes by volume respectively (Table 1), while Mexico and USA were the leading countries for export and import tomatoes by value. In contrast, Australia had an annual volume of production of 472,000 tonnes from 7734 hectares in 2009/10 (Table 2).

Table 1: *World's main tomato producers and exporters countries in 2009 by volume (tonnes) and main exporters and importers countries in 2010 by values*

Country *	Production(Tonnes)	Country *	Exports (Tonnes)	Country #	Exports (Tonnes)	Price/kg+	Country #	Imports (Tonnes)	Price/kg+
China	45 365 543	Netherlands	976 435	Mexico	1 509 616	1.06	USA	1 532 492	1.23
USA	14 181 300	Spain	829 500	Morocco	784 965	0.73	Russia	699 282	1.11
India	11 148 800	Turkey	542 259	Turkey	574 279	0.83	Germany	681 216	1.96
Turkey	10 745 600	Morocco	410 118	Jordon	371 257	0.63	France	497 388	1.22
Egypt	10 278 500	Belgium	200 483	USA	224 278	1.67	United Kingdom	384 602	1.74
Italy	6 878 160	France	196 456	Belgium	191 101	1.47	Canada	193 587	1.56
Iran	5 887 710	Portugal	106 559	France	189 462	1.87	Italy	97 271	1.36
Spain	4 603 600	Italy	93 185	Canada	166 870	2.14	Czech Republic	91 419	1.45
Brazil	4 310 480	Poland	72 385	Italy	128 797	2.23	Sweden	85 683	2.02
Mexico	2 591 770	Egypt	23 867	Israel	66 568	1.11	Belgium	77 338	1.88

Source: French Ministry of Agriculture; the Statistical Division (FAOSTAT) of the Food and Agriculture Organization of the United Nations (FAO) and United Nations Conference on Trade and Development (www.unctad.info/en/Infocomm/AACP-Products/COMMODITY).

* *Main tomato producers and exporters countries by volume (Tonnes) in 2009*

\# *Main tomato exporters and importers countries by value (US $) in 2010*

\+ *Price per kg in US ($)*

The majority of global tomato production occurs in sub-tropical/tropical regions of the world in countries with large populations. These countries include China, Turkey, India and Egypt where large domestic consumption accounts for much of the production. Countries in temperate climatic regions tend to be the biggest importers of tomato, but in a number of cases also have large domestic production, through use of protected cropping, and significant exports of higher value fruit. Much of the research on tomato crop production has focussed on intensive production systems, often greenhouse systems, in these developed countries in the temperate climate zones. Few developed countries have large scale tropical/subtropical zone field tomato production systems.

AUSTRALIAN TOMATO PRODUCTION

Australia is one developed country where domestic tomato production is dominated by field production in subtropical and tropical production regions. While area and volume of production in Australia are low by global standards, the crop is a significant one for the country as production is predominantly for domestic consumption. Australia is a net exporter of fresh tomato and a net importer of processed tomato products (Table 2), but import and export volumes for both fresh and processed tomatoes are very low. There is considerable yearly and seasonal variability in tomato production primarily as a result of weather patterns affecting the field based production systems.

Table 2: *Production of tomato, business involved, gross value production, exports, imports and consumption in 2007-2011 in Australia.*

		2007-08	2008-09	2009-10	2010-11
Production Area (ha)	Fresh Tomato	4487	3789	4292	7150
	Processing Tomato	2308	3000	3442	2850
	Total	6795	6789	7734	10000
Production (000 tons)	Fresh Tomato	231	169	207	407
	Processing Tomato	151	271	265	87
	Total	382	440	472	494
Business Involved	Fresh Tomato	927	841	809	N/A
	Processing Tomato	N/A	N/A	N/A	22
Per Capita Consumption (Kg/person)	Fresh Tomato	18	20	21	18
	Processing Tomato	23	24	23	24
Gross Value Production ($million)		405	342	347	418
Exports Fresh Tomato (Tonnes)		4671	2708	3480	2385
Imports Fresh Tomato (Tonnes)		1254	1390	1629	3360
Processed Exports (Tonnes)		7	7	8	7
Processed Imports (Tonnes)		49	48	37	55
Apparent Processed Consumption (Tonnes)		143	222	207	107

Sources: Australian Food Statistics 2010-11. ABS, International Trade, Australia, cat. no. 5465.0, Canberra; ABS, Agriculture, Australia, cat. no. 7113.0, Canberra; Australian Processing Tomato Research Council, Victoria; ABARES Australian Vegetables Growing Farm Survey 2012. ABS 2012, Value of Agricultural Commodities Produced, Australia, cat. no. 7503.0, Australian Bureau of Statistics, Canberra.

Tomato is the second largest vegetable crop in Australia by both volume and value (Table 3). Potato is the dominant crop grown for both fresh market and processing, and has a combined production volume of 1.88 million tonnes in 2010/11. Tomato production in Australia in 2010/11 occupied approximately 10,000 ha, of which around 80% was for fresh tomato production. The area of production of field grown tomatoes has increased in recent years and it may be due to the involvement of the new tomato growers and /or increase in their business size. The fresh tomato industry produced 407,000 tonnes of saleable fruit with a gross value of production of $A328m. The state of Queensland is Australia's largest vegetable producer, and tomato production represents around 13% of the total value of vegetable production in the state. The crop is therefore significant to the state's economy, and in particular to the economies of the regional areas in which the majority of the crops are grown.

Table 3: *Proportion of vegetables production from each state, 2010–11 (in percentage and value terms)*

Vegetables	Values (AUS $ Million)	Queensland %	Victoria %	South Australia %	New South Wales %	Western Australia %	Tasmania %	Northern Territory %
Potatoes	553	9	20	34	11	9	16	0
Tomatoes*	418	55	13	12	11	9	1	0
Mushrooms	293	14	33	7	34	0	0	0
Onions	274	13	9	49	5	10	14	0
Melons	188	29	3	2	28	15	0	23
Lettuce	164	39	34	6	10	8	2	0
Carrots	131	10	20	20	1	34	16	0
Beans	130	73	19	0	1	5	2	0
Capsicums	114	73	4	9	3	8	2	0
Broccoli	105	28	47	2	5	16	2	0
Sweet corn	86	42	16	0	11	31	0	0
Pumpkins	71	36	3	4	35	18	1	3
Asparagus	69	0	97	0	2	1	0	0
Herbs	46	58	27	3	10	2	0	0
Cauliflowers	43	27	30	9	17	12	5	0
Green peas	10	13	20	0	5	1	61	0
Other vegetables	645	40	20	6	18	3	0	6
Total vegetables (%)	100	32	22	14	13	11	6	2
Total Value (AUS $ million)	3338	1077	729	500	439	357	184	52

Source: ABS 2012, Value of Agricultural Commodities Produced, Australia, cat. no. 7503.0, Australian Bureau of Statistics, Canberra

** The values in million is for both processing and fresh tomatoes and the percentage value is only for fresh tomato production in each state*

The majority of Australia's processing tomato production is summer crops grown in the temperate zone in the state of Victoria (Table 4). The Victorian region produces approximately 87 percent of the total processing tomato production in Australia, while the states of New South Wales and Queensland produce around 11 and 1 percent respectively (PTRC, 2012-13).Two processing tomatoes companies, Cedenco and SPC Ardmona, operate in Australia, while a third company, Heinz, ceased operations in 2012.

Table 4: *Tomato production (tonnes) both processing and fresh by state in Australia in 2007-010*

State	2007-08	2008-09	2009-10
Victoria	174 379	243 647	285 962
Queensland	132 444	138 153	101 842
New South Wales	46 848	27 546	55 177
South Australia	14 808	10 390	14 202
Western Australia	12 317	19 540	13 085
Tasmania	997	773	1 632
Northern Territory	30	43	1
Total	381 823	440 092	471 883

Source: GTIS-ABS for 2009/10; Australian Food Statistics 2010.

The main production regions for field grown fresh tomato in Queensland are Bundaberg, Bowen, Granite Belt and Locker Valley. The dry tropical or wet sub-tropical climate regions of Bowen and Bundaberg respectively are optimal for production through the autumn, winter and spring seasons, whereas the southern Queensland regions of the Granite Belt and Locker Valley support summer production. The capacity to produce field grown crops year round in Queensland provides an advantage for tomato production compared to other regions of Australia.

The Bundaberg region in Queensland has seen rapid expansion in tomato production over the past few years (Table 5). The tomato production sector is a major contributor to the local economy and a significant employer in the region. The research undertaken in this project is focussed on this region and aims to support the continued expansion in production by local producers.

Table 5: *The area of tomato production and production values by different growers in Bundaberg in 2002-2010.*

		2002	2003	2004	2005	2006	2007	2008	2009	2010
Cherry Tomato	Area (ha)	80	95	170	240	150	170	115	150	190
	Value*	8.4	9.1	13.1	20.4	23.6	25.8	14.0	25.9	25.9
Roma and Gourmet Tomato	Area (ha)	640	640	650	695	860	830	1120	1510	1470
	Value*	54.9	58.3	52.1	62.8	68.4	94.3	86.5	130.2	136.5
Total Production	Area (ha)	720	725	820	935	1010	1000	1235	1660	1660
	Value*	63.3	67.4	65.2	83.2	91.9	120.1	100.5	156.1	162.4

Source: Lovatt, JL, Queensland Government, Department of Agriculture, Forestry and Fisheries, Bundaberg Research Facility, Queensland, Australia

*Australian $ in million

Queensland field tomatoes are sold to wholesale markets or direct to super market chains in Australia, and a small volume of fruit is exported. New Zealand, Singapore, Papua New Guinea, Indonesia and New Caledonia are the main exporting markets. Of the exported fruit, more than 90% tomato was exported from Queensland (ABS, 2012).

The market for field grown fresh tomato in Australia is dominated by two supermarket chains, Woolworths and Coles. These supermarkets set supply volumes for different types of tomato fruits, with specific quality specifications, and suppliers compete to gain contracts for supply of fruit to the supermarkets. A key requirement for contracts is a consistent supply of quality fruit to the supermarkets in all seasons of the year to satisfy consumer's demand. As a high production cost country, field production relies on a combination of practices to maximise productivity and keep production cost as low as possible.

PRODUCTION ENVIRONMENT

Tomato production occurs in all tropical, subtropical and temperate zone where seasonal field production of fresh and processing and a small but increasing volume of greenhouse production occurs. Field production in the temperate zone is restricted to fresh market and processing tomato in the winter season. Field production of fresh market tomatoes occurs over a much more extended period in the subtropical and tropic regions in Australia, with near year round production possible. Seasonal weather variability therefore plays a much greater role in influencing production of tomatoes in these regions than in the single summer season production in the temperate zone.

Bundaberg and Bowen regions are the main production regions for field grown fresh tomato in Queensland, producing more than 80% of the States tomatoes. The two regions are in different climatic zones, with Bundaberg situated at - 29.91^0 latitude and 152.32^0 E longitudes whereas the Bowen is situated at - 20.02^0 latitude and, 148.22^0E longitude. The average rainfall in Bundaberg and Bowen are similar, being 965.8 mm and 907.2mm, respectively, but the more northerly Bowen region is in a tropical zone whereas Bundaberg is sub-tropical.

The climatic differences between the regions result in differing production seasons, with only the summer season where production is marginal in both regions. While climate in both regions is favourable for tomato growth for most of the year, the cooler winter season in Bundaberg can result in delayed maturity and variability in yield. The hotter and wetter summer season in the Bowen region results in a longer period where summer production is challenging compared to Bundaberg. The maximum day/night temperature range of 28/22 ^{0} C is considered favourable temperature range for tomato crop (Peet et al., 1998). The average maximum and minimum temperature in all seasons in Bundaberg and Bowen are 26.6^0 C, 16.4^0 C, 28.6^0 C and 19.6^0 C respectively (Australian Bureau of Metrology Data). Growth of the tomato plant is retarded if the night temperature is below 13^0 C and a high day temperature above 30 ^{0}C even for 4 hours has negative effects in flowering and fruit set (Peet et al., 1998). The temperature range in Bundaberg is therefore suitable for tomato crop production except some cold days in winter season, where sometimes low night temperature restricts growth and some hot days in summer season where high temperature can reduce yield. The temperature in Bowen in winter is within the suitable range but during an extended summer season the high day and night temperature range may induce flower abortion and very low fruit set, resulting in low yield.

PRODUCTION SYSTEMS

Tomato production systems in Australia may be divided into three broad categories; field production for processing, field production for fresh market, and protected cropping systems for fresh market. These three systems are distinctive in terms of tomato varieties, management practices and harvesting systems used.

Processing tomato systems utilise determinate tomato cultivars, are direct seeded, use either drip or furrow irrigation and are grown without trellising. The crops are not pruned or trained, and all fruit is harvested in a single mechanised harvesting operation. Growth regulators may be used to promote uniform ripening. Field production for the fresh market is based on use of semi-determinate type tomatoes on a trellised cropping system. The height of the vertical trellis is about 1.8 meters, with horizontal wires on each side of the plants to support the crop. Wires are added and tightened as the crop develops until the canopy reaches the top of the trellis, with five wires on each side of the crops normally used. Side shoots from the lowest nodes on the plants are normally removed but branching higher in the canopy is allowed to develop. Some pruning of shoots above the height of the trellis is commonly practiced. Drip irrigation and fertigation is almost universally used in the major production regions. Crops are hand harvested and multiple passes through each crop occur as fruit ripening within each plant is not synchronous. Fruit from production sites is transported to packing sheds where grading lines incorporating colour sorting are used to grade and pack fruit.

The greenhouse tomato industry has until recently been characterised by small producers in low cost plastic house structures. Recently two major greenhouse developments have occurred in Australia, the Blush Tomato in Guyra, New South Wales (NSW) and d’ Vine Ripe tomato company in Adelaide, South Australia producing tomatoes in 40 and 27 hectare protected cropping structures respectively. These modern, computer controlled facilities incorporate sophisticated technology for fertiliser, irrigation and temperature control in addition to carbon dioxide enrichment.

Indeterminate tomato types are utilised, and plants are pruned to remove all the side shoots and trained using a moveable trellis system. Crops are grown in hydroponics using inert substrates. Fruit are hand harvested but self-powered mechanical aid picking trolleys using automatic guidance system. The packing sheds in the hi-tech greenhouses are fully automated.

The investment in greenhouse tomato production in Australia underlines increasing fresh market competition between field and greenhouse producers, with consistency of supply and quality favouring greenhouse production. The quality of tomato fruits and consistency in required volume can be maintained more easily in protected cropping systems compared to field grown crops. Production costs however tend to be lower in field production as the infrastructure investment and facility running costs in greenhouse systems are high. Field tomato producers are therefore seeking to improve consistency and quality while retaining lower costs of production in order to remain competitive and profitable. A strategic area of focus for field tomato producers is gaining an understanding of the factors contributing to variability in harvest date and yield, and using this understanding to develop tools to better manage the variability. Modelling and generation of knowledge to underpin models, is thus an area of interest to the industry.

CROP MODELS

Crop models are a versatile tool in both research and the integrated management of vegetable crop production. Crop modelling has emerged over the past 30 years to become a major focus of research attention, and much has been learnt in the development and application of crop modelling. 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.

Crop models may be described as quantitative schemes for predicting the growth, development and yield of crops based on a given set of genetic features and relevant environmental and crop management variables (Monteith, 1996). Most models are specific to individual cultivars or varieties of an individual crop but may be adopted to suit other cultivars through modification of the responses to environmental and crop management variables. The majority of the models include temperature as an environmental input variable, with other environmental and crop management variables incorporated based on the level of influence of the factors on crop growth and development processes and the intended purpose of the model. In all cases, the crop models are based on mathematical algorithms that either represents the reactions which occur within the plant and the interactions between the plant and its environment, or can accurately forecast a crop growth, development, or yield parameter using selected input data.

The mathematical basis and selected inputs for a crop models vary with intended application, with published models currently being used for many different purposes. Many models can be used as research tools as a natural continuation of the experimental approach to a problem; for example significant advances in modelling leaf and canopy photosynthesis come from studies on tomato and chrysanthemum plants (Acock, 1991). Models may also be used to integrate knowledge across disciplines and research areas for further improvements in describing and understanding complex systems. Crop models have been developed for use as teaching materials to students, with the SIMULSERRE educational software on production and management of greenhouse tomato crop (Gary *et al*., 1998) an example of a crop model with application in teaching. Crop models have also found application in testing hypotheses, comparing different production or future climate scenarios, risk assessment within decision making processes, and in policy analysis, while models exist for each of these purposes, by far the greatest application of the crop model has been in predicting the timing of harvest and yield of crops.

Predictions of the timing of harvest and crop yield are the two most important model outputs for decision making in the crop production system. These outputs help large scale commercial 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 & Jones, 2000). Harvest date and yield models vary from relatively simple heat unit models based solely on temperature inputs, for example models developed for tomato (Perry *et al*., 1997) and cucumber crops (Perry *et al.*, 1986), to complex mechanistic models incorporating a range of inputs for a series of components parts covering different processes in the crop (Marcellis *et al.*, 1998; Boote et al., 2013; Wada et al., 2013), and decision support systems capable of integrating crop, climate and economic components in modular model structures to deliver outputs able to be aggregated at different temporal and special scales (Rosenzweig *et al*., 2013). 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.

Several tomato crop models have been developed for greenhouses production in temperate climate US and European production conditions such as TOMGROW (Dayan et al., 1993a), TOMSIM (Heuvelink, 1996), HORTISIM (Gijzen, *et al.*, 1998), TOMPOUSE (Abreu et al., 2000), but few models exist for field tomato production such as CROPGROW (Scholberg et al., 1997) and these models have limited application outside the production regions for which they were produced (Scholber et al., 2000).

The development of sophisticated production systems for both field production and protected cropping has allowed growers to meet expanding global demand for tomato products. Tomato crop models underpinning decision support systems (DSS) have been one of the key innovations supporting modern tomato production systems. Crop modelling has become an important tool in many agricultural industries, and a wide range of models have been developed covering all significant crops and incorporating a broad range of crop specific inputs (Monteith, 1996; Boot et al., 2012; Adam et al., 2012). 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 & Jones, 2000). Harvest date and yield models vary from relatively simple heat unit models based solely on temperature inputs, for example models developed for tomato (Perry *et al*., 1997) and cucumber crops (Perry *et al*., 1986), to complex mechanistic models such as the model described by Marcellis and Gijzen (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.

CROP MODEL TYPES

Crop modelling has its origins with the development of computers which allowed rapid manipulation and analysis of data. Crop models have evolved from relatively simple simulations of processes such as light interception and photosynthesis to the complex modular models currently available to simulate an array of productivity, environmental and economic components of cropping systems (Hansen & Jones, 2000; Adam et al., 2012). Crop modelling is thus a broad field and covers many styles of model that may be classified based on structure, functionality or objective. This chapter focuses on one crop model objective, yield forecasting, and is not intended as a comprehensive review of the full spectrum of crop modelling research and application. More extensive coverage of crop modelling can be found in a number of excellent texts covering crop modelling and decision support systems (Matthews and Stephens, 2002; Soltani and Sinclair, 2012; Teh, 2006).

Crop models can broadly be classified into two different groups based on the approach used in crop modelling. The two types of mathematical models are mechanistic and empirical, sometimes referred to as scientific and engineering approaches. Mechanistic, explanatory or process-based crop models are developed based on an understanding of plant physiology and the plant responses to environmental changes. In contrast, the mathematical algorithms develop in empirical models do not rely on any relationships between input data and plant responses generated from an understanding of plant processes (Passioura, 1996). For this reason, empirical models are commonly referred to a black box models as they are not able to explain any of the plant processes that link the input data and the model output (Penning *et al*., 1989).

Many of the early crop models were empirical and were developed from agronomic trials relating crop yields to defined management or climatic variables using correlation and regression analysis. Empirical crop models are much simpler than mechanistic models, generally using only a few variables and processes to predict crop yield. Mathematical algorithms including polynomials, exponential functions, hyperbolae, sigmoidal curves and several environmental factors combined in a multiplicative function (Larsen, 1990) have all been used in empirical model development. The approach identifies the algorithms that best describe previously recorded outputs (for example, crop yields, timing of growth and development processes) using input data (generally environmental factors) recorded at the time of generation of the output data. Empirical crop models may be very accurate when based on large amount of quality crop production data, but are generally only applicable to the production system and environment from which the data were drawn.

Mechanistic models are considered more valuable than empirical models, particularly for research purposes. In contrast to the limited situations in which black box models may be used, these models may be used to test hypotheses, synthesize knowledge and to help understand complex systems. Most explanatory crop models are photosynthesis based models and are process oriented whereas the descriptive models, based on plant growth analysis, are classified as function oriented models (Gary *et al*., 1998). Mechanistic models contains sub-models at least one hierarchical level deeper than the response to be described and its sub models are descriptive. As our understanding of the complex processes of plant functioning is far from complete, the mathematical algorithms within the sub models are essentially empirical, but the structuring of the sub models within complex mechanistic models better reflects the processes involved in determining the overall response being modelled. Mechanistic crop models do have some disadvantages when compared to empirical models, having longer computing time and usually containing many more input variables (Larsen, 1990) making the model parameters harder to estimate. Both empirical and mechanistic crop models have been used for prediction of harvesting date (growing period) in horticultural crops, but mechanistic models incorporating components based on the photosynthetic process are more commonly used than empirical models for prediction of yield (Marcellies *et al.*, 1998) as limitations associated with computing time have now largely been overcome.

Mechanistic models require detailed knowledge of key processes in crop growth and development. Physiological processes and biochemical reactions driving developmental events such as germination, development of leaves, stems, flowering and fruit growth all affect the desired model output parameter and are therefore important in model development. Models predicting yield invariably incorporate aspects of the photosynthetic process. At the simplest level, the light intercepted by the crop leaf area is calculated to simulate photosynthetic production and its subsequent use for respiration and conversion into structural dry matter. Crop growth can be estimated by using the amount of absorbed light that demonstrated strong linear relationship between cumulative absorbed solar radiation and accumulation of the dry matter in different crops (Vos and Heuvelink, 2009). The partitioning of assimilates or dry matter among the different plant organs can then be modelled and the fresh weight of any part or organs can be estimated from the dry weight. Most models are based on this direct relationship between intercepted radiation and dry matter production, as well as between dry matter production and leaf area expansion (Fredrick and Lemeur, 1997; Vos and Heuvelink, 2009). Where reproductive structures are incorporated in models, specific environmental requirements for initiation of flowering and formation of fruit also need to be addressed (Boote et al., 2012). The effects of limited water and nutrients availability is also considered in many field crop models, although for horticultural crop grown under intensive production systems these parameters, along with impacts of pests and diseases, are often ignored as it is assumed that management intervention precludes the factors from impacting significantly in crop growth and development.

Simple heat unit models (Austin and Ries, 1965; 1968; Perry *et al.,* 1997) to more complicated models (Wolf et al., 1986; McAvoy et al, 1989a; Cockshull et al., 1992; Hisaeda and Nishina (2007); Higashida, 2009; Wada et al., 2013) based on solar radiation are two weather based approaches used for predicting of harvest time and yield in tomato crops. Perry *et al.,* (1997) examined heat unit models to predict harvest time in field grown tomatoes in southeast USA. Heat unit summation methods were found to provide an improved accuracy of harvest time prediction when compared with the industry practice of prediction based on a standard number of days after planting. Many studied in greenhouse tomato crops have also concluded that yield prediction can be done based on solar radiation. Higashide (2009) described that yield can be predicted using a model based on solar radiation from 10 to 4 days before anthesis. Hisaeda and Nishina (2007) also explained that the yield in greenhouse tomato crops can be predicted based on cumulative solar radiation 8 weeks to 1 week before harvesting. Wada et al., (2013) found that yield can be predicted from the simulation model of integrated solar radiation and averaged air temperature at 19 to 27 ºC in single –truss system in greenhouse grown tomato crops.

Heat unit accumulation models were also used for predicting first harvest and yield of other fruits and vegetables crops. Perry and Wehner (1996) described that heat unit models can predict more accurately than calendar day methods for predicting cucumber harvesting in North Carolina. Tan et al., (2000) also used that heat unit models best predict the duration of chronological time from emergence to harvesting of broccoli. Umber et al., (2011) studied the heat unit requirement for harvesting of two new banana hybrids for exports, while Marra et al., (2002) concluded that thermal time models can predict harvesting time of peach fruit during the first 25 to 52 days of fruit development period in different cultivars. Heat unit models reduced the prediction error from 69 % to 22 % depending on cultivar when compared to a calendar day method in high bush blueberry fruits (Carlson & Hancock, 1991). Hueso et al., (2007) noted that heat unit models are superior to calendar day method for predicting harvest maturity of the 'Algerie' loquat, but only in water- stressed trees.

GREENHOUSE TOMATO MODELS

The tomato is a globally important vegetable crop and as such has been widely studied. Many of the processes of plant growth and development that are required for crop model development have been identified and documented. 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 (eg Perry *et al*., 1997; Warnok and Isaak, 1969) to black box harvest date prediction (eg Hoshi *et al.*, 2000) and complex mechanistic models including HORTISIM (Gijzen, *et al.*, 1998); TOMGROW (Dayan *et al.*, 1993a); TOMSIM (Heuvelink, 1996); TOMPOUSE (Abreu *et al*., 2000); and CROPGROW (Scholberg *et al*., 1997). Other models have focused on specific aspect of crop development such as dry matter partitioning (eg Heuvelink, 1996) and postharvest aspects such as fruit firmness (eg Schouten *et al*., 2010), fruit quality (eg Schouten *et al.*, 2007) and pack house operations (Miller *et al*., 1997). The mechanistic 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 mechanistic models, the most widely reported and adopted models are TOMGROW (Dayan *et al*., 1993a), TOMSIM (Heuvelink, 1995b), CROPGROW (Scholberg *et al*., 1997) and TOMPOUSE (Abreu *et al*., 2000). 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.

TOMGROW (Dayan *et al.*, 1993a) is a dynamic crop model developed for indeterminate type tomatoes grown under controlled environmental conditions in greenhouses. This model is reported to be useful for managerial decision support system to produce economically optimum level (Dayan *et al*., 1993b). The model was designed to respond to dynamically changing temperature, solar radiation and CO_2 concentrations in predicting harvest date and yield in single stemmed plants. Key assumptions in the model are that no water or nutrient stress occurs in the production system. The total dry matter production is based on a quantitative description of carbon balance including gross CO_2 assimilation plus maintenance and growth respiration. The modular set up of the model is designed to provide flexibility so that it can adapted to other crops or production situations.

A major drawback of TOMGROW crop model is that the effects of nutrient and water stress on the growth of field grown tomato cannot account for. For this reason, McNeal *et al.*, (1995) found that the TOMGROW model did not adequately describe the growth of field grown tomatoes. In addition, only fruit production on the main stem is considered as all side shoots are assumed to be removed (Vooren *et al.*, 1986). Field production of tomatoes does not always involve removal of side shoots and, as the presence of the side shoots will influence assimilate partitioning to both vegetative and reproductive organs on the side shoots, the capacity of the model to simulate fruit development and yield on both main and side stems is likely to be compromised.

TOMSIM (Heuvelink, 1995a) is also a dynamic simulation model that explains the dry matter distribution between vegetative and reproductive plant parts and distribution among individual fruit trusses in greenhouse tomato. This model has also flexibility for new input parameters to apply for different environmental conditions. The quantitative data used to validate the model for dry matter distribution is limited to temperate greenhouse conditions and the number of set fruit per truss was not modelled as fruit per truss is considered to be a set characteristic for a specific cultivar (De Koning, 1996a). The capacity to determine the number of set fruit per truss as an input parameter in the model still may be a serious limitation to use of the model for field production.

CROPGROW (Scholberg *et al.*, 1997) is a process oriented model and is based on the flow of carbon, water and nutrients within the soil-plant-atmosphere continuum. The model was developed and validated in determinate processing tomato cultivars grown under field conditions, and recently has been refined through addition of modified temperature parameters (Boote *et al.*, 2012). CROPGROW can addresses cultivar specific characters in the input parameters to determinate processing tomato cultivars grown under field conditions, but is restricted to semi-determinate cultivars. The model will predict the fresh fruit yield with marketable and non-marketable fruit based on fruit size at the mature green stages for determinate tomato cultivars. While it is developed for field production of determinate processing tomato cultivars, the applicability of the model to semi-determinate tomato cultivars such as those predominantly used for fresh market production has not been tested and/ or it may need minor to major modifications to the use of this model.

TOMPOUSE (Abreu *et al.*, 2000) is a simple model for the simulation of the weekly production of greenhouse tomatoes. This model was developed in France to predict yield in heated greenhouse and has also been calibrated in unheated greenhouse conditions in Portugal. The model predicts the number of fruits and fresh weight of harvested fruits. It requires limited climatic and crop data, features that suit the model for use at the grower's level. The model is less complex than TOMGROW, TOMSIM and CROPROW, and has not been validated for field conditions.

Based on our evaluation; these three models (TOMPOUSE, TOMGROW and, TOMSIM) were developed and validated for indeterminate tomato cultivars grown in the greenhouse where the crop growth period may extend to one year (Scholborg et al., 2000). Only the CROPGROW model was used to simulate the growth of field grown tomatoes, but was developed for determinate cultivars used in the processing tomato industry and no any recent models were developed for field tomatoes. The semi-determinate tomato cultivars which are grown under warm climate field conditions for the fresh market have different growth characteristics and cultural practices that the cultivars used in the development of these four models. It is therefore, unlikely that these models will be able to be adopted directly for use for field grown semi-determinate tomato cultivars in subtropical climate production system. CROPGROW model would be more reliable than other models to simulate the growth of semi-determinate field grown tomato due to its use in determinate field grown processing tomato and calibration and validation using new input parameters in this model will be required (Scholberg et al., 2000). Knowledge of the environmental and crop management factors in this system that impact on the processes upon which the model algorithms are based is needed to identify the aspects of the models that may need to be modified to fit the production system.

TOMATO GROWTH CHARACTERISATION

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 et al., 2000). The growth and development of all types of tomato is sympodial. 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 growth of the plant and fruit dynamics of the determinate processing tomato crops was also explained by Pan et al., 1999; Nichols et al., 1999; 2001). 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. Field production for the fresh market 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 and competition among sinks (fruits and new vegetative growth) will occur. 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 (Schmitz & Theres, 1999). 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 & Polowick, 1985).

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. Modelling of crop growth is therefore focussed 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 an explanatory model applicable to field tomato crops.

The juvenile period of the tomato plant varies with environmental conditions, primarily light intensity and temperature. The flowering time of the plant is mainly depends on the light intensity and temperature. 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, 1995b).

Recent studies have focussed on the genetic regulation of tomato plant development, and many genes which are responsible for controlling vegetative and reproductive growth processes in tomato have been identified. As an example, the SELFPRUNNING (SP) gene controls the regular vegetative to reproductive switch of inflorescence meristems, and over expression of SP and the CENTRORADIALS (CN) gene has been shown to result in an extended vegetative phase and in an increased leafiness of the inflorescence itself (Pnueli *et al*., 1998). A limited number of studies have also examined the molecular genetics of branching in tomato. The genes BRC-1, SIBRC-1a and SIBRC-1b are involved in the regulation of the branching pattern. These genes are expressed in axillary buds during bud activation leading to side shoot growth. There are likely to be many more genes related to development of the architecture and structure of the tomato plant and this area remains an important field of research in understanding tomato growth and development (Eliezer and Yuval, 2006; Rafael et al., 2009); while current tomato crop models do not incorporate gene parameters, it is likely that in the future crop models will be improved both through the knowledge gained from molecular genetic research and the inclusion of specific genetic parameters into crop models(Rafael et al., 2009).

LIGHT AND TEMPERATURE

Knowledge of physiological processes generated through both field and greenhouse studies are valuable to understanding aspects of growth and development of tomato plants in field conditions. Results of previous studies (Adams *et al*., 2001, Uzun, 2007) have shown that temperature and light are the main factors which determine productivity of tomato crops. Increased light intensity has been observed to promote the development of inflorescences, hasten flower initiation and increased the rate of leaf production (Kinet, 1977), with the effect linked to light integral i.e. total photo synthetically active radiation received. A maximum day/night temperature range of 28/22 ^{0} C is considered favourable for tomato growth, and night temperatures below 13^{0} C retard tomato plant growth (Peet *et al*., 1998). Temperature also has major role in fruit growth, maturity and ripening processes. Higher temperatures increase fruit growth rate but have a greater effect on rate of maturation which results in reduced final fruit weight (Sawhney and Polowick, 1985).

Light in the photosynthetically active wavelengths (Photosynthetic Photon Flux Density, PPDF) is a key determinant of the productivity of the tomato crop. Crop productivity is strongly influenced by the total solar radiation incident upon the crop, with a decrease in PPFD and duration of light period especially in the winter season resulting in reduced crop yield. The average radiation use efficiency (RUE) in greenhouse tomato is 2.5 g /MJ (De Koning, 1996b), allowing modelling of growth rate based on incident radiation and crop canopy area. Tomato plants are photoperiod-insensitive i.e. day neutral (Pneuli et al., 1998) perennials in their native habitat, and exhibit perennial characteristics of growth, even during one short seasonal cycle. The developmental versatility and architectural flexibility of tomato are reflected in a plethora of gene mutations, affecting single growth modules such as the primary shoot, or the whole plant constitution (Eliezer and Yuval, 2006). Dominique et al., 1998 explained that the growth rate is linked to light integral rather i.e. total photo synthetically active radiation received than day length per se, the production of tomato is negatively affected by both short and continuously long photoperiod. The growth and yield of tomato plants grown under continuous light were generally lower than plants exposed to 14 hours of photoperiod (Dominique *et al.*, 1998), but recent developments involving introgression of tolerance genes into modern tomato hybrid lines, results in up to 20% yield increase, showing that limitations for crop productivity, caused by the adaptation of plants to the terrestrial 24-h day/night cycle, can be overcome (Velez-Ramirez et al., 2014) The leaves in the upper most canopy layer of the tomato plant represent 23 % of the total leaf area but have been reported to assimilate 66% of the net CO_2 fixed by the canopy (Acock *et al.,* 1978). Optimum canopy structure, measured as leaf area index (LAI), for semi-determinate type tomatoes has not been described but may be similar to greenhouse grown indeterminate type crops where a leaf area index of five produces a photosynthetic rate of 40 to 45 µ mol CO_2 per m^2 per second (Acock *et al.*, 1978). The light intensity is generally higher in field grown crops than in greenhouse crops, so higher photosynthetic rates may be expected.

Temperature is considered to be the most important environmental factor for growth and development of the plant. The tomato plant can grow in a broad temperature range but for optimum production it has certain temperature limits, and these limits vary in the different vegetative and reproductive growth and developmental stages of the plants (Peet et al., 1998). The optimum temperature for the growth and development of tomato plant ranges from18 to 27°C and 15 to 18°C for day and night time respectively (Witter and Aung, 1969). The daily mean temperature has been shown to be more critical than night time temperature. At a daily mean temperature of 29 °C fruit number, fruit weight per plant and seed number per fruit were markedly decreased compared with 25 °C (Peet *et al*., 1998). Reduced yield at high temperature can be explained by the effect of temperature on fruit set in tomato due to failure of viable pollen production for fertilization on the anther of the flower. Temperature increase from 28/22 °C (day/night) to 32/26 °C significantly decreased fruit set, but had no significant effect on photosynthetic rate in tomato plants (Peet *et al*., 1998; Sato *et al*., 2000). Prior to anthesis, developing pollen grains and anthers accumulate starch temporarily, but a moderate temperature increase reduces starch concentration in developing pollen grains and the viability of the pollen decreases (Pressman *et al.*, 2002). This temperature effect highlights the need to understand the influence of environmental factors on both overall growth rate of the tomato plants and on specific developmental stages such as fruit set that is very sensitive to temperature range in the development of crop models.

Flowering and fruit set are critical developmental stages in the production of tomato crops. The number of flowers and the rate of fruit setting in the tomato plants are the main parameters determining the productivity of the crop. Production of viable pollen on the anther of the flower, pollen germination on the stigma, growth of the pollen tube to the ovule and fertilization are required for fruit formation. Each of these processes is sensitive to high temperature (Iwahori and Takahashi, 1964; Abdalla and Verkerk, 1968). Changes that have been reported to contribute to poor fruit set under high temperatures include style exertion out of the antheridial-cone (Abdaalla and Verkerk, 1968), and browning and drying of the stigma (Abdalla and Verkerk, 1968), ovule damage (Iwahori, 1965), restricted germination and elongation of the pollen tube into the style (Iwahori and Takasahah, 1964; Iwahori, 1965), low amount of pollen production and disturbed gametogenesis and reduced viability of the pollen (Iwahori and Takasasha, 1964). The tomato microspore mother cells in meiosis are very sensitive to high temperature 8-9 days before anthesis and almost all pollen grains were found to be morphologically abnormal after exposure to temperatures above 40° C for a few hours (Iwahori, 1965). Prior to anthesis, developing pollen grains and anthers accumulate starch temporarily, but a moderate temperature increase reduces starch concentration in developing pollen grains and the viability of the pollen decreases (Pressman *et al.*, 2002). Bhadula and Sawhney (1989) concluded that the deficiency in carbohydrate metabolism in the tomato anther leads to abnormal pollen development. Similarly a heat stress induced reduction in sugar delivery to reproductive tissue leads to failure of gametophyte development (Saini, 1997). As greater temperature fluctuations are likely to occur in field compared to greenhouse production systems, the importance of temperature effects on fruit yield is magnified and mechanistic models must incorporate these temperature responses on the growth and development of the tomato plants. This also explains why tomatoes are not grown in the high temperature part of the year.

Temperature and light intensity affect the rate of crop development as well as the yield, and so are key components of models predicting timing of harvest. The growth rate of any organ of the tomato plant depends on total availability of photosynthates, sink strength of the organ, plant water status, nutrition , temperature and different other parameters. The relative growth rate for the tomato plant have been reported in the range 0.16-0.29 g/g/d with net assimilation rate (NAR) being of 18 $g/m^2/d$ and the absolute growth rate of fruit reaches maximum value of 2-3 g/ per day four weeks after anthesis, while the relative growth rates peak one week after anthesis with values of 0.8 g/g/day (Varga and Bruinsma, 1986). Average dry matter accumulation by roots, stems and leaves were 3, 23 and 17 % of final biomass, respectively (Scholberg *et al.*, 2000). Temperature has major role for fruit maturity and ripening process, with a rise in temperature increasing the fruit ripening rate. Tomato fruit ripened 95, 65, 46, and 42 days after flowering when plants were grown under controlled environmental condition at 14, 18, 22 and 26 °C respectively (Adams *et al.*, 2001).

The interaction between temperature and light must also be considered when modelling crop development. Uzun (2006) found that the leaf number below the first fruit cluster declined linearly from 13 to 6 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 development of the first inflorescence was decreased with increased light intensity (Kinet, 1977) and the effect was greatest at lower temperatures. This response may explain why, in cultivars such as Money Maker, M82, or VFNT-cherry, the number of leaves to primary termination, under constant low or high daily light integrals, may vary between 6 and 16 and the number of leaves per sympodial unit between three and six (Eliezer and Yuval, 2006). Complex interactions between light and temperature effects are likely to occur in field grown tomatoes due to the cloud cover and other variability in weather conditions to which crops are exposed, and these interactions make accurate modelling of field tomato crops more difficult than greenhouse crops.

TOMATO FIELD CROP MODELS

Tomato growth and development under commercial field production conditions are influenced by environmental and crop management factors that are not considered in greenhouse models. Moreover, it has been explained that plant response under fluctuating environmental conditions is affected by adaptation mechanisms that are not needed in protected cropping systems (de Wit *et al.*, 1978; Scholberg et al., 2000). In both systems dry matter production will be determined by carbon balance, but different factors may limit the rates of the reactions controlling the carbon balance: gross photosynthesis minus losses from growth and maintenance respiration. Light intensity, carbon dioxide concentration and temperature account for much of the variability in carbon balance under greenhouse conditions (Dayan *et al.*, 1993b), whereas supply of water and nutrients may limit assimilate production under field conditions. Carbon dioxide concentration will also remain relatively stable under field conditions and so be unlikely to affect crop growth, while the range of light intensity and temperature to which crops may be exposed is broader than that experienced in greenhouse production. Less is known about the effects of these factors on carbon balance processes across this broader range under field conditions than is known for the narrower range relevant to greenhouse production, while the potential impact of exposure to more extreme conditions on developmental events such as flowering and fruit set will also need to be considered in field production models.

Greenhouse crop management includes removal of all side shoots to produce single stemmed plants of indeterminate type cultivars whereas more complex branching systems occur in the semi-determinant type cultivars grown for field production. Simulating dry matter partitioning, and the associated rates and patterns of nodal segment or sympodial unit production in a branched plant requires a level of understanding of the regulation of carbon partitioning that is not required to model production in a single stemmed plant.

The development of functional-structural plant models (FSPM) which describe the three dimensional architecture of plants, governed by physiological processes that are influenced by environmental factors, may assist in understanding development in branched semi-determinant type tomato crops. Functional-structural plant models integrate plant structure and plant functioning modules, and are a promising tool to explore effects of plant management practices and environmental factors on crop development (Vos *et al*., 2010). These models simulate the plant structural responses that result from variations in environment and management practices, providing a plant architecture component to mechanistic models based on plant physiological processes. The FSPM approach has been used to simulate light distribution and interception in greenhouse tomato production (Buck-Sorlin *et al.*, 2009) and optimise plant spacing (Yang et al., 2012) but not in field production.

The branching in field grown, semi-determinant type tomatoes may also introduce more complex assimilates partitioning patterns to flowers and fruits. Fruit growth rate simulations based on sink strength, quantified by potential growth rates, have shown close correspondence with measured values in validation experiments including both single and double stemmed plants in tomato (Heuvelink, 1996). An alternative sink function where sink size is related to the maximum organ biomass, which in turn depends on its primordium size, has been used successfully to simulate the growth latency in late developed tomato fruits in singled stemmed tomato plants caused by competition for assimilates among fruits (Zhang, *et al*., 2009). Simulations have not extended to plants with multiple branches or with greater than 7 fruit per truss. Descriptions of plant phenology, and particularly flower and fruit numbers in all trusses in field grown plants grown in different seasons are not readily available but are required in order to define the range of branching patterns and truss locations needed for validation of the sink strength modelling approach in field crops. This lack of detailed studies on growth and canopy characteristics in field grown tomatoes has also been highlighted previously (Scholberg *et al*., 2000).

While mechanistic models applicable to field tomato production are lacking, a number of empirical models have been published. Heat unit summation models are the one of the most popular models for a range of field crops and have been developed for field tomato production. Heat unit models are used to predict time from transplanting to harvesting by using daily mean of maximum and minimum and subtracting a base temperature (Warnok, 1970). The base temperatures used for heat unit calculation for tomato crops are much lower than 7 °C (Owens and Moore, 1974), 4.3°C (Warnok and Isaacs, 1969), and 6, 8, and 10°C (Calado and Portas, 1987) for different production locations. Simple heat unit models (Austin and Ries, 1965; 1968; Perry *et al.*, 1997) to more complicated models (Wolf et al., 1986; McAvoy et al, 1989a; Cockshull et al., 1992; Hisaeda and Nishina (2007); Higashida, 2009; Wada et al., 2013) based on solar radiation are two weather based approaches used for predicting of harvest time and yield in tomato crops. Perry *et al.* (1997) examined heat unit models to predict harvest dates in field grown tomatoes in southeast USA. Higashide (2009) described that yield can be predicted using a model based on solar radiation from 10 to 4 days before anthesis. Hisaeda and Nishina (2007) also explained that the yield in greenhouse tomato crops can be predicted based on cumulative solar radiation 8 weeks to 1 week before harvesting. Wada et al., (2013) found that yield can be predicted from the simulation model of integrated solar radiation and averaged air temperature at 19 to 27 ºC in single truss system in greenhouse grown tomato crops.

Heat unit accumulation models were also used for predicting first harvest and yield of other fruits and vegetables crops. Perry and Wehner (1996) described that heat unit models can predict more accurately than calendar day methods for predicting cucumber harvesting in North Carolina. Tan et al., (2000) also used that heat unit models best predict the duration of chronological time from emergence to harvesting of broccoli. Umber et al., (2011) studied the heat unit requirement for harvesting of two new banana hybrids for exports, while Marra et al., (2002) concluded that thermal time models can predict harvesting time of peach fruit during the first 25 to 52 days of fruit development period in different cultivars. Heat unit models reduced the prediction error from 69 % to 22 % depending on cultivar when compared to a calendar day method in high bush blueberry fruits (Carlson & Hancock, 1991). Hueso et al., (2007) noted that heat unit models are superior to calendar day method for predicting harvest maturity of the ‘Algerie’ loquat, but only in water- stressed trees.

Heat unit summation methods were found to provide an improved accuracy of harvest date prediction when compared with the industry practice of prediction based on a standard number of days after transplanting. The models were found to perform best when applied to specific locations and variability in accuracy of prediction was noted between seasons. This is expected as plants respond to temperature and thermal time, not the passage of real time, and may also respond to photoperiod. Therefore, incorporating day length into the model improved prediction accuracy of the field grown tomato crops.

Field tomato crop models based on heat unit calculations are limited in their application, with low accuracy in yield prediction and low transferability between production locations. The low transferability might suggest that the models are not sufficiently mechanistic i.e. they do not accommodate factors or influences that might change from one location to another. While mechanistic crop models have the potential to overcome these deficiencies, current tomato crop models have not been extended to incorporate the additional input variables required for field production simulation. The expanding global field tomato production, particularly in tropical and subtropical environments in developing countries, would benefit from availability of mechanistic crop models to aid the development of higher productivity systems during the current period of expanding global population and increasing climate variability.

CURRENT TRENDS IN CROP MODELLING

Rapid advances in crop modelling have been made in the past decade. The development of advanced software engineering technologies and expanding knowledge of the genetic and physiological basis of plant growth and development processes have contributed to new modelling approaches. Modular framework models such as APSIM (Agricultural Production Systems Simulator, Keating *et al*., 2003), CROSPAL (CROP Simulator: Picking and Assembling Libraries, Adam *et al*., 2010), and APES (Agricultural Production and Externalities Simulator, Donatelli *et al*., 2010) enable simulation of a range of interactions between cropping system components (Adam *et al*., 2012). These models use a modular system covering areas including crop growth and development, soil carbon, nitrogen and water dynamics, climate and management interactions. This approach has particular application in farming systems that incorporate multiple production components and climate interactions, so is likely to be beneficial when applied to field tomato production.

The combination of three dimensional plant structures modelling with mechanistic plant functioning components to create functional–structural plant models (FSPM) is another recent advancement with significant potential application in field tomato production. This modelling approach has the capacity to simulate both the functional (e.g. photosynthesis, transpiration, N metabolism) and structural (e.g. breaking buds or keeping buds dormant, shape and orientation of organs) changes induced by environmental or management factors, and the interactions between these responses (Vos *et al*., 2010). The increased complexity in plant architecture in branched, semi determinate field grown tomatoes compared to single stemmed indeterminate type cultivars in greenhouse production suggests a role for FSPM in both research and agronomic decision making for producers.

Advances in understanding of the genetic and molecular regulation of plant growth and development will increasingly be incorporated into mechanistic crop models. More detailed knowledge of plant functioning is leading to more accurate simulations of plant growth. This trend is demonstrated in a proposed multi-scale approach to modelling tomato fruit growth (de Visser et al., 2012) where processes occurring at lower hierarchical levels, including cell division, cell expansion and sub cellular gene related processes, are integrated to model fruit development. This approach may help identify gaps in knowledge of fruit development processes as well as deriving more accurate simulations of fruit growth and final fruit size.

Increasingly, crop models are being used as a tool in decision support systems (DSS) in addition to being a valued research tool. Improved model predictive capability combined with faster processing speeds in personal computers have facilitated the development of DSS user interfaces designed to deliver model outputs for use in crop agronomic decision making. Crop models are also increasingly being used to assess effects associated with increased climate variability, and are proving to be a valuable research tool in the assessment of likely impacts of projected future climates on crop production and in the development of adaptation strategies for cropping under these climate scenarios (Lobell et al., 2009; Wenjiao et al., 2013). This trend of increasing use of models for agronomic applications as well as larger scale systems research is likely to accelerate over the coming decade.

This PhD research project examined the different aspects of field grown tomato in sub-tropical environmental condition which have impact on first harvesting date and yield. The data generated from the research project were used to incorporate into a field grown tomato crop model for improving predictability of harvest date and yield which can be used by the commercial field tomato growers in the region, and importantly identifies factors that need to be considered in model development for this production system.

CHAPTER 2

MATERIALS AND METHODS

This chapter describes the transplanting materials, cultural practices and assessment methodologies common to the series of experiments carried out in the project. In addition, the statistical procedures used in the thesis are also described. The experimental work in the PhD project was undertaken in the 4 years from 2011 to 2014, and consisted of 4 major field trials as well as assessment of commercial crop data. Methods unique to specific experiments are described within the materials and method sections of the relevant chapters later in this thesis. A brief summary of the main experimental work done in the project is listed in Table 1.

Table 1: *Overview of main experiments**

Main experiments (Chapter No.)	Location	Start date	End date	Brief description
Commercial Crop Monitoring (Chapter 3)	Middlehusers: Latitude -25.16 ° and Longitude152.21° East; Loeskos: Latitude -25.01° and Longitude 152.39° East; Redritch: Latitude -25.17° and Longitude 152.35° East	February 2011	October 2011	The aim of this experiment was to see the variability within and between the location and seasons in crop development and its impact on harvesting and yield. Roma and Gourmet tomato were used in the experiment.
Analysis of commercial crop data (Chapter 4)	217 Commercial crops data recorded by SP Exports between 2008 and 2011.	July 2011	December 2012	The aim of this experiment was to find the trends of variation and the main factors of variation on harvesting and yield. In this experiment ninety nine Roma and hundred eighteen Gourmet crops data were used between 2008 and 2011.
Seedling age and pruning experiment (Chapter 5)	Queensland Government Dept of Agriculture, Forestry and Fisheries Bundaberg Research Facility (Latitude -24.85° and Longitude 152.40 ° East)	April 2012	November 2012	The aims of the experiment were to find the effect of seedlings age on flowering and the effect of pruning on harvesting and yield, Roma tomato was used in the experiment.
Carbon partitioning (Chapter 6)	Zaina Farm , Bundaberg Latitude -24.98° and Longitude 152.31° East	June 2013	September 2013	The aims of the experiment were to find the effect of branching pattern on carbon partition and the effect of fruit loads on photosynthesis. Gourmet tomato was used in the experiment.
Modelling harvesting time and yield of field grown tomato (Chapter 7)		February 2011	December 2014	The aim of this research was to develop a superior model to the industry standard calendar day model for predicting first harvest date of field grown tomato.

* The weather data were collected from the Bundaberg Aero Club (Latitude - 24.89 ° and longitude 152.32 ° east) during the research period for analysis of the data for all experiment except some weather data collected locally in Chapter 6. The terrain appears flat so the local climatic gradient of Bundaberg is quite strong, perhaps less than in some other tomato producing areas, but climatic variation especially less in temperature will occur, so weather data can be utilized. The trial sites are within 30 km range from the Bundaberg Aero Club.

TRANSPLANTING MATERIAL

Seedlings are raised in a commercial seedling nursery (Wide Bay Seedlings Pty Ltd, 1971 Mungar Road, Pioneers Rest, Queensland) in plastic plug trays of four centimetre cell size. A mixture of peat and vermiculite was used as the propagation substrate. The trays were held in a germination room at 28 ° C after sowing to promote germination, and the germinated seedlings were subsequently transferred to greenhouse conditions. The seedlings were transferred to a hardening off area exposed to direct sunlight one week before delivery to the transplanting site. Four to five weeks old seedlings were used in all trials (4 weeks in summer and 5 weeks in winter), apart from trial presented in Chapter 5 where seedlings age was a treatment used in the experiment. The standard seedlings height ranged from 130 to 150 mm when seedlings trays were dispatched from the nursery.

CROP MANAGEMENT PRACTICES

Tomatoes are a relatively deep rooted crop, and therefore tillage is always undertaken to prepare land for transplanting. While equipment varied between sites used in the project, ground preparation generally consisted of one or two passes with a chisel plough for primary tillage and, a single with a rotary hoe for secondary tillage to produce a fine soil tilth and a final pass with a bed former. Drip tape for irrigation is laid in the beds at a depth of approximately 5 cm during bed formatting. The bed height and width was approximately15 cm and 70 cm respectively. The beds are covered with polyethylene plastic mulch prior to planting. White plastic was used in summer transplanted trials (Commercial crop monitoring) and black plastic mulch, which promotes increased soil temperature, was used in winter and spring transplanting. The weekly transplanting time is categorised as summer (48-9 weeks in subsequent year), autumn (10-22 weeks), winter (23-34 weeks) and spring season (35-47 weeks) for the crops.

All transplanting utilised seedlings transplanted manually by using the waterwheel type transplanters. The plant to plant and row to row spacing was 45 and 140 centimetres respectively. A trellis system was installed 5 weeks after transplanting when plants reached a height of approximately 30 centimetres (Figure 1). All trials utilised a vertical trellis approximately 1.8 metres high. Wooden stakes were driven into the ground at approximately 3 metres spacing in the rows and attached using wires to buttress guys at the ends of each row. Horizontal wires on each side of the plants are used to support the plants. The first wire is usually placed approximately 25 centimetres above the ground and other subsequent wires are placed about 25 centimetres above the previous one and in total 5 horizontal wires are used for support to the plants.

Figure 1: *Fixing of the stakes for trellis crop in the bed of tomato crops at the government research station, Bundaberg, in 2012*

Generally, the first pruning was done after the flowering of the first truss where only the side shoot below the first truss of the main shoot was kept and removed other shoots growing from axil of the leaves below this except in pruning experiment. Second pruning was also done normally after flowering of the third truss where any regrowth of the shoots from the first pruning and any new shoots coming below first truss were removed. The top growing shoots of the tomato plants above the trellis was pruned as a final pruning normally two weeks before harvesting of the fruits to divert the assimilate to the fruits.

Tomato plant has a relatively deep root system and in deep soils roots penetrate up to 1.5 meter. In general a prolonged severe water deficit limits growth and reduces yields which cannot be corrected by subsequent heavy watering. The flowering stage has the highest demand for water. All trial sites were irrigated using buried drip tape application (Figure 2). Timing and rate of irrigation was managed through monitoring of soil moisture, or in the case of trials on commercial farms through established irrigations scheduled developed by the growers. There were no signs of water stress in plants in any of the trials conducted in the project. Total water requirement (ETm) after transplanting of a tomato crop grown in the field for 90 to 120 is 400 to 600 mm, depending on the climate and this is also related to reference evapotranspiration (ETo) for different crop development stages (FAO, 2015).

Figure 2: *Irrigation systems for the tomato crops at the government research station, Bundaberg in 2012.*

The fertilizer requirement of the crops was assessed through soil testing prior to site preparation and using petiole sap analysis during crop development. A pre-plant basal fertilizer application was used to adjust soil nutrient levels during site preparation. During crop development, water soluble fertilizers were applied through the drip irrigation system at different split doses at appropriate times based on the sap analysis results and the stage of development of the crop as recommended by soil analysis laboratory reports and/or HORTUS: a consultancy for the growers in Bundaberg region and the fertilizer rate varies on soil types and crop growth and development stage (Figure 3). The fertigation tank was flushed thoroughly after each fertilizer injection by the drip systems.

Figure 3: *Water soluble fertilizer kept inside the fertigation tank for the tomato crops applied through drip irrigation systems in Bundaberg, in 2013.*

Weeds were managed through cultivation prior to transplanting and use of plastic mulch on the beds. Where necessary, the inter-row herbicide applications were used to control weeds during the crop growth. Roundup- a non-selective herbicide is generally used to control post emergence weeds. Rain and high humidity can increase development and spread fungal diseases, such as target spot and grey mould, and bacterial diseases. Low humidity favours mites and powdery mildew while rainfall near harvest can result in skin cracking of the tomato fruits. Pests and diseases were controlled through the standard industry chemical program as recommended by the crop agronomist engaged by the growers. Regular crop scouting was used to assess pest and disease pressure, and determine appropriate timing of chemical use. Both hydraulic and air-curtain boom sprayers were used during the project for application of insecticides and fungicides. Potato moth, Queensland fruit fly, silver leaf white fly and some thrives is the common insect pests of tomato. Maldison (440g/L product) or Methyl Bromide (1000 g/ kg) is used to control fruit fly and thrives for tomato. Bacterial spot, bacterial wilt, fusarium wilt, root-knot nematodes and soft rot are also common diseases of field grown tomato crops.

FRUIT YIELD ASSESSMENTS

The fruit were harvested based on the colour of the mature fruits. Usually, the fruits were harvested when the colour of the mature fruits reaches close to half colour i.e. more than 25% but less than 50% of the surface shows tannish yellow, pink, or red colour. Sub-sequent harvesting of the fruits was done at 2-4 day intervals. The harvested fruits from each experimental plant were kept in the tagged plastic bags and the fruit numbers and weight were recorded in the laboratory.

STATISTICAL ANALYSIS

The descriptive statistics of data in this study were calculated using Minitab 16. The analysis of the variance (ANOVA) of the collected data was performed by one way, two ways or general linear model using Minitab 16 for pairwise comparison or comparison with control based on the nature of the collected data at 95 percent confidence levels at

Tukey's. Regression analysis of the data was also performed using Minitab 16 and R version 3.1.1. Generalised additive model (GAM) and a linear mixed model of R was used to analyse the collected data. Data were transformed by square root method in excel and Johnson transformation in Minitab software when necessary to ensure normality and homogeneity of variances. The details information of the research design and appropriate data analysis methods based on specific research design are explained in each chapter of the thesis.

CHAPTER 3

EFFECT OF LOCATION AND SEASONAL VARIABILITY ON TOMATO CROP DEVELOPMENT UNDER FIELD CONDITIONS: A PRELIMINARY STUDY

ABSTRACT

The research described in this chapter was conducted to identify the developmental characteristics linked to commercial yield that displayed greatest variability under subtropical production of field grown tomatoes. Environmental factors such as light and temperature have previously been shown to have a strong influence on plant growth and crop yield. This study documented climatic factors and examined variability in plant growth and development characteristics in two field-grown tomato cultivars near Bundaberg, Queensland, Australia. Six sites were selected for the trial, with three Roma and Gourmet fruit type to cover three planting times and three production locations. Crop monitoring assessed a range of parameters including growth, development and yield characteristics of each of the 20 plants at each site. The study showed that only flowering time had a weak relationship with first harvesting time of tomato crop and no relationships with other measured plant growth characteristics such as node, leaf and shoot numbers at the time of first truss flowering. It was also found that there were no significant relationships between measured plant growth parameters such as node numbers at first truss flowering time, frequency of harvesting time, harvesting duration, fruit truss numbers, shoot with fruit truss and the fruit yield of the harvested fruits of the tomato crop. This preliminary research demonstrates that the relationships between growth and yield characteristics in field tomatoes are more complex than in glasshouse tomatoes.

INTRODUCTION

Tomato crop growth and development is influenced by environmental conditions and cultural practices, so understanding the scale and nature of these influences will contribute to improved capacity to predict and manage production. Temperature and light are considered the most important environmental factors for the growth and development of the tomato plant (Adam et al., 2001). There are certain temperature limits in different stages of growth and development for the optimum production. The development of reproductive organs such as flowering and fruit set are the most critical developmental stages and are considered the main parameters for the yield (Adams et al., 2001; Sato et al., 2000). The growth and development of the tomato plant is also influenced by resource characteristics cultural practices including soil types, transplanting methods, pruning strategies, weed control and insect pest management of the tomato crops. Effects of environmental factors on crop growth and development on glasshouse tomatoes have been well documented (Acock et al., 1978; De Koning, 1996b; Peet et al., 1997; 1998) but very limited research on how these affect field grown tomato crops has been published.

Tomato growth and development under commercial field production conditions are influenced by environmental and crop management factors that may not be adequately considered in models developed for greenhouse tomato production. In both systems dry matter production will be determined by carbon balance, but different factors may limit the rates of the processes controlling the carbon balance: gross photosynthesis minus losses from growth and maintenance respiration. Light intensity, carbon dioxide concentration and temperature account for much of the variability in carbon balance under greenhouse conditions (Dayan et al., 1993a), whereas supply of water and nutrients may limit assimilate production under field conditions. Carbon dioxide concentration will also remain relatively stable under field conditions, while the range of light intensity and temperature to which crops may be exposed is broader than that experienced in greenhouse production. Less is known about the effects of these factors on carbon balance processes across this broader range under field conditions than is known for the narrower range relevant to greenhouse production, while the potential impact of exposure to more extreme conditions on developmental events such as flowering and fruit set will also need to be considered in field production models.

The plant architecture becomes bushy due to branching systems in field grown, semi-determinant type tomatoes and may also introduce more complex assimilates partitioning patterns to flowers and fruits. Fruit growth rate simulations based on sink strength, quantified by potential growth rates, have shown close correspondence with measured values in validation experiments including both single and double stemmed plants in tomato (Heuvelink, 1995b). Simulations have not extended to plants with multiple branches or with greater than 7 fruit per truss. Descriptions of plant phenology, and particularly flower and fruit numbers in all trusses in field grown plants grown in different seasons are not readily available but are required in order to define the range of branching patterns and truss locations needed for validation of the sink strength modelling approach in field crops. This lack of detailed studies on growth and canopy characteristics in field grown tomatoes has been highlighted previously (Scholberg et al., 2000).

The phenology of the tomato plant is mainly influenced by temperature. High temperature has been shown to reduce crop yields in experimental and glasshouse studies (Uzun, 2007). Also the sub-optimal temperatures have been shown to result in more vegetative growth in plants, which in turn reduces final yields. The number of leaves before initiation of first flowering decreases by increased light intensity but, in overall the number of leaves increases on the tomato plants. Further, high light intensities can prolong the time taken for fruiting to occur because of prolific leafy vegetative growth and a large allocation of resources to leaves (Scholberg *et al.*, 2000). In field grown tomatoes, the temperature dropping below optimum levels has an adverse effect on fruit production. Exposure to low temperature in the field induces tomato plants to produce flowers showing alterations in morphology and pattern of floral organ fusion, and to produce low quality, abnormal fruits (Barten et al., 1992). Low temperature also affects fruit growth rate and ripening. Longer duration of 10°C at the time of fruiting periods may greatly postpone fruit ripening, decrease single fruit weight and increase production of low quality hollow fruit (Cheng et al., 2002). Greenhouse production permits controlled optimum temperature levels for crop production but in field grown tomatoes the temperature is more variable and the risk of temperature outside optimum ranges is higher.

Knowledge of physiological processes generated through both field and a greenhouse study is valuable to understanding aspects of growth and development of tomato plants in field conditions. Results of previous studies (Demers et al., 1998; Adams et al., 2001, Uzun, 2007) have shown that temperature and light are the main factors which determine productivity of tomato crops. Higher temperatures increase fruit growth rate but have a greater effect on rate of maturation which results in reduced final fruit weight (Sawhney & Polowick, 1985). The physiological processes affecting the rate and pattern of plant development may vary with the different developmental stages of the plant. In semi-determinate and indeterminate tomato cultivars the growth and development processes of vegetative and reproductive organs are continuous. Only vegetative growth occurs in the juvenile growth period of the plant before initiation of the first flower, but at the end of this period growth and development of vegetative and reproductive organs occur simultaneously (Lozano et al., 2009). The phenology of field grown tomato plants is poorly described and is therefore an area that requires study to support the development and validation of a tomato field crop model.

The aim of this study was to find the variability within and between the tomato crops planted in different seasons and locations and to see the relationship of the plant phenological characters with harvesting time and yield.

MATERIALS AND METHODS

SITE DESCRIPTION

The research work reported in this chapter was carried out on commercial, field grown tomato crops, near Bundaberg, Australia. The first Roma and Gourmet crops (hereafter referred to as ‘Roma-February’ and ‘Gourmet-February’) were located at - 25.16° latitude and 152.21° E longitude; the second crops ‘Roma-March’ and ‘Gourmet-March’ were located at - 25.01° latitude and 152.39 ° E longitude and the final two crops ‘Roma-April’ and ‘Gourmet-April’ were located at - 25.17 ° latitude and 152.35 ° E longitude . The soil types at each site were red ferrosol, kandosol (light sandy loam) and brown ferrosol respectively (Isbell, 2002). The monthly weather data were collected from Bundaberg Aero Club (Latitude - 24.89 º and longitude152.32 º East) close to the crop research trials in 2011 (Table 1). The research blocks were located in flat land a short distance (within 30 km range) from the Bundaberg Aero Club, so temperature data represents the research areas.

Table 1: *The monthly weather data from the Bundaberg Aero Club[@] close to the tomato crop production in 2011.*

2011		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	30.4	31.1	29.3	27.1	23.9	20.1	22.2	23.8	25.5	27.2	30.0	29.0
	Min*	21.1	21.9	21.1	17.8	12.7	9.7	8.4	10.4	11.4	16.4	18.6	19.3
Rainfall	mm	179.4	38.2	212.0	63.6	52.8	39.2	14.4	39.8	10.6	59.6	0.4	209.6
Relative Humidity (%)	9am	73	71	76	76	71	75	67	71	61	61	56	65
	3pm	66	62	66	59	52	51	46	50	41	57	54	63
TCSR+	MJ/ha	802.4	689.8	570.4	542.8	523.0	440.1	482.1	485.9	652.5	661.8	872.2	773.2

**Maximum and minimum Temperature was based on mean of maximum and minimum temperature of the month.*
+ Total Cumulative Solar Radiation (TCSR) was based on the cumulative solar radiation of the days on each month.
a Mega joules per hour.
@ Justification of use of data is given in Chapter 2

EXPERIMENTAL DESIGN

Six crops were selected for the trial, with three Roma and three Gourmet fruit type crops. In order to gain an understanding of the relationship between plant phenology and climatic variables, the study was repeated over three different transplanting periods – two in summers and one in autumn, across three locations. Transplanting date varied between the three locations and covered the major production times for the Bundaberg region. At each of the three locations, adjacent blocks of the Roma and Gourmet cultivars, transplanted on the same day or within 7 days of each other, were selected.

The first Roma and Gourmet crops were transplanted on 23rd and 22nd of February 2011 respectively (Roma-February and Gourmet-February); the second crops were transplanted on 10th and 17th of March 2011 (Roma-March and Gourmet -March) & the last two crops were transplanted on 26th and 28th of April 2011 (Roma-April and Gourmet-April).

TRANSPLANTING MATERIALS AND CROP MANAGEMENT PRACTICES

The transplanting materials and crop management practices were adopted as in Chapter 2. All crops were managed according to standard commercial practice with trellising, sub-soil drip irrigation under plastic mulch, fertilization at rates based on soil nutrient and plant sap test results, whilst crop protecting chemical applications for pest and disease management were applied as required.

Within each crop, monitoring and sampling were conducted on five plots, each containing four plants. 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.

METHODOLOGICAL APPROACH

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

FLOWERING DATE OF THE FIRST TRUSS

Flowering time of the first truss (date that the first flower reached anthesis) was recorded in each sample plant in all trials. The plants were monitored from appearance of the truss at 2 day intervals. Once flower opening commenced, monitoring was carried out every day at approximately midday. The flowering date of the first truss of each plant was recorded when the first flower of the first truss was fully opened and anthers were dehiscing.

NODE NUMBERS ON THE FIRST TRUSS OR THE POSITION OF THE FIRST TRUSS

The position of the first truss (node number on the main stem) was recorded at flowering. Node number one was defined as the node at the base of first true leaf. Nodes were counted in ascending order on the main stem to determine nodal position of the first flowering truss on each plant. At the time of flowering, no leaf abscission had occurred so leaf position on the stem was a reliable measure of node numbers.

NUMBER OF FULLY OPENED LEAVES

Number of fully opened leaves on each sample plant was also counted at the flowering time of the first truss as well as on all the side shoots of the sample plant. The leaf was called fully opened when all the leaflets were held at an angle of 90° to the main leaf blade.

NUMBER OF SIDE SHOOTS

The number of side shoots was counted and recorded at the flowering time of the first truss on each sample plant.

FLOWER AND FRUIT NUMBERS ON FIRST, SECOND AND FOURTH TRUSSES

Flower and fruit numbers on the first, second and fourth trusses were recorded. The flower numbers were counted when all the buds of the respective trusses had flowered. Fruit numbers were recorded after completion of fruit set, approximately 4 weeks after flowering on each of the trusses (no abortion of fruit after this stage and also easy for counting) .

TOTAL NUMBER OF SIDE SHOOTS WITH TRUSSES AND TOTAL TRUSSES

The numbers of side shoots with trusses on each plant were recorded at the time of commercial harvest of each crop. Plants for sampling were tagged to prevent commercial fruit pickers from harvesting fruit from these plants. The tagging clearly defined research areas to reduce the risk of harvesting of fruits from the sample plants by the commercial fruit pickers. Each harvested truss was assessed to determine total number of fruit per plant.

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 on the day of each commercial harvest. The number and total weight of harvested fruits from the first truss and other trusses were recorded separately on each sample plant and each harvest sampling date. All the fruits left on the sample plant after the date of last commercial harvest on each crop were also harvested, and total numbers and weight of the fruits were recorded. Plants used in the trial were harvested at the time of commercial harvest of the crop in which the trial was located, so fruit harvesting frequency (number of harvesting of the fruits from the same plants) and harvesting duration from first harvest to last harvest of each crop was recorded for analysis.

ADJUSTED HARVEST TIME

The first harvest time was recalculated for each crop in an attempt to define the date of a consistent crop development stage (remove variation in harvest time driven by commercial harvest time decisions). The decision for commercial first harvesting time of the tomato crop is based both on the number of fruits ready to harvest and by market demand and other management factors. The physiological ripening time of each fruit in the first truss was different from the timing of commercial first harvesting necessitating an adjustment to the actual first harvesting time of the first truss in each plant. Ripening patterns of individual fruit were recorded and the date that the first fruit was physiologically ripe was then approximated based on the maturity of the fruit at commercial harvesting time and the mean days required for ripening fruit from the ripening pattern analysis.

STATISTICAL ANALYSIS OF THE DATA

The data collected from six trial crops of Roma and Gourmet were analysed by using Minitab version 16 to determine the variances in measured parameters. Transformation of the data was performed by Johnson transformation in Minitab version 16 and also by square root transformation in excel where normality assumption and homogeneity of variance of the data were violated in the study. The comparisons of the different measured variables were performed by one way analysis of variance in Tukey's method at 95 percent confidence interval and all the statistically significant findings are reported at $p \leq 0.05$. The regression analysis between measured phenological traits of the tomato plants and first harvesting time and yield of the crops were also performed by using Minitab version 16. The box-plot was also prepared to show the trend of variation of flowering time, time from transplanting to first harvest, duration of harvest and fruits yield of Roma and Gourmet tomato crops transplanted in different months by using Minitab 16.

RESULTS

VARIABILITY OF PLANT PHENOLOGICAL TRAITS AND HARVESTING TIME

Phenological characteristics of the crops varied between the transplanting times (Table 2), but general patterns were consistent across cultivars. The node numbers at the time of first truss flowering were lowest in both cultivars transplanted in March, with each cultivar x transplanting time forming statistically significant groups. It is not possible to determine if this difference is due to timing of the crop, management and site effects, or other factors, but temperature does not appear to have had a major influence given the April transplanted crops produced flowers at an intermediate node number despite being exposed to lower temperature than the crops transplanted in March or February. Conversely, the number of shoots with a fruit truss was significantly higher in March than any other transplanting time. Investment in the number of leaves and shoots prior to first flowering declined between the February and April transplanted crops of the Roma cultivar, yet the April transplanted of the Gourmet variety was characterised by a significantly higher investment in the number of leaves and shoots at the time of first flowering. The mean flowering time of the first truss of Gourmet tomato and the first harvesting time of both Roma and Gourmet tomato transplanted in April was significantly higher.

The mean chronological age of Roma crops at first flowering differed by five days across different transplanting seasons, whilst for Gourmet crops the difference was 14 days (Figure 1 A and B). The coefficient of variation (CV) in flowering date (time taken from transplanting to first flowering) within Roma crops were 12.53, 14.1 and 19.65 % in the crops transplanted in February, March and April respectively. The CV’s for these same crops at commercial harvest date however, were 7.35%, 2.55% and 6.24% respectively. The CV’s for flowering time within Gourmet crops were 12.94, 16.1 and 4.66 % in the crops transplanted in February, March and April respectively, yet the CV’s for harvesting for these same crops were 6.37%, 3.44% and 3.66 %. Substantial variation in flowering time appears to be overcome by harvesting time (Figure 1).

Table 2: *Summary of crop development variables of the Roma and, Gourmet crops transplanted in February, March and April 2011. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters in each row represent there was no difference.*

	Roma-February	Roma-March	Roma-April	Gourmet-February	Gourmet-March	Gourmet-April
Node number at first truss	9.0 ± 0.2^{a}	6.5 ± 0.1^{c}	7.6 ± 0.2^{b}	7.6 ± 0.1^{a}	6.6 ± 0.2^{b}	7.1 ± 0.1^{b}
Leaf number count at first flower	12.3 ± 0.2^{a}	10.5 ± 0.3^{b}	8.6 ± 0.4^{c}	11.6 ± 0.1^{b}	10.7 ± 0.2^{b}	13.9 ± 0.4^{a}
Shoot number count at first flower	1.4 ± 0.1^{a}	1.3 ± 0.1^{ab}	0.7 ± 0.2^{b}	1.2 ± 0.0^{b}	1.2 ± 0.1^{b}	3.4 ± 0.1^{a}
First flowering day	22.5 ± 0.6^{a}	17.4 ± 0.5^{b}	19.6 ± 0.8^{b}	24.5 ± 0.7^{b}	17.7 ± 0.6^{c}	30.8 ± 0.3^{a}
First harvesting day	70.6 ± 1.1^{b}	71.7 ± 0.4^{b}	100.0 ± 1.4^{a}	69.6 ± 0.9^{b}	69.6 ± 0.5^{b}	109.9 ± 0.9^{a}

RELATIONSHIP BETWEEN PHENOLOGICAL TRAITS AND HARVESTING TIME

The variation of coefficient of determination (r^2) was found in regression analysis between the first commercial and adjusted harvesting time with plant phenological traits such as node, leaves, and shoots numbers at flowering as well as flowering time of the first truss (Table 3; Figure 2-5). Adjusting the harvesting time data did not improve the coefficient of determination (r^2) value of the regression of all parameters of the crops.

Despite an apparent relationship between low node numbers at flowering and first flowering day for Roma and Gourmet tomatoes (Table 2); the statistical relationship between node numbers at first truss flowering and harvest time was very weak (Table 3). Significant relationships between node numbers at first truss with commercial first harvest were only in the Roma-February and March crops. A significant relationship between expanded leaf at the time of flowering of the first truss and commercial first harvesting time was found in all Roma crops; but in Gourmet tomatoes it was only in the crops transplanted in February and March. Significant relationships were also found in the Gourmet crops transplanted in February and March as well as the Roma crops transplanted in February, March and April when expanded leaf number at first flowering was regressed against the adjusted first harvesting time.

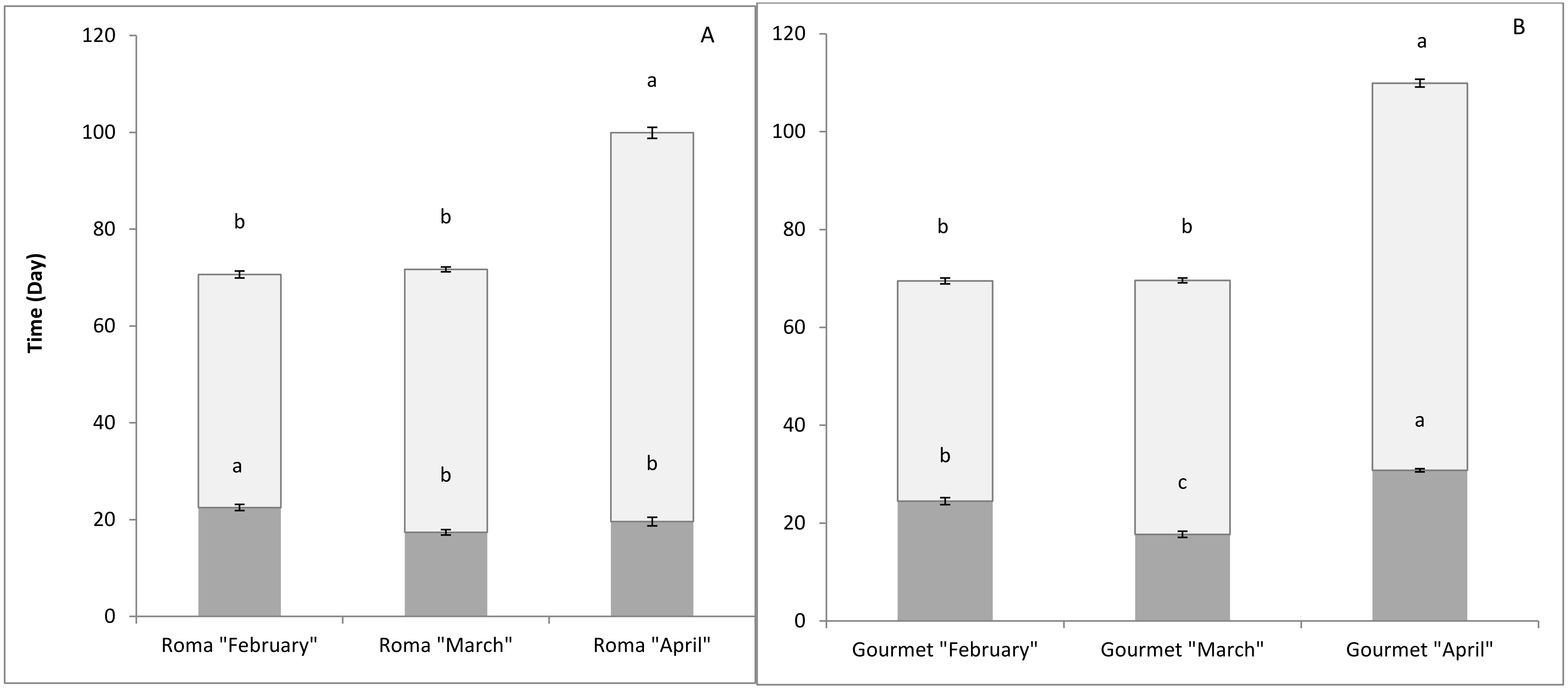


Figure 1: *Time between transplanting to flowering and flowering to harvesting for Roma (A) and Gourmet (B) tomatoes transplanted in February, March and April 2011 in Bundaberg.*

Table 3: *The coefficient of determination (r²) of commercial and adjusted first harvesting time with node, leaves and, shoots numbers at first truss flowering as well as flowering time of the first truss of Roma and Gourmet tomato crops transplanted in February, March and April in Bundaberg, 2011.*

	Commercial First Harvesting				Adjusted First Harvesting			
Crop	Node Number	Leaves Number	Shoots Number	Flowering Time	Node Number	Leaves Number	Shoots Number	Flowering Time
Gourmet-1*	1	29	23	52	1	21	22	69
Gourmet-2*	3	23	32	39	17	31	31	20
Gourmet-3*	5	0	11	22	3	1	6	36
Roma-1*	35	55	0	51	30	46	0	68
Roma-2*	34	58	11	39	27	31	11	33
Roma-3*	0	27	10	22	0	26	7	46

**The numbers 1, 2 and 3 in Roma and Gourmet tomato represents the crops transplanted in February, March and April respectively.*

Theory predicts that the higher the shoot number at the time of first truss flower, slower the first harvest time of the plant (Scholberg et al., 2000; Uzun, 2007). Despite this, a significant relationship was observed only between these parameters in the Gourmet crops transplanted in February and March. The relationship was also tested between shoot numbers at the time of first flowering and adjusted first harvest time (Figure 4) and a significant relationship was only observed in the Gourmet crops transplanted in February and March. There was a high level of variability in the flowering time of the crops, and this clearly indicates that flowering time alone does not explain the variability in harvesting time of the crops; other factors may also have impact on first harvesting time of the tomato (Figure 5). Highly significant positive relationship were found between flowering and first harvesting time of Gourmet and Roma tomato transplanted in February, but little or weak relationship between the two parameters was observed in other crops. Adjusting the commercial harvesting time data had improved the coefficient of determination (r^2) value of the flowering time of Gourmet and Roma except in the crops transplanted in March.

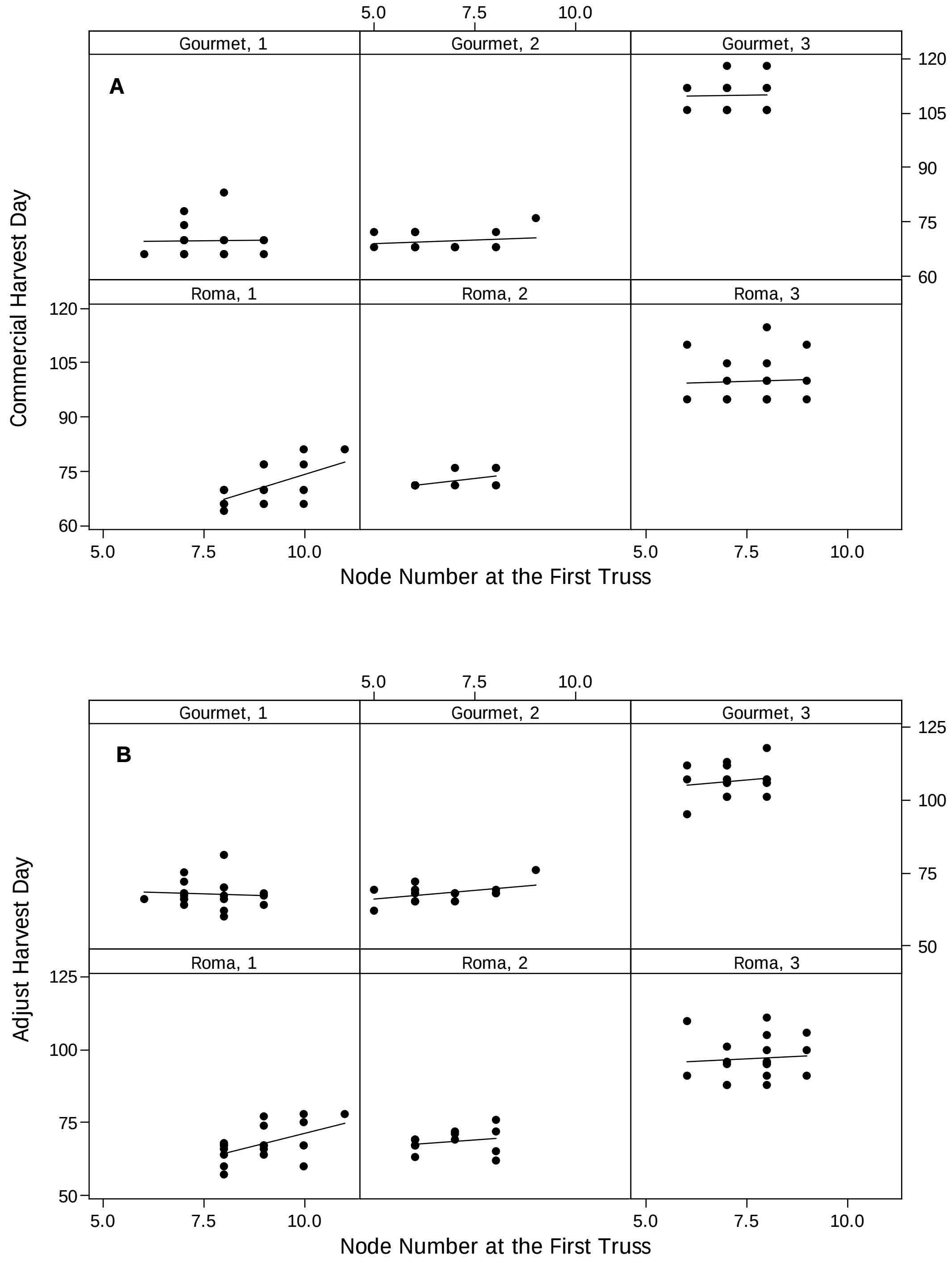
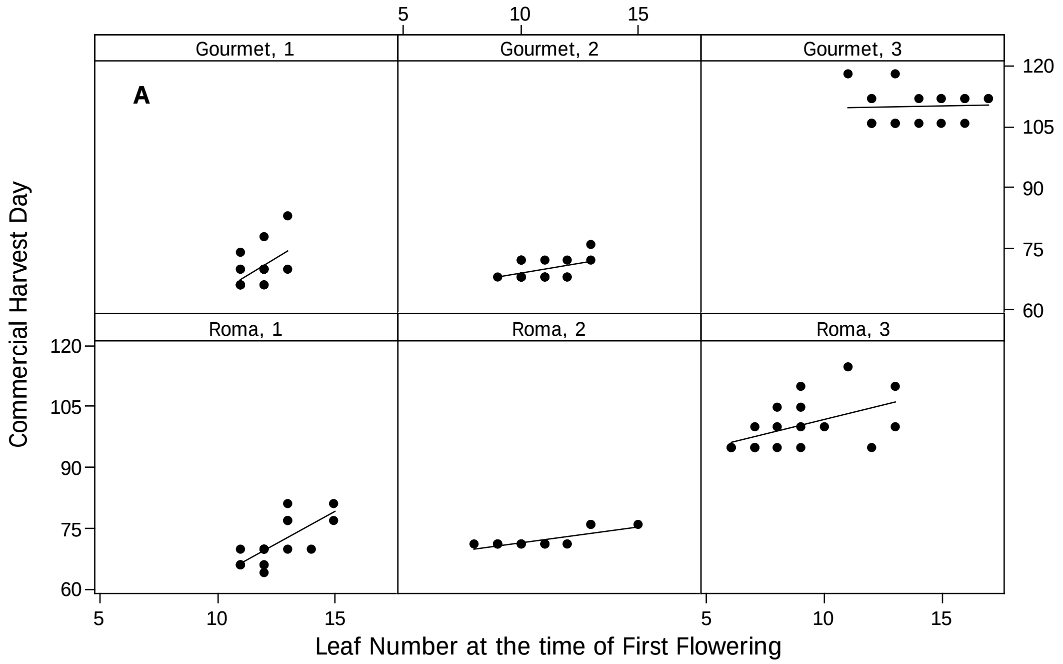


Figure 2: *Relationship between node number at first truss and the commercial (A) and adjusted (B) first harvest day of Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The numbers 1, 2 and 3 represents the crops transplanted in February, March and April respectively. The regression equations are given in Appendix (Table 1).*



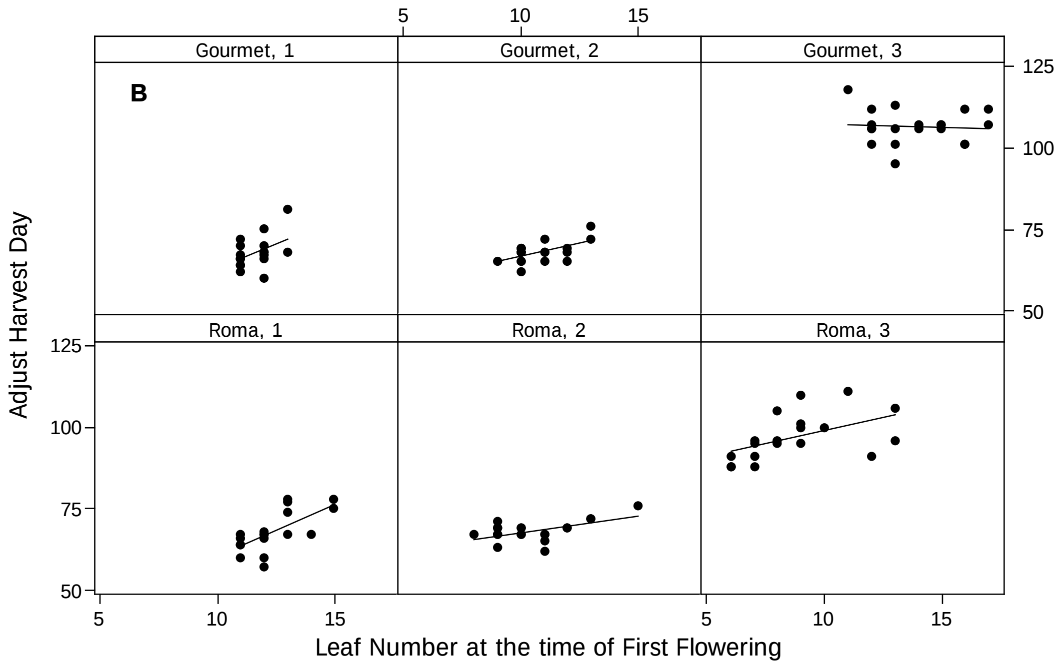
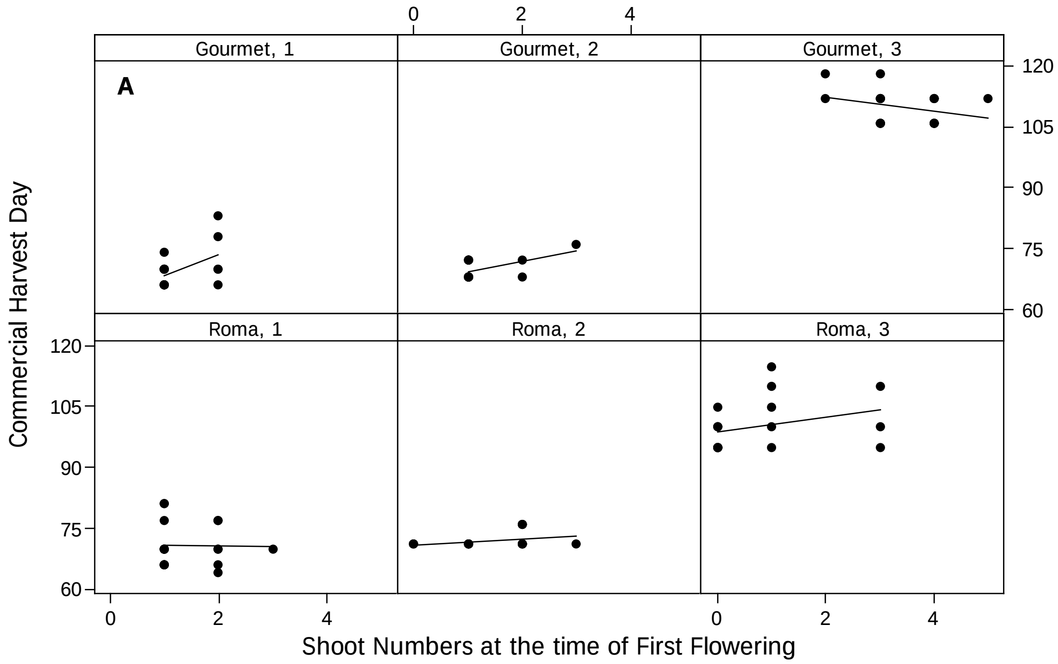


Figure 3: *Relationship between leaf number at the time of first flowering and commercial (A) and adjusted (B) first harvest day of Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The numbers 1, 2 and 3 represents the crops transplanted in February, March and April respectively. The regression equations are given in Appendix (Table 2).*



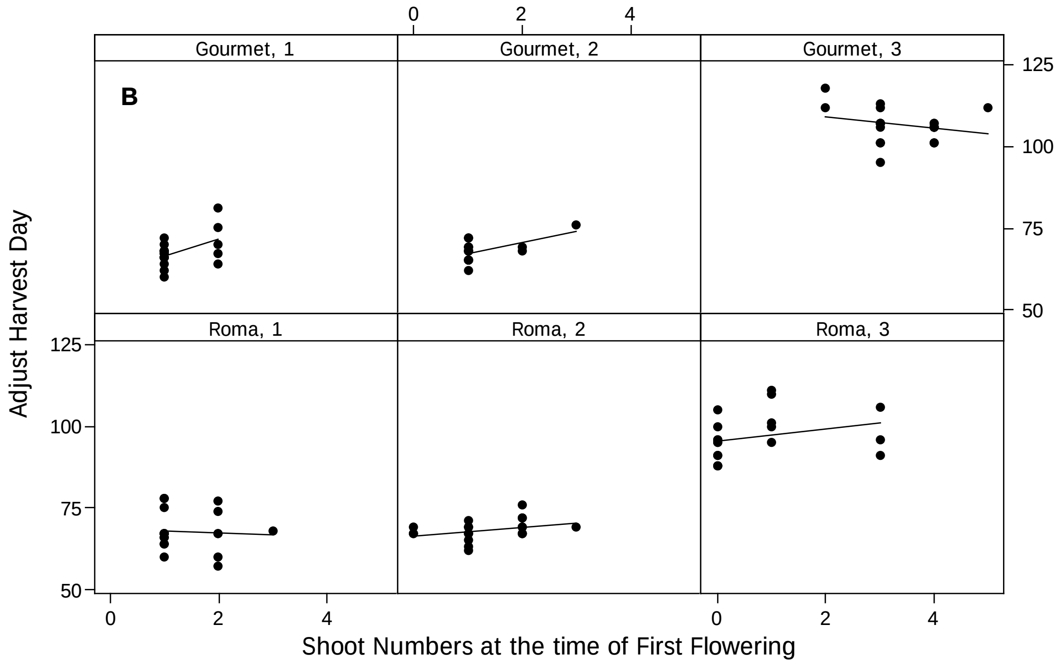
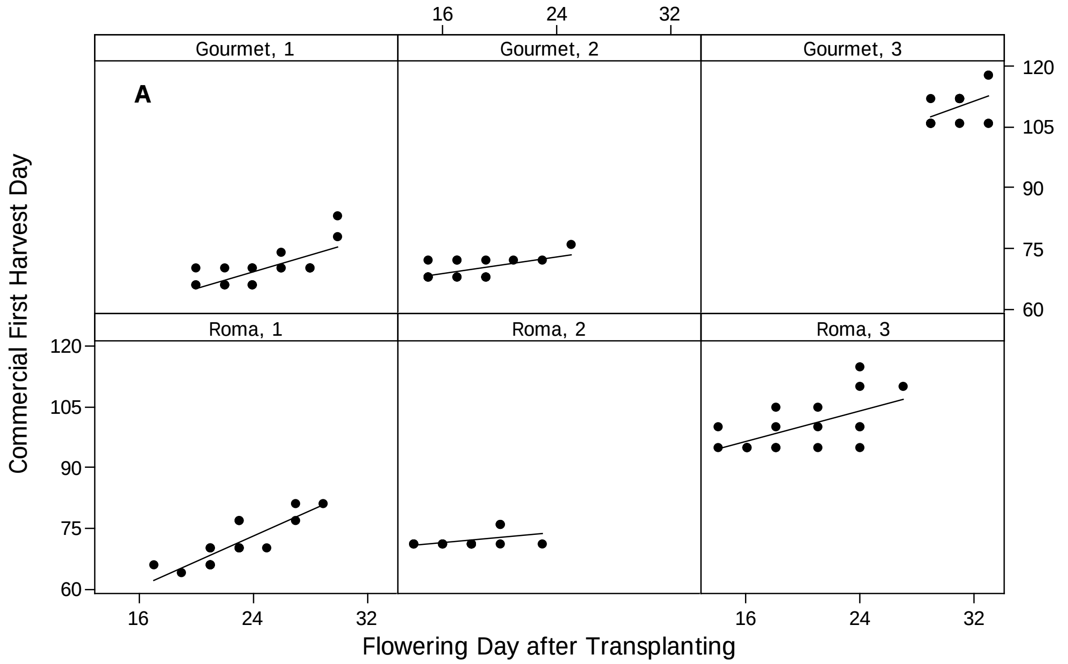


Figure 4: *Relationship between shoot numbers at the time of first truss flowering and commercial (A) and adjusted (B) first harvest day of Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The numbers 1, 2 and 3 represents the crops transplanted in February, March and April respectively. The regression equations are given in Appendix (Table 3).*



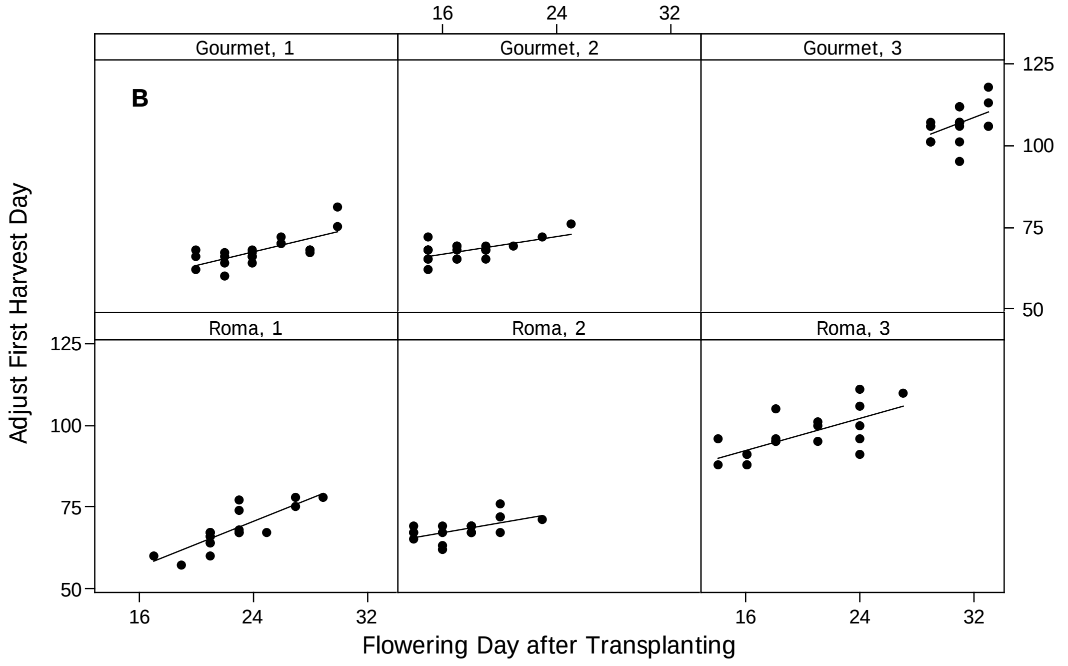


Figure 5: *Relationship between flowering day after transplanting and commercial first harvest (A) and adjust first harvest day (B) of Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The numbers 1, 2 and 3 represents the crops transplanted in February, March and April respectively. The regression equations are given in Appendix (Table 4).*

VARIABILITY OF PLANT PHENOLOGICAL TRAITS AND YIELD

The variation of phenological traits of yield was observed in both Roma and Gourmet tomato transplanted in February, March and April (Table 4). The lowest yield in Roma and Gourmet crops was in crops transplanted in February with an average yield of 5.45 kg and 4.72 kg per plant respectively. Significantly higher yield in Roma and Gourmet crops were produced in crops transplanted in March; an average yield of 9.64 kg and 7.34 kg per plant respectively. The number of fruits per plant was significantly higher in March than any other transplanting time. Fruit set was high in all crops, with greater than 94% of first truss flowers converted to fruit in Roma crops and 80, 84 and 98% fruit set in the three Gourmet crops. The data do not preclude variability in flowers initiated per truss and resultant fruit set being significant contributors to harvest time and yield variation between commercial crops, but are suggestive that this is not a major cause under the production conditions of this research.

HARVESTING TIME AND YIELD PATTERN

The first harvesting day was found to be comparatively delayed in both Roma and Gourmet crops planted in April compared to February and March planted crops. It was observed that the plants producing an early flowering truss at a low node position produced more side shoots, each containing one or more trusses (Table 2). Normally, greater truss numbers on plants at the lower nodal positions on side shoots and therefore in the effective harvesting area of the trellis produced more fruits, which was reflected in the higher total fruit weight (Table 4).

The relationship between harvested fruit numbers and their weight is described in Figure 6. Strong, significant positive relationships between number and weight were found in all Gourmet and Roma crops. The coefficient of determination (r^2) value of regression line was 0.90, 0.60 and 0.76 in Gourmet and 0.82, 0.85 and 0.94 in Roma crops transplanted in February, March and April respectively.

Table 4: *Summary of yield characteristic of Roma and Gourmet crops transplanted in February, March and April 2011 in Bundaberg. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values followed by the same letters in each row represent there was no difference.*

	Roma-February	Roma-March	Roma-April	Gourmet-February	Gourmet-March	Gourmet-April
Flower numbers in first truss	8.4 ± 0.3^{a}	7.4 ± 0.3^{a}	7.4 ± 0.3^{a}	5.4 ± 0.3^{b}	6.7 ± 0.2^{a}	7.0 ± 0.3^{a}
Fruit numbers in first truss	7.9 ± 0.2^{a}	7.3 ± 0.3^{a}	7.1 ± 0.3^{a}	4.3 ± 0.3^{b}	5.8 ± 0.2^{a}	6.9 ± 0.3^{a}
Number of total fruit trusses	13.6 ± 0.6^{b}	18.8 ± 0.8^{a}	11.5 ± 0.6^{b}	12.3 ± 0.3^{b}	14.2 ± 0.4^{a}	12.3 ± 0.5^{b}
Number of shoots with fruit truss	4.8 ± 0.2^{b}	6.1 ± 0.2^{a}	4.8 ± 0.2^{b}	4.2 ± 0.2^{b}	5.5 ± 0.1^{a}	4.8 ± 0.1^{b}
Total number of fruits	62.8 ± 2.8^{c}	121.2 ± 4.3^{a}	94.9 ± 5.3^{b}	44.0 ± 2.2^{c}	74.1 ± 2.2^{a}	63.7 ± 3.0^{b}
Total fruits weight (kg)	5.45 ± 0.30^{c}	9.64 ± 0.35^{a}	7.31 ± 0.36^{b}	4.72 ± 0.24^{b}	7.34 ± 0.24^{a}	5.21 ± 0.22^{b}
Harvesting frequency (number)	12.6 ± 0.3^{c}	16.8 ± 0.2^{a}	14.5 ± 0.3^{b}	12.1 ± 0.3^{c}	18.5 ± 0.3^{a}	13.4 ± 0.1^{b}
Harvesting duration (day)	62.5 ± 1.8^{c}	98.8 ± 0.4^{a}	68.0 ± 1.4^{b}	63.2 ± 1.5^{b}	97.4 ± 0.5^{a}	55.1 ± 0.9^{c}

RELATIONSHIP BETWEEN YIELD PARAMETERS AND HARVESTED FRUITS

The variation of coefficient of determination (r^2) of different parameters on yield and harvested fruits was observed in both Gourmet and Roma tomatoes (Table 5; Figure 7-9). There was only one weak relationship between node number at first truss and total harvested fruits in Roma crops transplanted in February. There was no significant relationship between fruit truss number and harvested fruits except for Roma crops transplanted in February and March. The relationship between shoot with fruit truss and harvested fruits was also weak, but significant only in Gourmet tomato transplanted in March and in Roma transplanted in February and March.

The relationship between fruit harvesting duration and weight of harvested fruits was assessed to test the hypothesis that a longer fruit harvesting duration would result in a higher total number and weight of harvested fruit. The regression analysis using data from all individual plants revealed that there was no significant relationship between fruit harvesting duration and total number of harvested fruits except in Roma-February. Plants used in the trial were harvested at the time of commercial harvest of the crop in which the trial was located, so fruit harvesting frequency was a reflection of the commercial crop management decision processes. The relationship between fruit harvesting frequency and number of harvested fruits was not strong but was significant in Gourmet transplanted in February as well as in Roma crops transplanted in February and March.

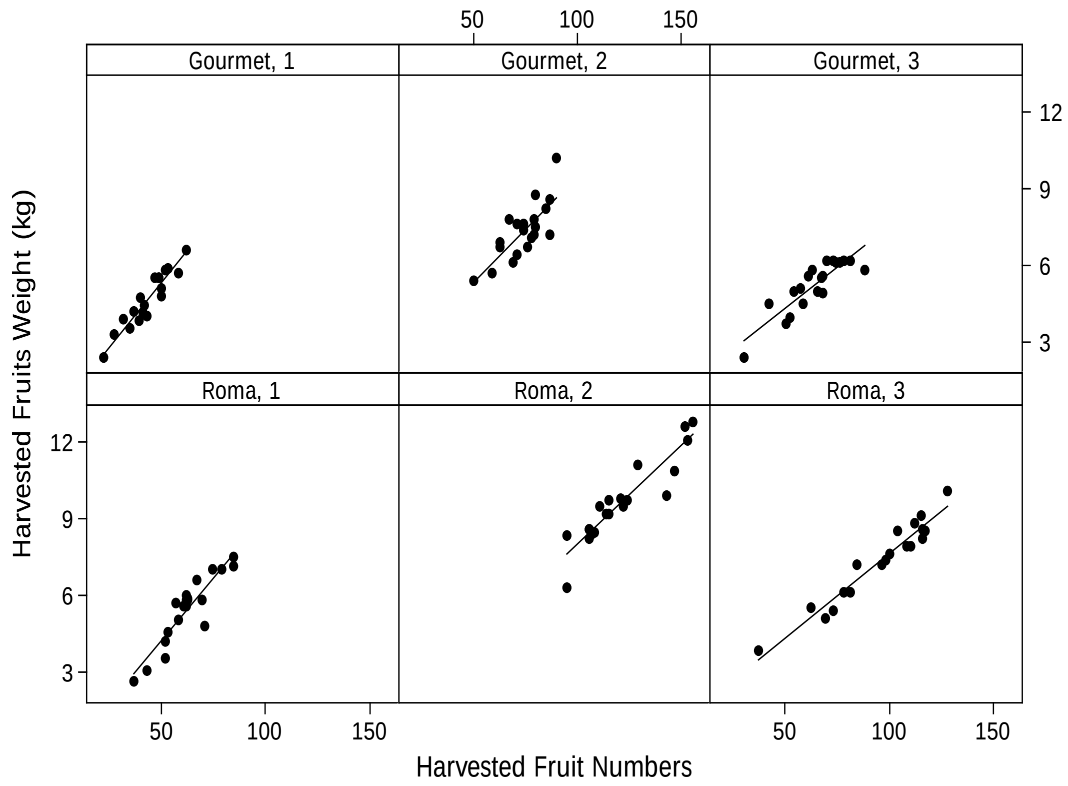


Figure 6: *Relationship between harvested fruit numbers and harvested fruits weight(kg) in Roma and Gourmet tomato crops transplanted in February, March and April in Bundaberg, 2011.The regression equations are given in appendix (Table5). The number 1, 2 and 3 represents the crops transplanted in February March and April respectively.*

Table 5: *The coefficient of determination (r^2) of regression analysis of harvested fruits with node, fruit truss numbers, shoots with fruit truss, fruit harvesting duration and harvesting frequency of Roma and Gourmet tomato crops transplanted in February, March and April in Bundaberg 2011.*

	Node number	Fruit truss number	Shoots with fruit truss	Fruit harvesting duration	Harvesting frequency
Gourmet-1*	0	10	2	13	36
Gourmet-2*	0	1	29	0	0
Gourmet-3*	6	6	0	9	2
Roma-1*	24	48	43	22	32
Roma-2*	0	32	46	15	24
Roma-3*	2	3	0	0	13

The numbers 1, 2 and 3 in Roma and Gourmet tomato represents the crops transplanted in February, March and April respectively.

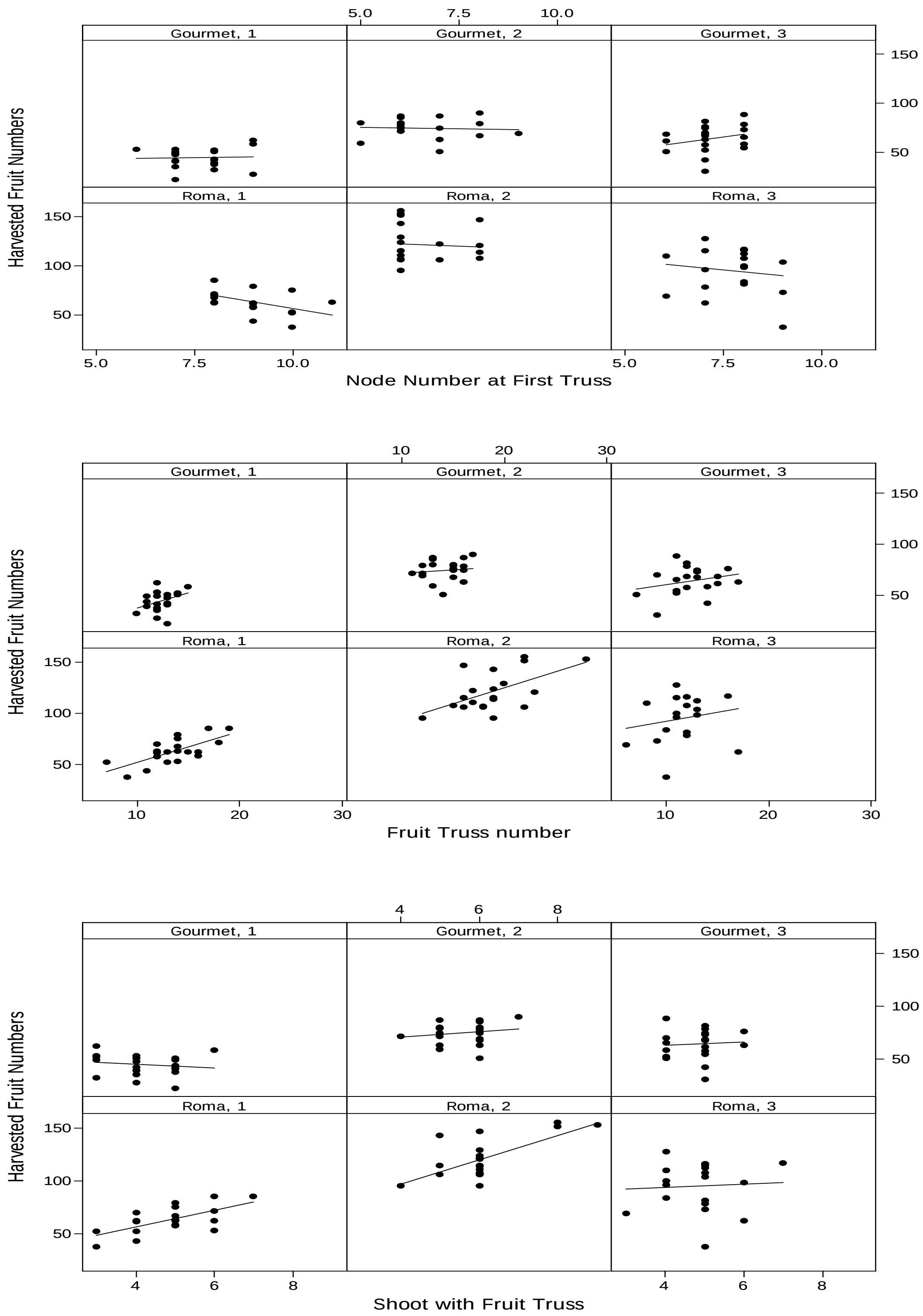


***Figure 7:** Relationship between node number at first truss (A), fruit truss number (B) and shoot with fruit truss(C) to harvested fruit numbers in Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The number 1, 2 and 3 represents the crops transplanted in February March and April respectively. The regression equations are given in Appendices Table 6-8 respectively.*

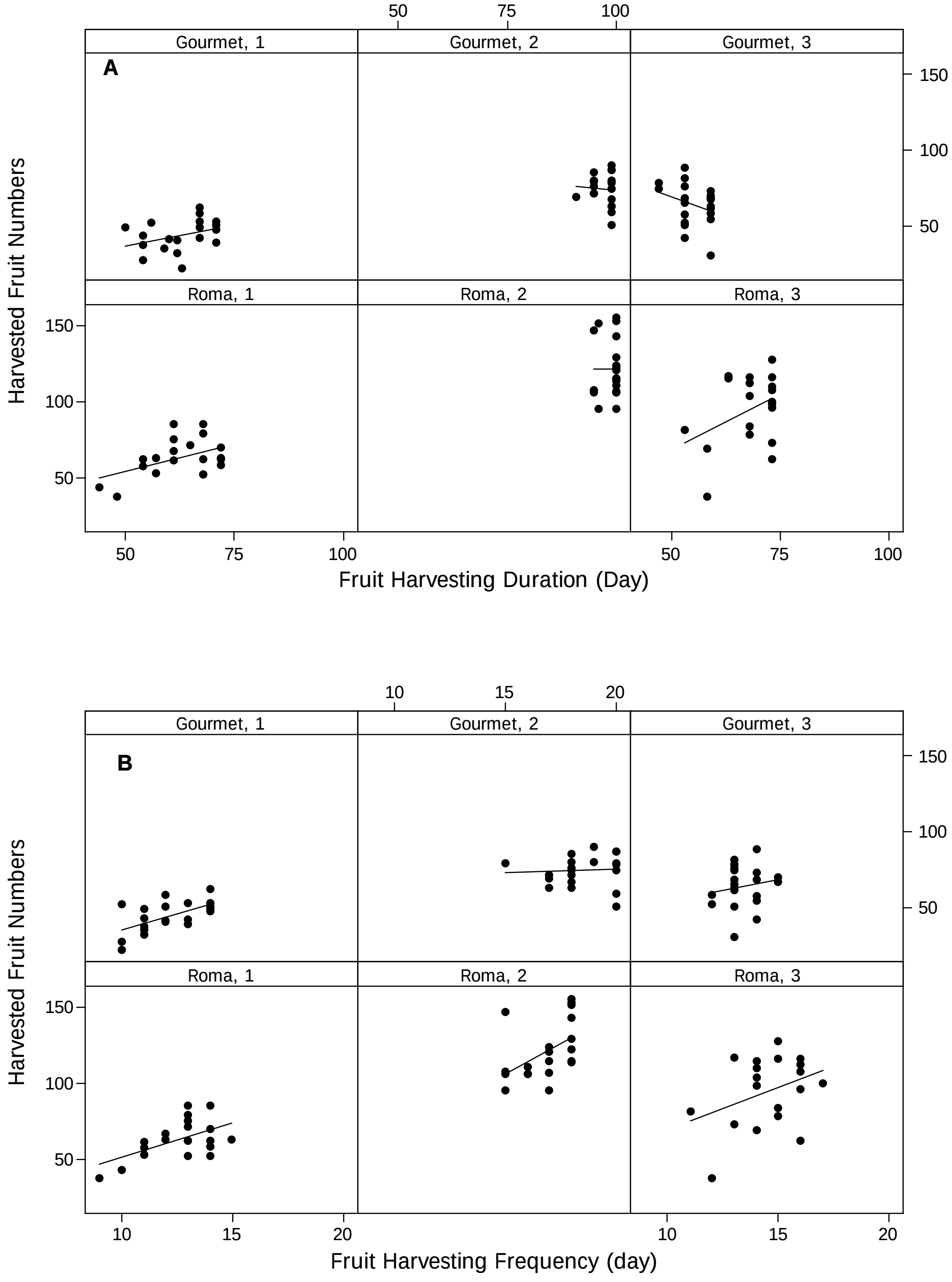


Figure 8: *Relationship between fruit harvesting duration (A) and fruit harvesting frequency(B) to harvested fruit numbers in Roma and Gourmet tomato crops transplanted in Bundaberg, 2011. The numbers 1, 2 and 3 represents the crops transplanted in February, March and April respectively. The regression equations are given in Appendices Table 9 and 10 respectively.*

VARIATION ON FLOWERING, HARVESTING AND YIELD

The coefficient of variation of the flowering time, harvesting time, harvesting duration and yield of Roma and Gourmet tomato transplanted in February, March and April is given in Table 6 and displayed less variation on these parameters between the plots within a crop than between the crops (Figure 9 & 10). The flowering time of Roma crop transplanted in February was comparatively lower variation than other crops. The flowering time between the crops differed significantly (Table 2 & 4); but no significant differences between the plots within the crops. The coefficient of variation of first harvesting time of the Roma crop was lowest i.e. 2.55 followed by 6.24 and 7.35 in the crops transplanted in March, April and February respectively (Figure 9 B). The time from transplanting to first harvest varied significantly between the Roma crops, but no significant differences existed between plots within the crops. The duration of fruit harvesting was variable between plants in Roma crops with a coefficient of variation of 13.15 compared to 9.17 and 2.08 in the crops transplanted in February, April and March respectively (Figure 9 C). The duration of fruit harvesting also varied significantly between the crops, but no significant were found between plots within the crops. The coefficient of variation in yield displayed high variability for all crops and % CV was lowest in Roma -March crop at 16.65 followed by 21.95 and 24.75 in April and February crops respectively (Figure 9 D). The difference in yield between the crops in Roma was also significant, but no significant differences between plots within the crops were identified except in Roma -February.

The flowering time in Gourmet crop transplanted in April showed comparatively lower variation than other crops with coefficient of variation of 4.66. Differences in flowering time between the crops were highly significant but not significant between the plots within the crops (Figure 10 A). The first harvesting time was comparatively less variation than other parameters in both Roma and Gourmet tomato crops. The between crop differences in first harvest time were highly significant, but there were no significant differences between plots within the Gourmet crops (Figure 9 B &10 B). The variability in duration of fruit harvesting was higher in Gourmet -February compared to the other crops with coefficient of variation of 10.81. The duration of fruit harvesting varied significantly between Gourmet crops but no significant differences were found between plots within the crops (Figure 10 C). Variability in yield was lowest in Gourmet-March crop with a % CV of 15.03 followed by 19.43 and 22.82 in April and February crops respectively. The differences in yield between the crops were also significant, but not significant between plots within the crops except in Gourmet -March (Figure 10 D).

Table 6: *The coefficient of variation (CV) of flowering time, harvesting time, harvesting duration and yield of Roma and Gourmet tomato crops transplanted in February, March and April in Bundaberg 2011.*

Crop	Flowering Time	Harvesting Time	Harvesting Duration	Yield
Gourmet-1*	12.94	3.66	10.81	22.82
Gourmet-2*	16.10	3.44	2.46	15.03
Gourmet-3*	4.66	6.37	7.30	19.43
Roma-1*	12.53	7.35	13.15	24.75
Roma-2*	14.10	2.55	2.08	16.65
Roma-3*	19.65	6.24	9.17	21.95

**The numbers 1, 2 and 3 in Roma and Gourmet tomato represents the crops transplanted in February, March and April respectively.*

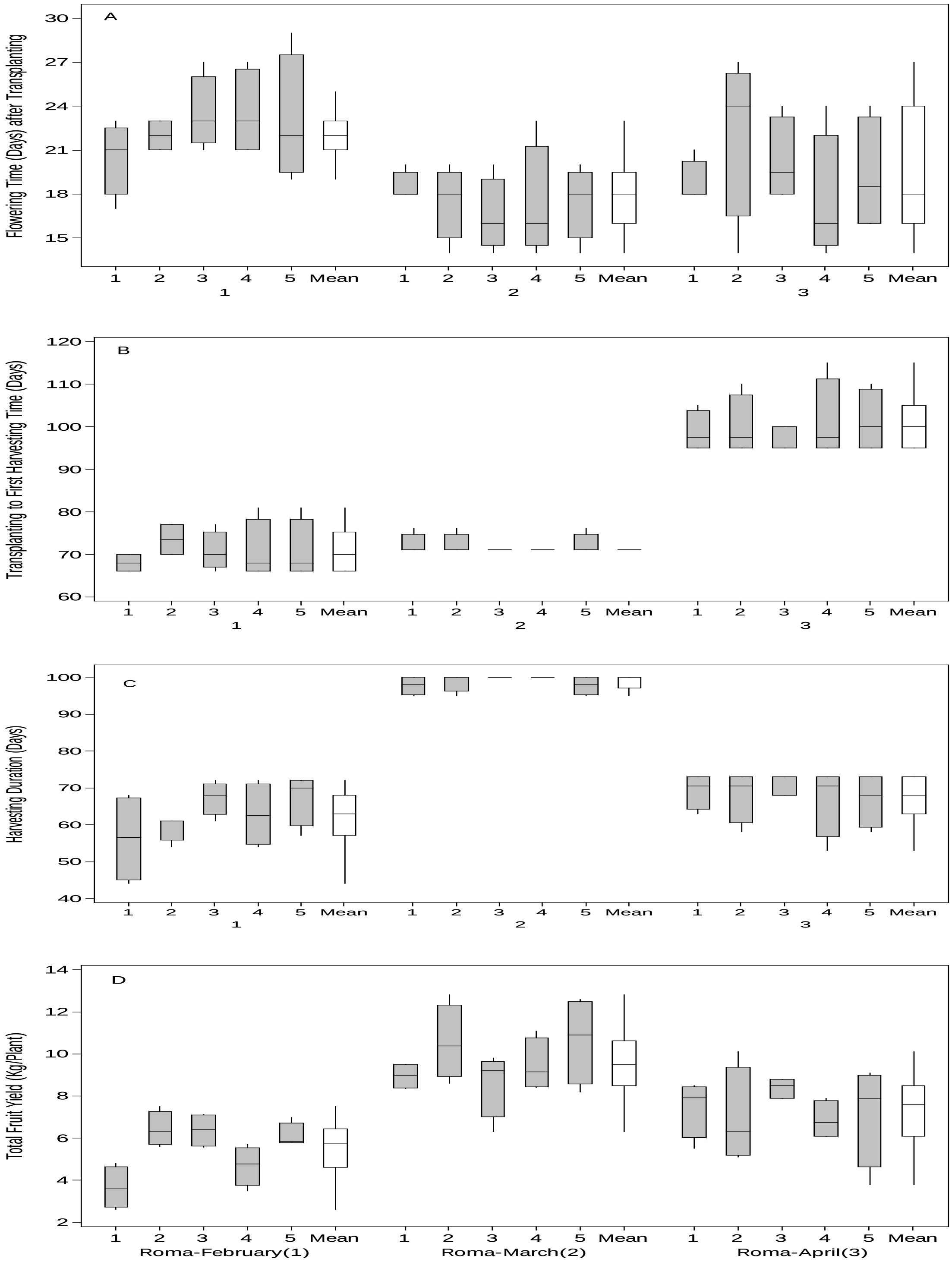


Figure 9: *Variation of flowering time (A), transplanting to first harvesting time (B), harvesting duration (C) and total fruit yield (D) in plots and its mean in blocks of Roma tomato transplanted in February, March and April in Bundaberg, 2011. Median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles and there is lack of data above 75th and 25th percentile in first harvesting time and duration. The numbers 1, 2, 3, 4 and 5 are the crop plots of Roma-February, Roma-March and Roma-April in the X-axis. The plots 1, 2,3,4,5 and mean are repeated in all crops of the x-axis.*

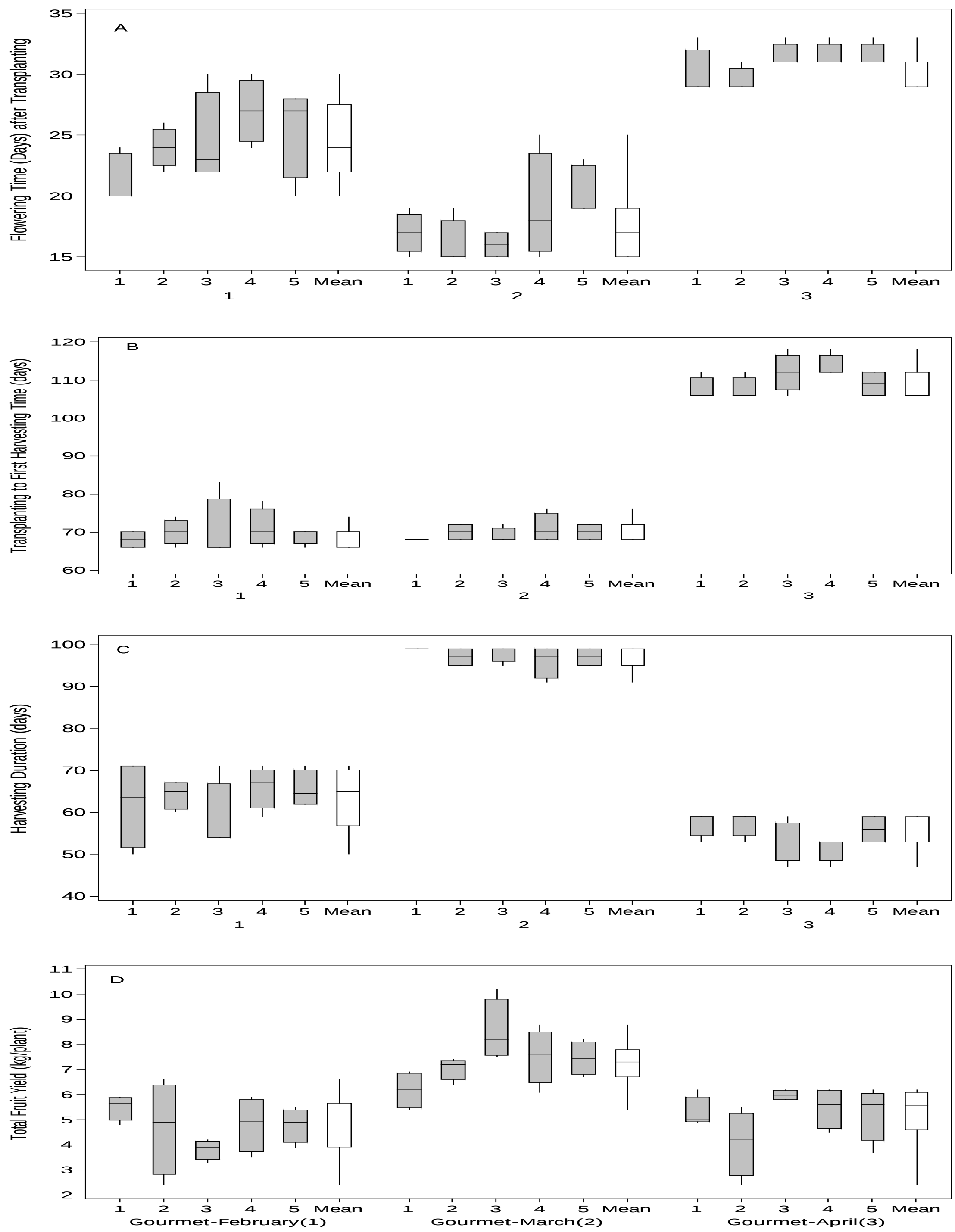


Figure 10: *Variation of flowering time (A), transplanting to first harvesting time (B), harvesting duration (C) and total yield (D) in the plots and its mean in block of Gourmet tomato transplanted in February, March and April in Bundaberg, 2011. Median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles and there is lack of data above 75th and 25th percentile in first harvesting time and duration.. The numbers 1, 2, 3, 4 and 5 are the crop plots of Gourmet-February, Gourmet-March and Gourmet-April in the X-axis. The plots 1, 2,3,4,5 and mean are repeated in all crops of the x-axis.*

CUMULATIVE YIELD TRENDS

The pattern of fruit maturation on plants was described by plotting cumulative fruit weight, as a percentage of total harvested fruit weight, over the duration of the harvest period. It was observed that the fruit maturation pattern varied between crops in both Roma and Gourmet (Figure 11 and 12). As expected, the crop was harvested over a shorter duration in both Roma and Gourmet crops transplanted in February compared to the March and April transplanted crops that matured in cooler weather. The harvesting duration was short in the crops transplanted in April in both Roma and Gourmet tomato.

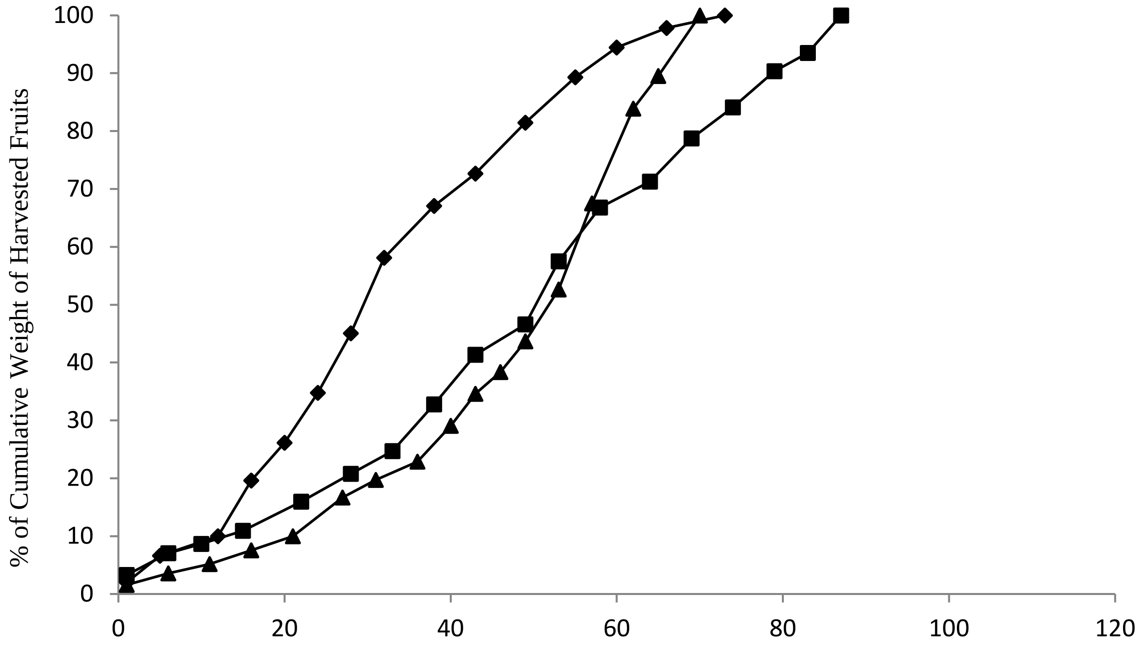


Figure 11: *Relationship between fruit harvesting days from first harvest and % of cumulative weight of total fruits in Roma tomato cultivar transplanted in February, March and April in Bundaberg, 2011. In the figure the legend —◆— for Roma -February —■— for Roma-March and —▲— for Roma-April crop*

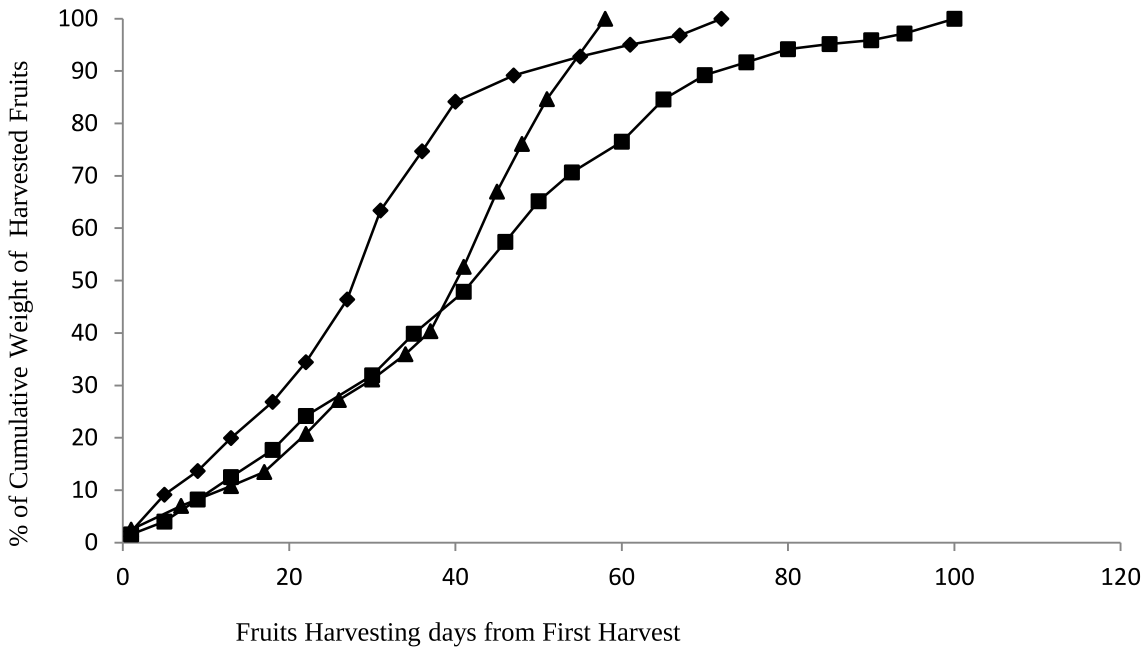


Figure 12: *Relationship between fruits harvesting days from first harvest and % of cumulative weight of harvested fruits in Gourmet tomato crops transplanted in February, March and April in Bundaberg, 2011. In the figure the legend ◆ for Gourmet-February, ■ for Gourmet-March and ▲ for Gourmet-April crop*

The shape of the cumulative harvested fruit weight curves differed between the crops, with only the Rome transplanted in February and Gourmet transplanted in February and March crops displaying a flattening of the curve near the final harvesting (Figure 11 - 12).

DISCUSSION

Considerable variability both between plants within a crop and between crops planted at different locations and times was recorded in the trials described in this chapter. As expected, crops grown when temperatures were higher displayed faster rates of phenological development. This relationship under field conditions is consistent with the considerable volume of literature describing the effects of temperature on yield characteristics for tomatoes under glasshouse conditions (Peet et al., 1997; 1998; Adams et al, 2001; Uzen, 2007) and also with the thermal time relationships previously described for field grown tomatoes (Perry et al., 1997). Within crop variability cannot be explained only by the temperature response, and the scale of the variability recorded in this research highlights both the importance of crop establishment practices to promote uniformity and the potential impact of factors other than temperature on plant development.

Significant variability between crops in the physiological age of plants at initiation of the first truss, measured as node number at which the truss formed, was recorded. Similar research findings were also described for glasshouse tomato crops (Kinet, 1977 and Uzen, 2006). Kinet (1977) found that the nodes/leaves formed before initiation of the first inflorescences decreased with increasing light intensity, and Uzen (2006) mentioned that the node number below the first truss declined linearly with decreasing temperature in the range of 7.4 to 24.2 degrees Celsius but that the effect was modified by light intensity. Under field conditions, tomato crops are exposed to large fluctuations in temperature, light intensity and other environmental factors within short periods of time, and therefore prediction of effects of the interactions between these environmental factors is complex.

Both Roma and Gourmet crops transplanted in March flowered earlier and at lower node number than the crops planted in February and April when conditions were warmer and cooler respectively, demonstrating that temperature alone did not control flowering time. The April planted Roma crop also flowered earlier than the February planted crop while the April planted Gourmet crop flowered later than the corresponding February crop, showing that cultivar and/or transplant condition may also affect the interactions between the different factors regulating flowering time. The tomato plants in their native habitat are day neutral i.e. photoperiod-insensitive (Pneuli et al., 1998) for flowering; therefore doesn't respond to photoperiod for flowering and the trial results suggest that site related management factors as well environmental conditions may have influenced flowering time. Differences in node number at which the first truss was initiated showed that the variation in flowering time was due to differences in the time of initiation rather than simply plant growth rate, and therefore an interaction effect of factors, including temperature and light intensity, may have contributed to the development of inflorescences at lower node in March planted crops as temperature alone does not explain the response. Transplanting seedlings age, physiological status or transplant stress were also considered others potential factors influencing flowering time of the tomato plants and further examination of the effects of these variables on field tomato development are required.

The other hypothesis to explain the early flowering in the Roma and Gourmet crops transplanted in March relates to soil type. The crops were transplanted in sandy soil in contrast to the heavier textured soil of the February and April crops. More frequent irrigation was required at this site and the resultant soil drying and wetting pattern leads to the possibility of root to shoot non-hydraulic signalling in the plant influencing flowering node and flowering time. Root derived signals associated with exposure to dry soil are known to influence shoot growth rate in tomato (Sharp et al., 2000; Hussain et al., 1999) and in other crops this response has been manipulated through partial root zone drying to enhance flower and fruit development (Bindon et al., 2008; Posades et al., 2008; and El-Sadek,2013). The possibility of soil type and /or interaction of water and nutrients effects on flowering time, whether through root system signalling or alternative mechanisms, highlight the need for multiple factors to be assessed in development of predictive systems for field grown tomato crops.

Further evidence for the effects of soil conditions on flowering comes from the differing flowering times of the two 'April' crops which were transplanted only 2 days apart. The Gourmet-April crop was transplanted in wet soil following heavy rainfall whereas the Roma crop was transplanted earlier. Transplanting in wet soil is likely to have compacted the soil, reducing root system growth and uptake of plant nutrients from the soil (Tracy et al., 2013). This mechanism may explain the delayed flowering in the Gourmet crop transplanted in April. The literature also suggests that soil salinity often affects the timing of development of the crops, with Pasternak et al (1979) reporting that onions flowered earlier under salt stress conditions whereas salinity delayed flowering of tomato crops. Heavy metals in the soil reduce the growth of tomato and other crops that delays the flowering and harvesting time of the crops (Hildebrandt et al., 2007). Soil compaction, salinity and drought also reduce the growth and development of the crops and yield (Daei et al., 2009; Miramari, 2009). A penetrometer can be used to measure the compaction of the soil, normally in research trials but in SP Exports i.e. a commercial company it was not used. As soil conditions in field crop production may vary greatly from site to site, the potential for soil factors such as heavy metals, compaction and salinity to affect flowering time and subsequently harvesting time cannot be discounted.

The results suggest that there were no significant differences between plots within crops, suggesting uniformity within sites for each crop, but the variation was observed between Roma and Gourmet tomato cultivars in each site. Within crop variation in flowering time in Roma was observed to be in the range of 9-13 days (mean 11 day) and for Gourmet 4-10 days (mean 8 day) that indicate the cultivar specific characteristics in the same growing environment. The coefficient of variation(CV) from transplanting to flowering day was in the range of 13- 20 % in Roma and 5- 16 % in Gourmet crops and flowering to 1st harvesting time in all crops was not consistent, with the coefficient of variation (CV) for all crops in the range of 4-7 %. The Roma and Gourmet tomato cultivars have different propensity to be variable in the flowering and first harvesting time and similar research findings have been described by Bhattarai and Subedi, 1996; Hussain et al., 2002; and Pandey et al., 2006. Improvement in variability change between flowering and harvesting time also indicate that other independent factors are responsible and it is important for commercial production of the tomato as improved within crop-uniformity leads to more efficient harvesting operations.

Significant differences in the time to first harvesting were found between crops for both Roma and Gourmet tomato, but the differences did not follow the same pattern as for flowering time. The crops transplanted in February and March were grown at comparatively higher temperature than the crops transplanted in April, and reached first harvesting earlier. Higher temperatures during the fruiting period have previously been shown to accelerate fruit ripening in glasshouse grown tomatoes (Sawhney & Polowick 1985; Zhang et al., 2005). The April transplanted crop was exposed to significantly lower temperatures at the later stages of fruit development than the February and March crops, accounting for the large difference in harvesting time in both Roma and Gourmet tomato crops.

The crop phenological traits of tomato plant such as node, leaves and shoot numbers at first flowering time had no or very weak relationship with first harvesting time of the crops, indicating other factors involved in harvesting time of the crops. The flowering time only explained approximately 50 percent (r^2 = 20-69 % for Gourmet and 33-68% for Roma tomato crops) of the harvesting time of the tomato crops. The variation in coefficient of determination (r^2) between flowering time and first harvesting time of each crop of Roma and Gourmet tomato crops demonstrating that there are other environmental and edaphic as well as site related management factors that impact variation on first harvesting time of the tomato fruits. While the factors that affect initiation of the first truss remain to be identified, the variability noted for late summer/autumn transplanted crops does not appear to have contributed to big variations in time of first harvest. The potential for flowering time differences to have a greater effect on harvesting time in crop production in cooler temperatures or in spring transplanted crops when temperature increases as the crop develops was not assessed in this trial but cannot be discounted.

The variation of phenological traits of yield parameters of each crops suggest that with similar cultural practices adopted in crop management for all crops; there are other factors in each location of the transplanted crops that impact on growth and development of the plants. The high variation in tomato crop yield in all crops of Roma and Gourmet tomato indicates that different factors have impacted on growth and development and yield of the crops, supporting the research findings to Lobell et al., 2009. Crop yield was significantly higher in the crops transplanted in March than February or April for both Roma and Gourmet tomato. The March crops flowered earlier and at a lower node number, and developed a higher number of shoots with fruit trusses. The increased number of lateral branches emerging at nodes above the first truss resulted in a higher total number of fruit trusses and these produced higher yield than the crops planted in February and April. The production of higher yield on the crop transplanted in March might be due to soil related factors that was also explained earlier (Sharp et al., 2000; Hussain et al., 1999; Bindon et al., 2008; Posades et al., 2008; and El-Sadek, 2013) and/ or optimum temperature for the growth and development of the plant (Scholberg et al., 2000; Cheng et al., 2002; and Uzun, 2007). The result also suggests that due to the strong relationship between fruit numbers and weight of the fruit the fruit numbers can be used for the yield. There was no or very weak relationship between phenological traits of the tomato plant (yield parameters) and yield of tomato that indicates other factors have impact on yield and similar research was also explained in processing tomato crops grown in Mediteranian region (Patane and Cosentino, 2010) and greenhouse grown tomato crops (Kleiber et al., 2014).

The total cumulative harvested yield pattern of Roma and Gourmet tomato crops showed that the crops transplanted in March has longer period of harvesting duration compare to other crops due to site related and other factors that were also explained earlier in the discussion. This flattening of the curve of Roma and Gourmet tomato also suggest that the plants producing the number of marketable fruits late in crop development. In contrast, crops not displaying this pattern may either have had their harvest terminated while fruit were still maturing on the plant or be producing a larger number of smaller sized fruit that were considered not commercially marketable. Trusses located at lower node positions, including on lateral shoots emerging from lower nodes, produce predominantly marketable fruit; in contrast trusses which are located at higher nodes tended to produce either small fruits or poorly quality fruit due to defects such as sunburn and therefore contribute less to harvestable yield and similar research findings was also explained by Lozane et al., 2009 in tomato crops.

CONCLUSION

A consistent level of variability in key plant development parameters was found within crops suggesting the uniformity within the sites of the crops but significance variation were found between the crops. The significant variation between the crops indicates that there are also other factors than temperature that are likely to account for some of the variation of the crop. Flowering time and the node at which the first flowering truss was initiated varied between crops that indicate other independent factors such as transplanting seedlings age, interaction of environmental and edaphic factors were identified as the possible sources of early flowering. Flowering time only explained approximately 50% of variability in initial harvesting time, demonstrating the need to do further research on other environmental and edaphic factors affecting on time of harvesting and yield.

CHAPTER 4

ANALYSIS OF COMMERCIAL CROP DATA

ABSTRACT

The research described in this chapter was conducted to identify the factors that impact on first harvesting time and yield of field grown tomato crops in sub-tropical climatic conditions. The commercial production data from 217 of Roma and Gourmet type field tomato crops grown by SP Exports in the Bundaberg region in Queensland, Australia over the 4 year period 2008-2011 were analysed. Information on weather data for these years was collected from the Bureau of Meteorology weather records from Bundaberg Aero Club weather station closest to the tomato crop production blocks and assessed the impact for time to harvest and yield. Significant differences in first harvesting time of Roma and Gourmet tomato crops were found between seasons and soils indicating that the temperature and soil types have impact on harvesting time of the field grown tomato crops (Appendix Figure 11 A). Significant differences in the harvesting duration of these crops were also found between seasons which indicates that temperature has the main role on ripening of the successive trusses for fruit harvesting and the levels of variability was also found to differ in different soil types. Significant differences in yield were found only between seasons for Roma crops. No significant impact of soil and seasons were found on yield of Gourmet crops. Yield was highly variable within seasons and with soil types which indicates that more research is required to identify the impact of temperature and soil factors and their interaction on the yield of field grown tomato.

INTRODUCTION

Tomatoes have been produced as a major crop in the Bundaberg region for 35 years, with expansion to year round production in the past seven years. Detailed records of commercial tomato production in Bundaberg were first collected by the State Government Department of Agriculture in 1977, and the first recorded production was a total marketable yield of 3622.6 tonnes worth an estimated A$2.63 million (Lovatt, 2013). Initial production was seasonal and late winter transplanted/spring harvested crops dominated. Improvements in agronomic practices and access to new hybrid cultivars led to a continuous increase in production until 1988 when virus infections threatened the industry. A decade of declining production was arrested following release of new disease resistant cultivars, and extension of the production window to year round production has increased industry value to in excess of $100 million each year since 2007.

The recent expansion in production has occurred alongside the emergence of large scale, modern production companies utilising sophisticated crop management systems including extensive crop data collection. Crop records contain information such as production location, site details, production practices, transplanting and harvest dates, yields and commercial pack-out rates have been kept by major producers including the region’s largest producer, SP Exports. The soil types and the background of the cropping patterns of each location are kept as computerised records. The records also include production practices such as dates of land preparation, transplanting date of the seedlings, trellis and wiring and pesticide used in each location. The numbers of rows on each block, numbers of blocks as well as total numbers of plants and the predicted harvesting time in each location were also recorded. The weight of fruit harvested every day from the specific areas of each location is assessed, labelled on the harvested bins and recorded before fruit is transferred to cold room facilities in the packing shed. The net weight of packed fruits is recorded after grading to separate marketable from lower grade fruit. Maintenance of records in large production companies is generally designated to a trained employee responsible for aspects of quality assurance within the company.

While data have not been collected in a scientifically rigorous manner by most commercial operators, the large volume of crop record data can provide an indication of factors affecting harvest time and yield. Crop records have previously been used in tomato and other crops to examine a range of production environment and management practice impacts. McKeown et al., (2010) used crop production data and yearly production trends of tomato and other cool season vegetables crops over a 60 year period from 1940 to 2000 to assess potential impacts of global warming on yield. Lee et al., (2011) in California used historical production data of tomato and other crops to predict the future yield by comparing the 11 years moving averages on yield since 1956 to 2094. These overall yield predictions have value in long term trend predictions, but not for identification of localised factors that may be contributing to yield variability.

The high level of yield variability in commercial production has been noted in many studies (eg Sadras et al., 2002; Lobell et al., 2007) and has no doubt been a disincentive to use of commercial crop data in traditional agronomic and physiological studies, but where large data sets exist the heterogeneity is valuable in identifying factors that impact on yield. For example, the impact of nitrogen fertilizer management on irrigated rice yield in the Philippines (Cassman et al., 1996), effects of previous crop in a rotation on spring wheat yield in Canada (Bourgeois & Entz, 1996) and relationships between crop management practices and wheat yields in Argentina (Calvino & Sadras, 2002) have all identified strategies to improve yields based on commercial crop data analysis. In summarising the potential value of commercial crop data analysis, Lobell et al., (2009) noted that these studies can deliver information on the relative importance different factors (farmer skill, management practices, soil quality and environment) on crop development and yield.

Commercial crop records also provide data for development and validation of crop models. All process oriented and statistical models are based on the crop production data for a certain periods. Shin et al., (2013) had used crop simulated historical data of maize and peanut for validation of different yield prediction models in Florida, USA. Wenjiao et al., (2013) in China had used the historical data on crop yield to validate the crop model for predicting the production trend and factors affecting yield. Therefore, historical crop records are very important for development and validation of any crop models.

One example of the use of crop records in model development is their utilisation in development of basic heat unit crop models. The heat unit accumulation method has been used in many vegetables crops for predicting harvesting time. Perry et al (1997) found that heat unit summation methods were more accurate than a day counting or calendar dates method from transplanting to predict harvesting for tomatoes in the South Atlantic Coast region in USA. In the standard degree day method, a base temperature is subtracted from the daily average temperature for each day from transplanting to harvest and summation of these values derives the heat unit accumulation of that crop at harvest. While a number of studies have demonstrated the applicability of heat unit models in tomato, it is evident from the published studies that the base temperature and heat unit requirement of the crops vary between production locations. Heat unit requirement of the crops for ripening also depends on the specific cultivar characteristics i.e. early harvesting varieties ripened earlier than late ripened varieties and also solar radiation received by the plants in specific production location. There are no published reports on the heat unit requirement of tomatoes in regions with a similar climate and production system to the subtropical regions of Queensland, Australia so previously published heat unit models are unlikely to be accurate predictors of harvesting time.

Heat unit models are particularly effective when temperature is the major determinant of the development rate of crops. The data presented in the previous chapter documenting harvest time and yield in a small number of commercial crops revealed significant differences between the crops. The plant to plant variation within crops of 1st harvest time in Roma and Gourmet was 5 to 20 days and 8 to 17 days respectively. The mean number of days between transplanting and 1st harvest was significantly higher in crops transplanted in April than for crops transplanted in February and March in both Roma and Gourmet tomatoes. The factors other than temperature were also affecting the crop growth and development that was explained in the previous research Chapter 3, but with low coefficient of determination (r^2) in the regression analysis. Analysis of commercial crop data provides an approach to identify and assess the impact of factors other than temperature on field tomato development, and therefore to gauge the potential of simple heat unit summation or more complex mechanistic model approaches to predict timing of harvest and yield.

The aim of this research was therefore to utilise commercial crop data to assess whether factors other than temperature have a significant effect on harvesting time and yield in a sub-tropical production region. In this study, 99 Roma and 118 Gourmet crops commercially grown by the SP Exports between 2008 and 2011 at different sites, seasons and soil types were chosen for assessment of the production trends and the factors affecting the harvest time and yield.

MATERIALS AND METHODS

Analysis of production data from 217 field tomato crops grown in the Bundaberg region in Queensland, Australia over the 4-year period 2008-2011 was made possible by the project industry partner, SP Exports, generously allowing access to a database of commercial crop records. The crop records included details of a broad range of location, timing, production input and harvest parameters. Only crops of the fruit types denoted Roma and Gourmet were selected for analysis from the commercial crop database. Prior to extracting data, a list of key parameters was generated. This list reflected both the areas identified in crop monitoring research as likely to be influencing harvest time and yield as well as ideas from industry collaborators on factors considered important in the management of harvest time and yield.

Data from commercial crop monitoring records was extracted from the SP Exports database and used to generate a spreadsheet. Parameters included in the spreadsheet were transplanting dates, transplanting areas, first harvest date of the crops, harvest duration, yields and soil types for each production block. Calendar date values were converted to Julian date values in order to calculate the time from transplanting to first harvest and the duration of harvest from first to last fruit harvest.

Information on environmental factors was collected from the bureau of meteorology weather records from stations of the Bundaberg Aero Club weather station (Latitude -24.89 º and longitude152.32 º East) that represents the Bundaberg weather data in this region for the crop production (Table 1). The justification of using these data is given in Chapter 2.

Table 1: *The monthly weather data from the Bundaberg Aero Club*[@] *close to the tomato crop production blocks in 2008- 2011*

2008		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	30.4	31.1	29.3	27.1	23.9	20.1	22.2	23.8	25.5	27.2	30.0	29.0
	Min*	21.1	21.9	21.1	17.8	12.7	9.7	8.4	10.4	11.4	16.4	18.6	19.3
Rainfall	mm	179.4	38.2	212.0	63.6	52.8	39.2	14.4	39.8	10.6	59.6	0.4	209.6
TCSR+	MJm^{-2}a	717.5	570.1	696.5	624.8	502.1	438.5	402.2	578.3	638.9	754.0	765.9	862.7
2009		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	30.4	30.2	29.2	28.2	24.3	22.7	22.5	25.6	26.7	28.0	29.2	30.4
	Min*	22.3	22.4	20.2	18.7	14.3	12.0	10.4	13.6	14.7	16.4	19.5	21.6
Rainfall	mm	135.0	269.2	66.8	116.2	85.3	46.8	0.0	2.0	45.2	4.8	40.8	95.0
TCSR+	MJm^{-2}a	744.8	648.5	673.3	577.8	506.2	449.7	500.5	596.1	692.0	822.1	842.8	854.1
2010		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	30.8	29.5	28.3	27.9	24.8	22.7	23.0	22.9	25.7	26.8	27.0	29.0
	Min*	22.1	22.4	21.0	19.4	14.6	12.6	12.6	10.8	15.5	16.5	18.5	21.4
Rainfall	mm	85.2	398.5	293.8	29.2	20.7	9.9	23.4	126.0	129.8	49.8	79.6	572.8
TCSR+	MJ/ma	825.2	613.4	667.8	580.2	514.3	435.1	447.7	517.4	501.6	736.1	697.5	677.2
2011		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	30.3	31.0	29.3	27.1	23.8	22.0	22.3	23.8	25.5	27.2	30.1	29.1
	Min*	21.0	21.8	21.1	17.7	12.6	9.7	8.4	10.8	11.5	16.5	18.8	19.4
Rainfall	mm	179.4	38.2	212.0	63.6	52.8	39.2	14.8	51.2	10.6	59.6	0.4	209.6
TCSR+	MJ/ha	813.7	711.4	565.1	556.2	522.5	447.4	487.0	498.4	664.8	671.7	872.2	773.2

[*] *Maximum and minimum Temperature was based on mean of maximum and minimum temperature of the month.*

[+] *Total cumulative solar radiation (TCSR) was based on the cumulative solar radiation of the days on each month.*

[a] *Mega joules per hour*

[@] *Justification is given in Chapter 2 on the use of data*

Transformations of the harvest date data were required to adjust for variability in first harvest date caused by commercial factors. The initial harvest of fruit may occur early in the fruiting period if demand and/or price are high or later if demand and/or price are low. This makes comparison between crops problematic as the comparison isn't made at an equivalent stage of crop phenology. Transformation of the data was undertaken by plotting cumulative yield against date for each crop and selecting the date at which 2.5% of the total crop yield was obtained as the first harvest time. This was based on the historical crop records of the mean harvested fruit yield at first harvest with cumulative yield of each crop. The actual first pick occurred prior to this date in approximately 70% of the crops, and on the date in approximately 15% of the crops.

The calculation of the raw crop data was performed to identify the first harvest day, harvest duration and yield for each crop. The first harvest day of each crop was calculated by subtracting the transformed first harvest date from transplanting date. The harvest duration of each crop was calculated by subtracting the transformed first harvest day from the last harvest day of the crop. The company had recorded the yield data in kilograms of fruit per block or field and this figure was divided by the area of each block to calculate yield in tonnes per hectare. Generalised additive models (GAMS) were used to identify any yearly and seasonal trends in the time to first harvest, duration of harvest, and crop yield.

STATISTICAL ANALYSIS OF THE DATA

Seasonal and yearly trends and variance in the time to first harvest, duration of harvest, and crop yield of Roma and Gourmet field tomato crops produced by SP Exports in 2008-2011 were examined using a combination of descriptive and quantitative statistics. Because the *variation* at *each* time period in initial harvesting time, harvest duration and total and marketable yield was as important as identifying yearly trends in the data, each response variable was first described using exploratory co-plots and box-plots in R version 3.1.1.

Generalised additive models (GAMS) were used to identify any yearly and seasonal trends in the time to first harvest, duration of harvest, and crop yield. Generalised additive models are generalised linear models with a linear predictor involving a sum of smooth functions of covariates (Wood, 2006). All GAMS used in this chapter were fitted in R version 3.1.1 using the *mgcv* package, assuming a Gaussian error distribution and identity link function.

The response variables for the models were Harvest Duration, First Harvest Day and Industry Calendar day, measured in Julian days. The predictor variables examined were: week of transplanting, and year. Models were constructed using both predictor variables and no interactions terms were used in order to better compare between models.

The GAM plots presented in the results show the estimated flexible effects of time-related changes in the response variable. The x-axis represents the changes in response variable values over time (week of planting), obtained from the GAM. The GAM plots include the 95% point-wise confidence intervals (dotted) and are centred at zero to allow comparisons. The effective degrees of freedom obtained for each predictor are indicated on the y-axis.

For each cultivar, various GAMs were tested using the non-parametric smoothing function with a default of 10 knots, week and year. To compare and identify the most suitable models for use in describing the response of variables First Harvest Day and Harvest Duration, an ANOVA with a chi-square test was used. The following GAMs were selected from a series of ANOVAs for each crop:

Roma Tomatoes:

For Actual First Harvest Day:

First Harvest Day~ s(Week, bs =”cr”, by = factor (Year)

For Industry Predicted First Harvest Day

Industry Harvest Day ~ Week + s(Week, bs = "cr")

For Harvest Duration:

Harvest_Duration ~ Week + s(Week, bs = "cr")

Thus, whilst the variance in first harvest day required both week and year to be described adequately by a GAM, the industry predicted first harvest day and actual harvest duration were adequately described by the smoothing term and week only.

In gourmet tomatoes, all response variables were adequately described by the same GAM.

Response ~ Week + s(Week, bs = "cr") + Year

This model included the non-parametric smoothing term plus Week and Year as parametric terms. Year was treated as a factor.

A regression analysis comparing industry predicted harvest day and actual first harvest day of both Roma and Gourmet tomato crops was also done by using Minitab 16. One-way analysis of variance (ANOVA) of first harvest date, harvest duration and yield of the crops in each month was performed in Minitab. The comparisons of the different measured data were analysed by one-way analysis of variance and or general linear model in Tukey's method at 95 percent confidence interval and all the statistically significant findings are reported at $p \leq 0.05$. Data was transformed when necessary to ensure normality and homogeneity of variances by square root transformation in excel and also by Johnson transformation in Minitab 16.

RESULTS

Two tomato cultivars, one from each of the Roma and Gourmet tomato types, were selected for this study. A total of 99 Roma and 118 Gourmet tomato crops were chosen for analysis. The crops were transplanted between 2008 and 2011 in the Bundaberg region in Queensland, Australia (Table 2). The number of crops transplanted in 2008 was comparatively higher than in other years while the distribution of crops transplanted in different seasons was similar with a greater number of crops generally transplanted in spring and summer than autumn and winter. The study commenced in the middle of 2011; therefore the winter and spring crop records of 2011 were not available for the analysis. The average crop size was between 3.5 and 8.5 ha, resulted in crops that produced an average of approximately 300 tonnes of fruit. The total yield and marketable yield was comparatively higher in 2008 than in other years, and the marketable yield was around ten percent lower than total yield in all years for both Roma and Gourmet tomatoes.

Table 2: Number *of crops and area used in different seasons and yield of Roma and Gourmet tomato transplanted in 2008-2011 Bundaberg.*

Parameters	Roma				Gourmet			
	2008	2009	2010	2011	2008	2009	2010	2011
Crop Numbers	34	25	27	13	43	33	28	14
Summer Planting	12	6	8	6	15	8	10	11
Autumn Planting	8	5	5	7	13	8	5	3
Winter Planting	7	7	6	N/A	8	7	5	N/A
Spring Planting	7	7	8	N/A	7	10	8	N/A
Mean Crop Area (ha)	4.9 ± 0.4	5.4 ± 0.3	5.1 ± 0.4	3.5 ± 0.5	6.9 ± 0.6	8.5 ± 0.9	7.2 ± 0.8	6.3 ± 0.9
Yield (Ton/ha)	72.6 ± 3.0	72.4 ± 4.4	64.4 ± 3.2	68.7 ± 4.5	75.3 ± 4.3	65.7 ± 2.9	69.3 ± 4.4	51.4 ± 4.6
Marketable Yield (Ton/ha)	65.0 ± 2.7	64.7 ± 3.9	57.4 ± 2.8	61.0 ± 4.3	67.6 ± 3.9	58.8 ± 2.6	61.9 ± 4.0	46.0 ± 4.1

Analysis of the commercial crop data focussed on three aspects of crop performance; timing of the first harvest, duration of the harvest and the crop yield. Data analyses for each aspect are presented separately in the following sections of this chapter.

INITIAL CROP HARVEST TIME

The time between transplanting and first harvest time of Roma and Gourmet tomato varieties displayed high variability between months and seasons in 2008-2011(Table 3, 4 &5). The crops transplanted in late autumn and in winter required comparatively more days to harvest for both Roma and Gourmet tomato. The Roma tomato crops transplanted in late spring (i.e. in October and November) and early summer (i.e. December) ripened earlier than crops transplanted at other times of the year whereas Gourmet tomato crops transplanted in late spring (i. e. in October and November) displayed the earliest ripening. The time to first harvesting day of Roma tomato was higher for the crops transplanted in 2008 and comparatively lower for the crops transplanted in 2009. This trend was consistent with the mean temperature in the winter months for the 2 seasons (Table 3-4). Similarly, the Gourmet tomato crops transplanted in 2008 were harvested later than in other years.

The initiation of an overall upward trend in days to first harvesting was observed commencing in Roma crops transplanted in January and days to harvesting reached a peak in the middle of the May (Figure 1). The rate of increase was slow from the beginning of the January to the end of February, and increased for the crops transplanted in March to the end of April. A downward trend followed between June and October, before a stable phase of around 6o days from transplanting to first harvest that extended until the end of December for Roma tomato crops.

For Gourmet crops, days from transplanting to first harvest was found to be almost constant for crops transplanted between early January and mid-February, followed by a rapid increase reaching a peak for crops transplanted in mid- May. A correspondingly rapid decline for crops transplanted between mid-May and October where days to harvest reached its lowest point was recorded, and a slight increase through to December. The trend for Gourmet crops was for a more rapid increase and decline in days to first harvest over the winter period than was observed for Roma crops.

Table 3: *The first harvesting days and growing degree days from transplanting to first harvesting days in different months of Roma tomato transplanted in Bundaberg, 2012. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s family error rate. Values followed with the same letters on each row represent there was no difference.*

Year	Parameters	January	February	March	April	May	June	July	August	September	October	November	December
2008	1st Harvest	69.5 ± 0.5def	81.8 ± 2.8cd	89.0 ± 0.0bc	107.5 ± 2.0 a	109.5 ± 4.5a	109.3 ± 1.3a	104.5 ± 2.5ab	78.0 ± 4.0cde	60.0 ± 9.0f	65.6 ± 1.8ef	61.0 ±2.0ef	60.4 ± 1.2f
	GDD*	1759 ± 21abcde	1949 ±36a	1901 ± 0abcde	1981 ± 12a	1873 ± 81abcde	1925 ± 40ab	1945 ± 11abcd	1612 ± 41cdef	1353 ±214f	1646 ± 47def	1634 ± 53bcdef	1634 ± 35ef
2009	1st Harvest	N/A	56.5 ± 14.5d	71.5 ± 0.5bcd	99.6 ± 1.6a	98.0 ± 0.0 ab	93.0 ± 3.0ab	82.0 ± 4.0abc	73.0 ± 1.1bcd	61.3 ± 1.4cd	59.0 ± 1.0cd	60.0 ± 1.5d	56.0 ± 1.0d
	GDD*	N/A	1410 ± 346ab	1621 ± 37ab	1870 ± 85a	1758 ± 0ab	1720 ± 34ab	1617 ± 35ab	1566 ± 14ab	1393 ± 15b	1424 ± 17ab	1569 ± 51ab	1477 ± 13ab
2010	1st Harvest	67.5 ± 4.5cde	66.6 ± 3.8 de	84.0 ± 1.1bcd	85.3 ± 6.6abc	101.6 ± 1.2 a	101.5 ± 0.5 ab	N/A	77.0 ± 3.4cde	68.5 ± 1.5cde	64.0 ± 0.0e	58.0 ± 3.4e	61.0 ± 1.5e
	GDD*	1767 ± 130ab	1648 ± 68ab	1839 ± 29a	1650 ± 108ab	1795 ± 26a	1845 ± 13a	N/A	1559 ± 41ab	1521 ± 18ab	1504 ± 64 ab	1440 ± 46b	1610 ± 31ab
2011	1st Harvest	63.0 ± 0.5c	67.3 ± 0.8bc	89.0 ± 11ab.	95.0 ± 1.8a	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	GDD*	1650 ± 13a	1649 ± 27a	1760 ± 154 a	1686 ± 35a	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[*] *Growing degree days (GDD) from transplanting to first harvesting time of the crops*

Table 4: *The first harvesting days and growing degree days from transplanting to first harvesting days in different months of Gourmet tomato transplanted in Bundaberg, 2012. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s family error rate. Markings with the same letters on each row represent there was no difference.*

Year	Parameters	January	February	March	April	May	June	July	August	September	October	November	December
2008	1st Harvest	73.0 ± 0.5cd	75.4 ± .0.5bcd	83.5 ± 4.0bc	102.0 ± 2.4 a	107.7 ± 5.2a	108.0 ± 1.4a	100.0 ± 0.0ab	78.0 ± 5.0bcd	71.0 ± 1.0cd	62.0 ± 0.0cd	56.0 ±0.0cd	63.3 ± 0.3d
	GDD*	1832 ± 24abc	1774 ±27bcd	1793 ± 67abcd	1900 ± 35ab	2000 ± 59a	1905 ± 46ab	1849 ± 0abcd	1609 ± 47bcd	1618 ±13cd	1531 ± 24d	1502 ± 0bcd	1701 ± 12bcd
2009	1st Harvest	65.0 ± 5.0fgh	73.0 ± 0.0ef	78.5 ± 2.2 e	100.0 ± 0.5ab	107.0 ± 0.0 a	93.0 ± 3.0bc	88.7 ± 0.6cd	78.0 ± 0.0def	67.3 ± 0.7fg	57.0 ± 1.0h	58.0 ± 0.5h	61.3 ± 2.6gh
	GDD*	1693 ± 92abc	1812 ± 46ab	1713 ± 40ab	1858 ± 38 a	1898 ± 0ab	1681 ± 84abc	1714 ± 6 ab	1621 ± 0abcd	1522 ± 11 cd	1394 ± 36d	1505 ± 19cd	1625 ± 63bc
2010	1st Harvest	67.8 ± 1.4cd	65.0 ± 1.5d	74.0 ± 0.0bcd	89.0 ± 3.3 ab	102.0 ± 0.0 a	93.3 ± 1.3 ab	81.5 ± 0.5abc	69.0 ± 2.0 cd	66.0 ± 4.6cd	60.0 ± 1.0d	55.0 ± 0.0d	62.0 ± 0.0cd
	GDD*	1754 ± 40a	1623 ± 26ab	1722 ± 0ab	1753 ± 2ab	1842 ± 0ab	1716 ± 32 ab	1571 ± 21ab	1455 ± 12ab	1454 ± 107b	1441 ± 7ab	1379 ± 0ab	1632 ± 0ab
2011	1st Harvest	61.5 ± 0.4 c	62.4 ± 1.1c	75.0 ± 0.0b	107.0 ± 0.0a	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	GDD*	6121 ±.11b	1568 ± 14b	1683 ± 0b	1871 ± 77a	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* *Growing degree days (GDD) from transplanting to first harvesting time of the crops*

The variation between crops in first harvest day for Roma (Figure 1 top right) and Gourmet (Figure 1 bottom right) was high for crops transplanted at most times of the year and highly significant on both crops. The variation in first harvest time was lowest in Roma and Gourmet crops transplanted in the 45-48 and 41-48 week windows respectively. Variation was highest for the crops transplanted in weeks 9-12 and 25-28 on Roma and Gourmet crops respectively and relatively low in crops transplanted between weeks 33 to 53. The lowest and highest coefficient of variation (CV) was 2.25 and 11.05 in Roma and 2.09 and 10.65 in Gourmet tomato crops respectively (Appendices; Table 11). The variability for Roma crops was higher than for Gourmet crops transplanted in different weeks over the period 2008-2011.

The commercial practice for predicting the first harvesting day in the Bundaberg region has been to use the day count method (Figure 2). The estimated days from transplanting to first harvest was calculated based on industry specified durations for each week of the year. The weekly mean of the crops transplanted in 1-52 weeks in 2008-2011 was varied from predicted value of days to first harvesting day for both Roma and Gourmet tomato crops.

The statistical regression analysis showed that the strength of relationship between observed and industry predicted first harvesting time was significant on both Roma and Gourmet tomato crops (Figure 3 A & B) and the coefficient of determination (r^2) were 78 and 84 % respectively.

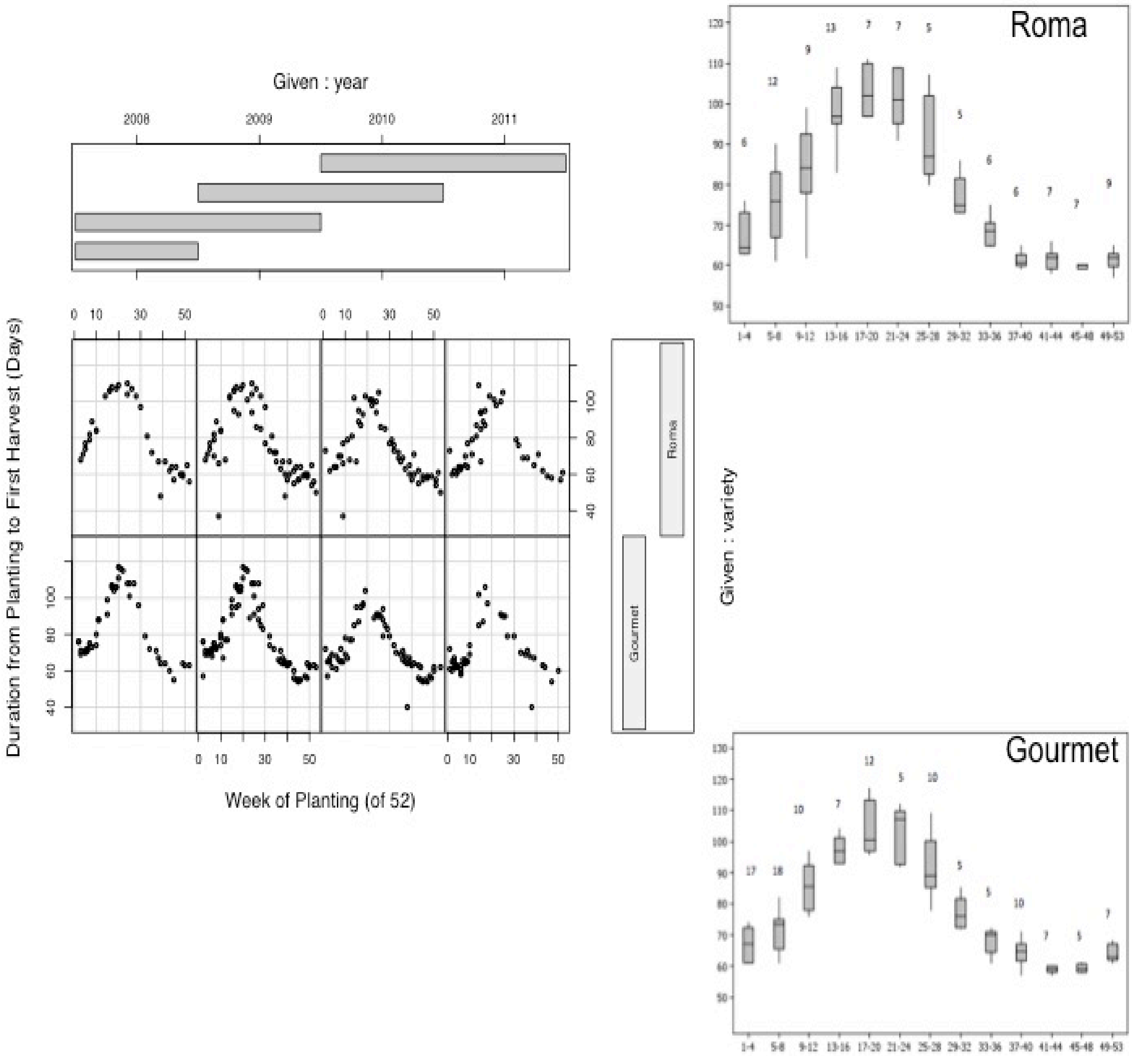


Figure 1: *The pattern of first harvesting day of Roma and Gourmet tomato crops transplanted at weekly intervals from 2008-2011 (left image). Smaller images represent variation in first harvest day across all four sampling years, where median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles. The number on the top of the box represents the number of crops transplanted in those weeks. There was more variance in time to first harvest in both varieties towards the middle of the year than at any other time.*

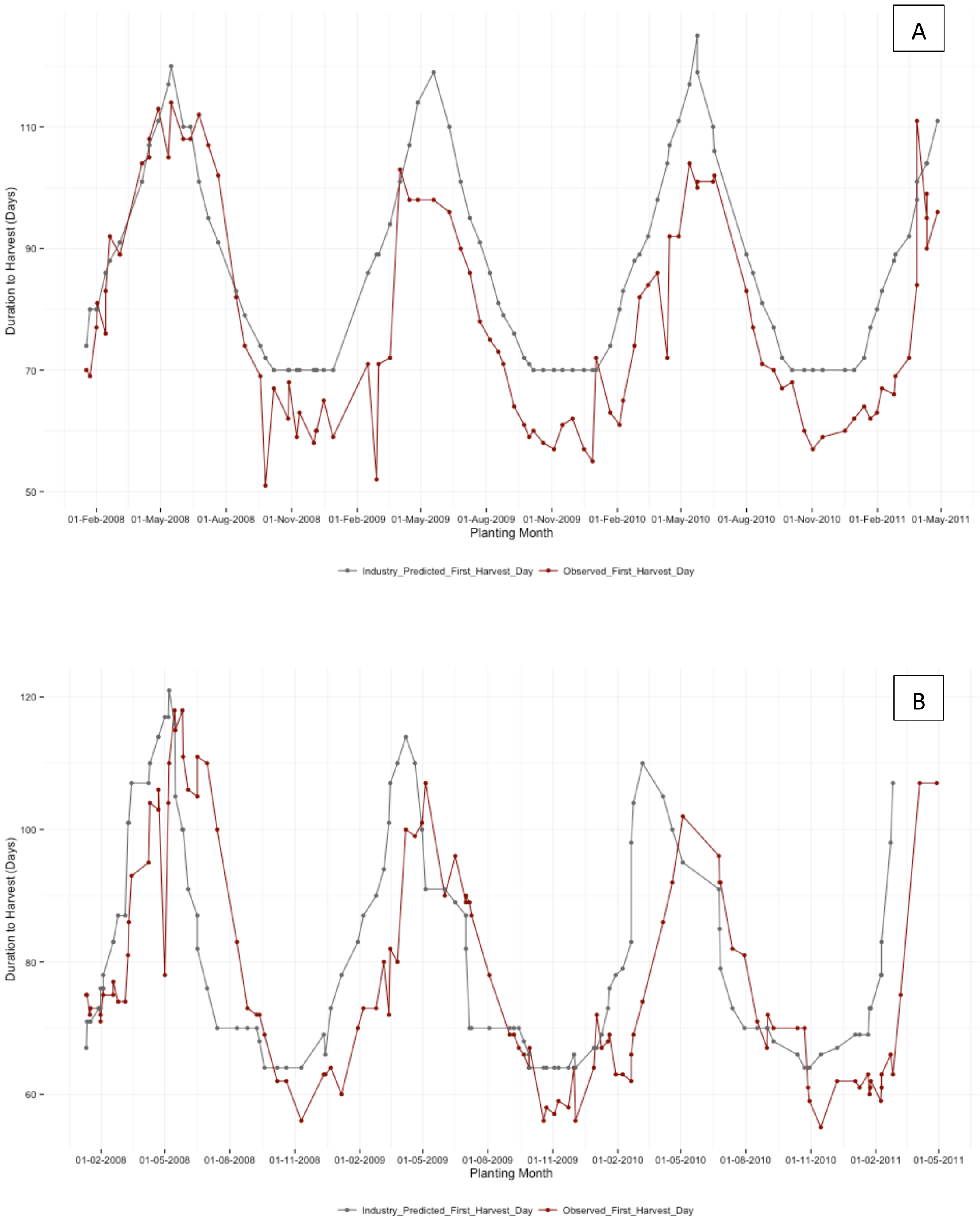


Figure 2: *Observed first harvest day from transplanting and industry predicted first harvest day of Roma (A) and Gourmet (B) tomato crops transplanted in Bundaberg in years 2008-2011. The legend* ‑•‑ *for observed first harvest day and the legend* ‑•‑ *for industry predicted first harvest day of the crops transplanted in 2008-2011.*

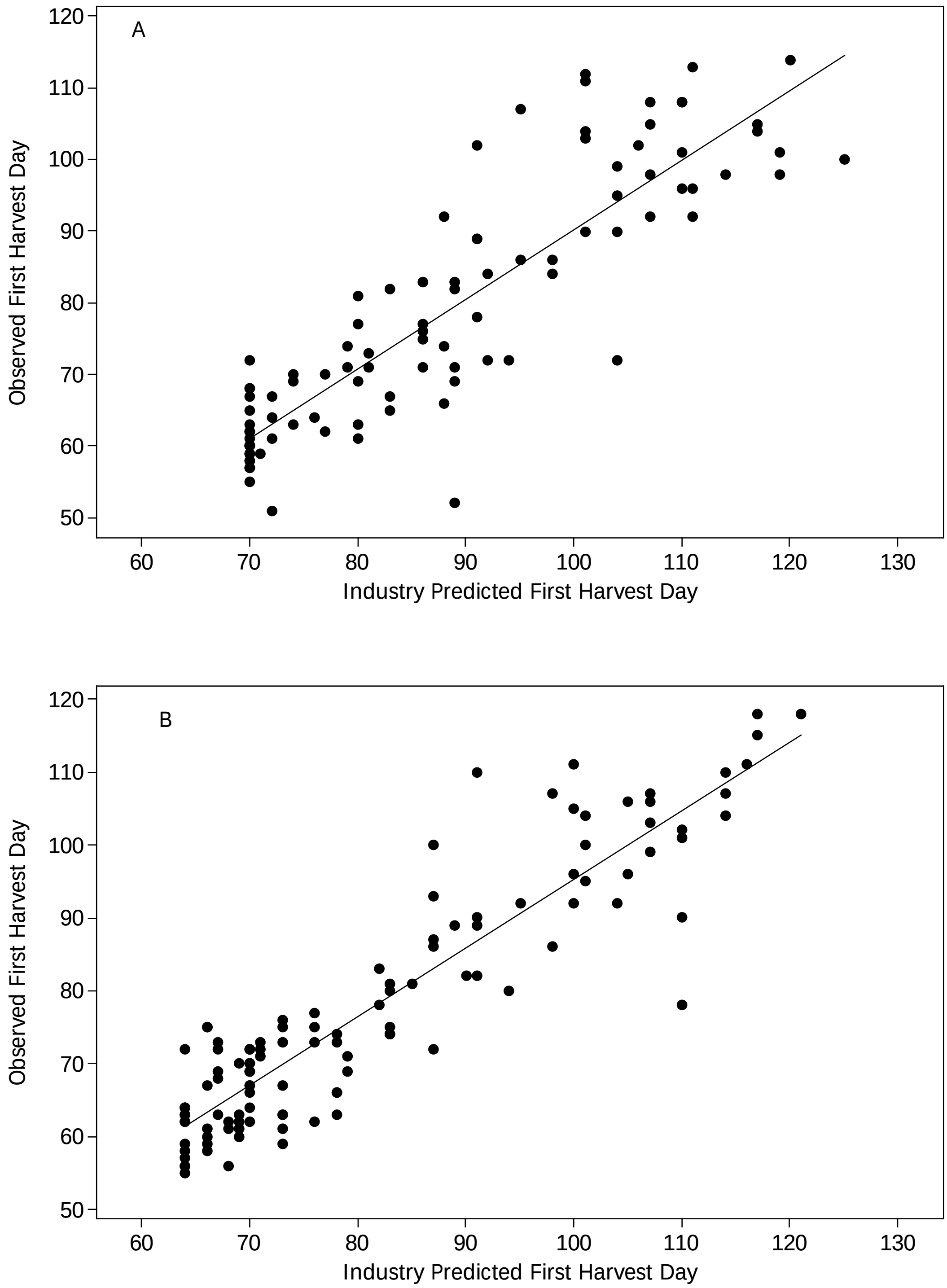


Figure 3: *Scatter plot of regression of observed first harvest day vs industry predicted first harvest day of Roma (A) and Gourmet(B) tomato crops transplanted in Bundaberg in years 2008-2011.*

Generalised additive models using cubic splines to describe seasonal and yearly trends in the measured first harvest day explained 87.9% of the deviance for Roma and 91% for Gourmet tomatoes, respectively. The effect of adding each year to the model was significant, with both week of transplanting and year having a highly significant effect on first harvest day (Figure 4 – Roma, Figure 5 - Gourmet).

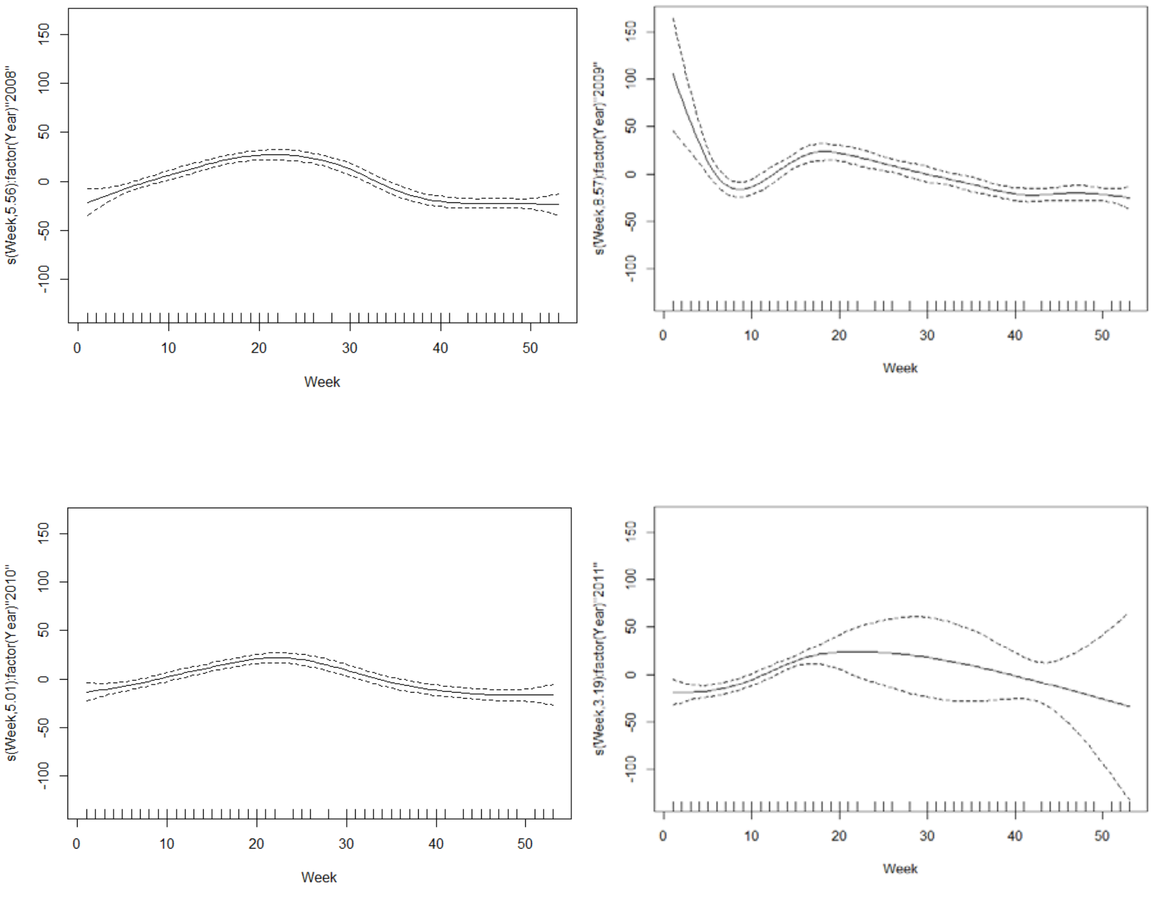


Figure 4. *(Top Left) GAM for* ***first harvest day*** *for Roma tomatoes* ***in 2008****, (Top Right)* ***in 2009****, (Bottom Left)* ***in 2010****, and (Bottom Right)* ***in 2011****, in relation to all weeks of transplanting +/- 95% confidence intervals. 'Model' presented beyond 20 weeks in 2011 is an artefact of the graphing process in R, there are no actual data present beyond 20 weeks in 2011.*

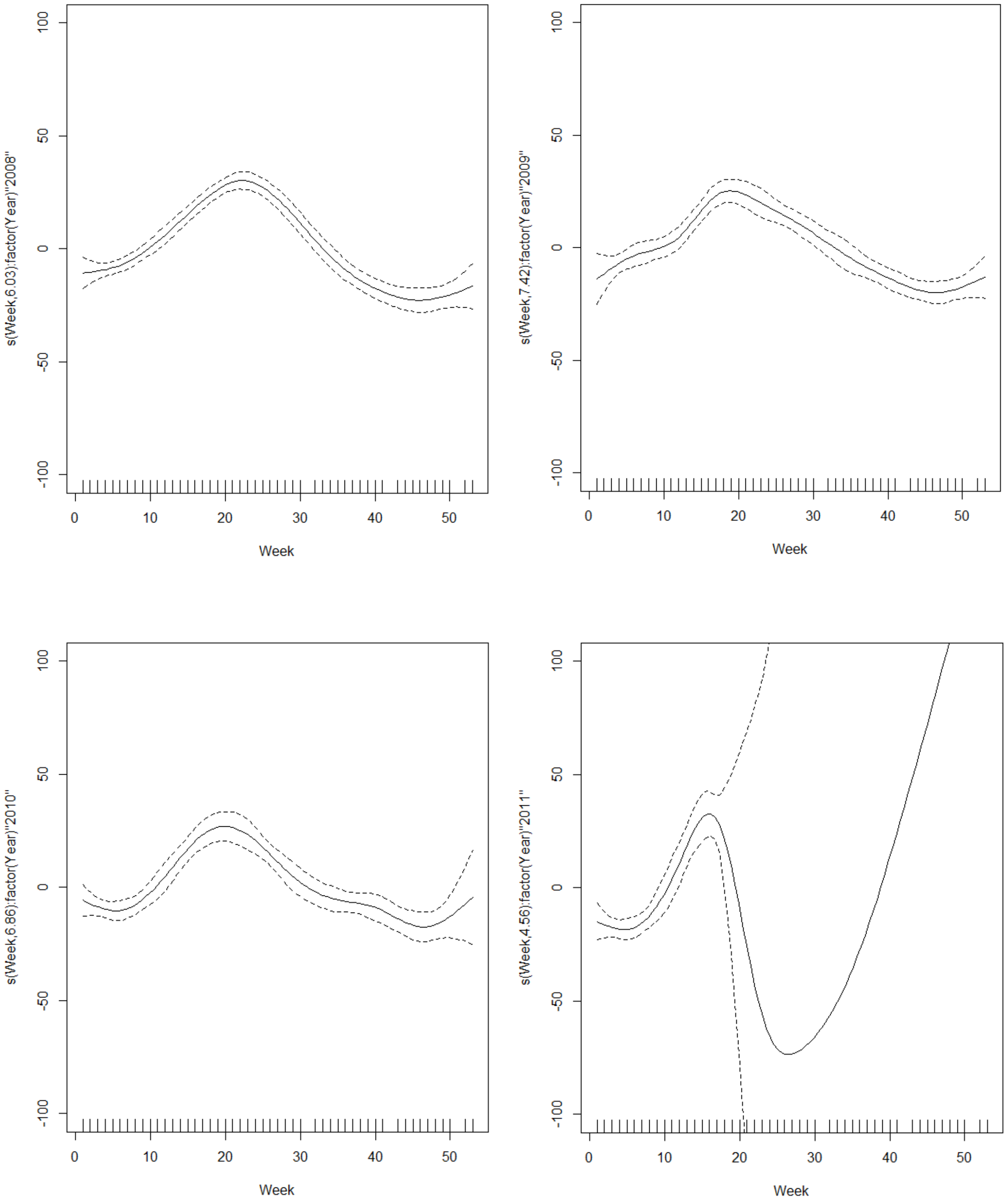


Figure 5. *(Top Left) GAM for* ***first harvest day*** *for Gourmet tomatoes* ***in 2008****, (Top Right)* ***in 2009****, (Bottom Left)* ***in 2010****, and (Bottom Right)* ***in 2011****, in relation to all weeks of transplanting +/- 95% confidence intervals. 'Model' presented beyond 20 weeks in 2011 is an artefact of the graphing process in R, there are no actual data present beyond 20 weeks in 2011.*

Generalised additive models using cubic splines to describe weekly and yearly trends in the industry predicted first harvest day explained 99.3% of the deviance for Gourmet tomatoes, whereas the weekly variation was sufficient to model variance in first harvest day in Roma tomatoes (99.3% of the variance explained – Figure 6). The effect of adding year to the model was significant for Gourmet tomatoes, with both week of transplanting and year having a highly significant effect on industry predicted first harvest day (Figure 7).

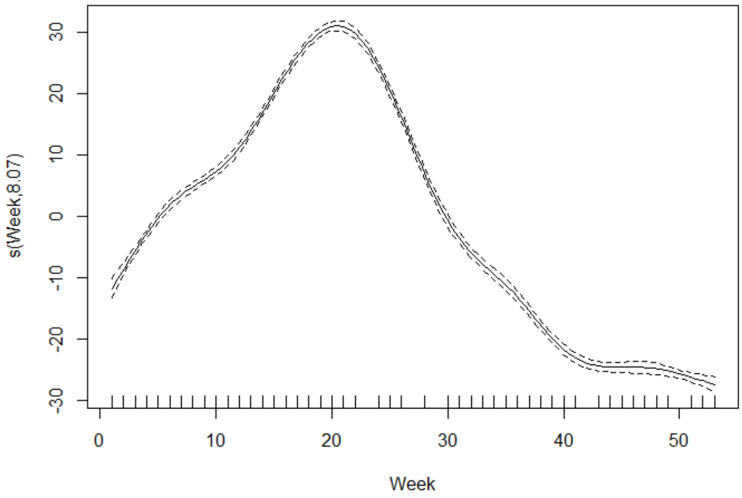


Figure 6. *Variation in industry predicted first harvest day for Roma tomatoes, +/- 95% confidence intervals for a Generalised Additive Model containing a non-parametric, ten –knot smoothing function and week.*

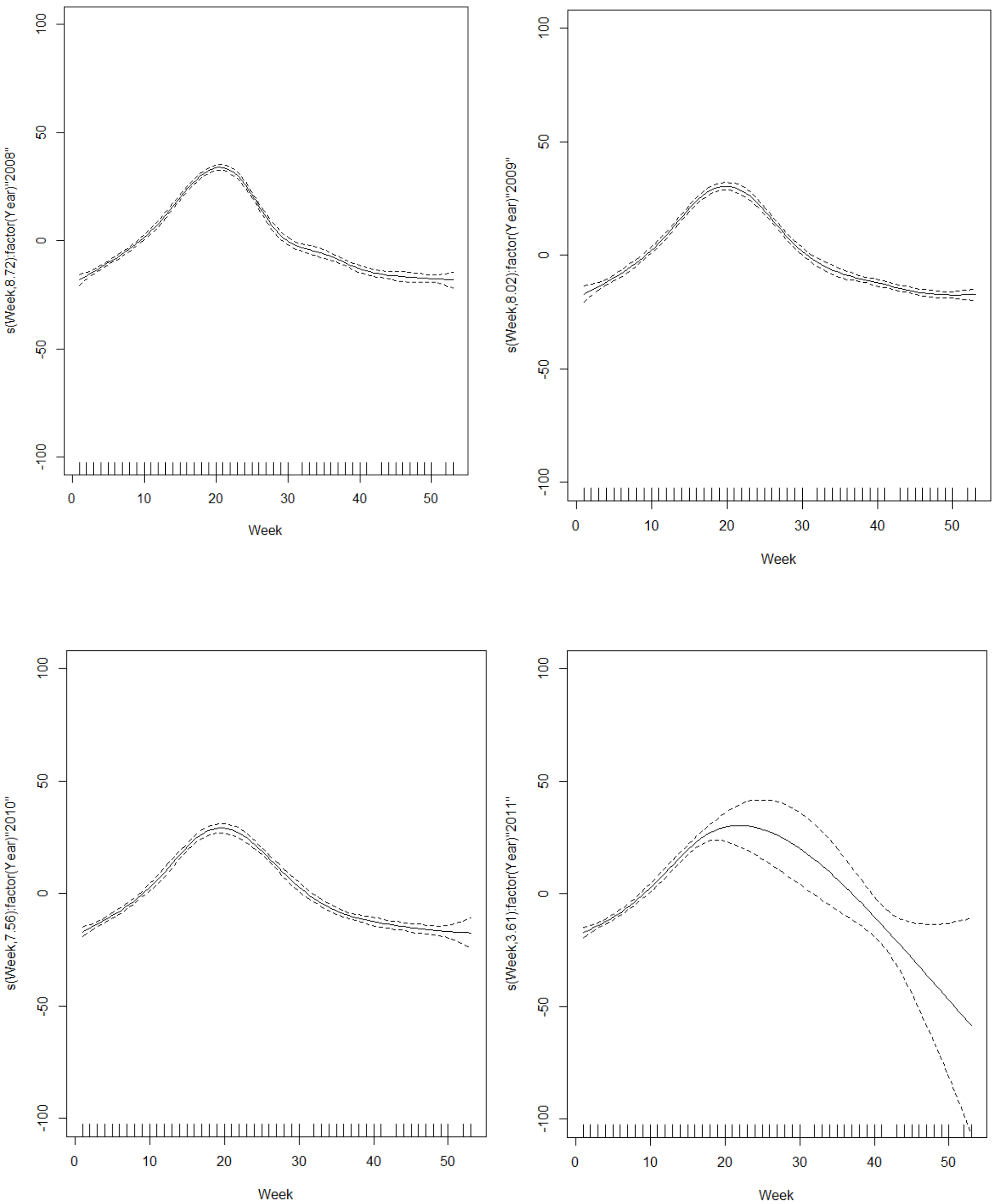


Figure 7. *(Top Left) GAM for i**ndustry predicted harvest day** for Gourmet tomatoes **in 2008**, (Top Right) **in 2009**, (Bottom Left) **in 2010**, and (Bottom Right) **in 2011**, in relation to all weeks of transplanting +/- 95% confidence intervals. 'Model' presented beyond 20 weeks in 2011 is an artefact of the graphing process in R, there are no actual data present or included in the statistical modelling beyond 20 weeks in 2011.*

DURATION OF HARVEST

SEASONAL VARIATION ON DURATION

Monthly variation in harvest duration was evident in both Roma and Gourmet crops. It was clearly evident that the crops transplanted at the end of summer and at the beginning of autumn had comparatively longer duration of harvest (Table 6).

TREND OF HARVEST DURATION

The overall pattern of harvest duration in both Roma and Gourmet crops was of increasing duration in the transplanting period from January to the beginning of March, where harvest duration peaked, and a decreasing harvest duration until mid-June followed by relatively stable harvest duration through to December (Figure 8). A GAM based on weekly planting data and a smoothing function was the most appropriate to describe variation in harvest duration in Roma crops, albeit that only 71% of the variance was explained by this best model. For the available data for Gourmet crops, the peaks and troughs in harvest duration previously described appeared to hold true for years 2008, 2010 and for the partial data set in 2011. Yet in 2009, harvest duration declined linearly over time until August/September (weeks> 35) (Figure 9). Transplanting week and year was sufficient to explain 86% of the deviance in generalised additive models used to describe gourmet harvest duration data.

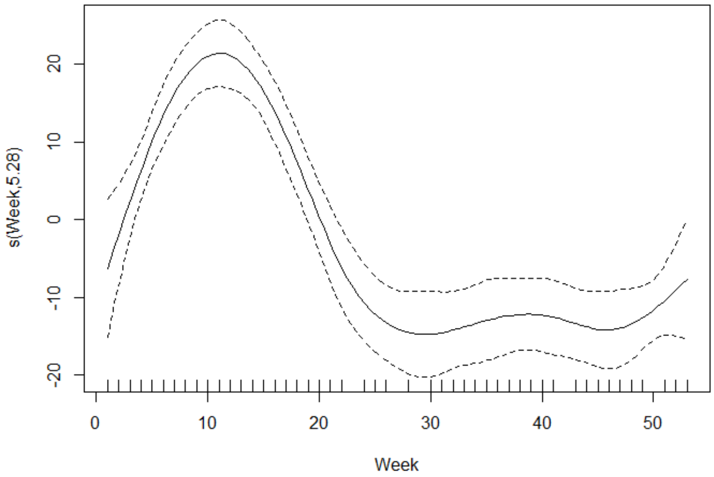


***Figure 8**. Variation in harvest duration for Roma tomatoes, +/- 95% confidence intervals for a Generalised Additive Model containing a non-parametric, ten–knot smoothing function and week.*

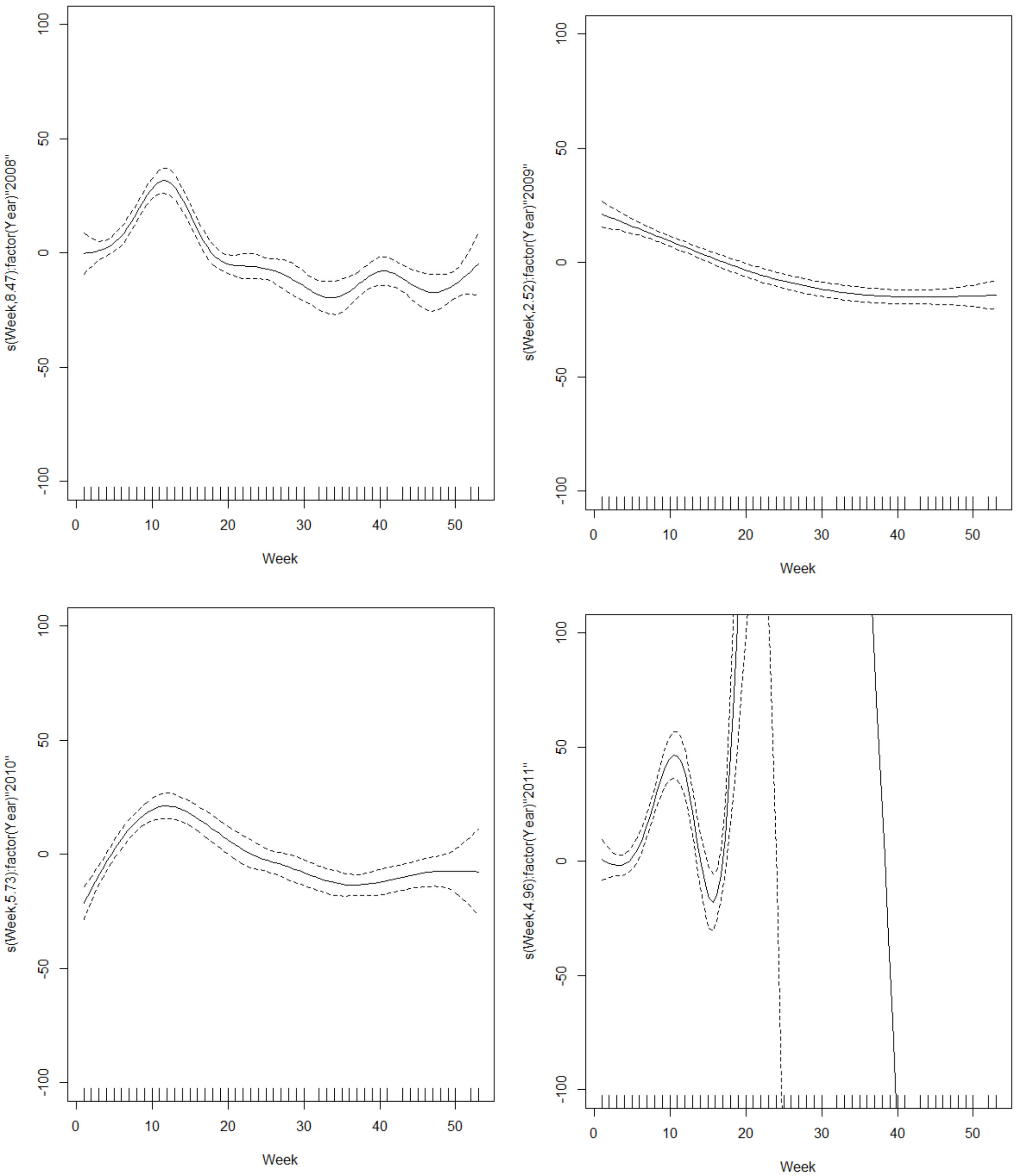


Figure 9. *(Top left) GAM for harvest duration for Gourmet tomatoes in 2008. (Top Right) in 2009, (Bottom Left) in 2010, and (Bottom Right) in 2011, in relation to all weeks of transplanting +/- 95 % confidence intervals. Model presented beyond 20 weeks in 2011 is an artefact of the graphing process in R, there are no actual data present or included in the statistical modelling beyond 20 weeks in 2011.*

Due largely to the differences in the pattern of the 2009 data, variability in duration of harvest between crops within each month of transplanting for Roma and Gourmet tomato crops followed a consistent trend (Figure 10). The Roma crops transplanted in weeks 1 to 20 (days 1 – 140) and 49 to 53 (day 343 – 365/6) had comparatively high variability in duration of harvest. The variability was also high for Gourmet crops transplanted in weeks 1 to 16 (days 1 – 112) and 49 to 53 (day 343 – 365/6). Consistent, low variation in harvest duration for crops transplanted in weeks 21-48 (days 147 – 334) and week 17-48 (days 113 – 342), for Roma and Gourmet respectively, suggesting that crops maturing in the spring and summer months will have a predictable harvest duration. The harvest duration was only significant on Roma tomato crops ($P = 0.001$ and $F = 7.9$; Appendix Table 11 A). The lowest and highest coefficient of variation (CV) was 5.60 and 17.08 in Roma and 6.53 and 20.41 in Gourmet tomato crops respectively (Appendix; Table 11).

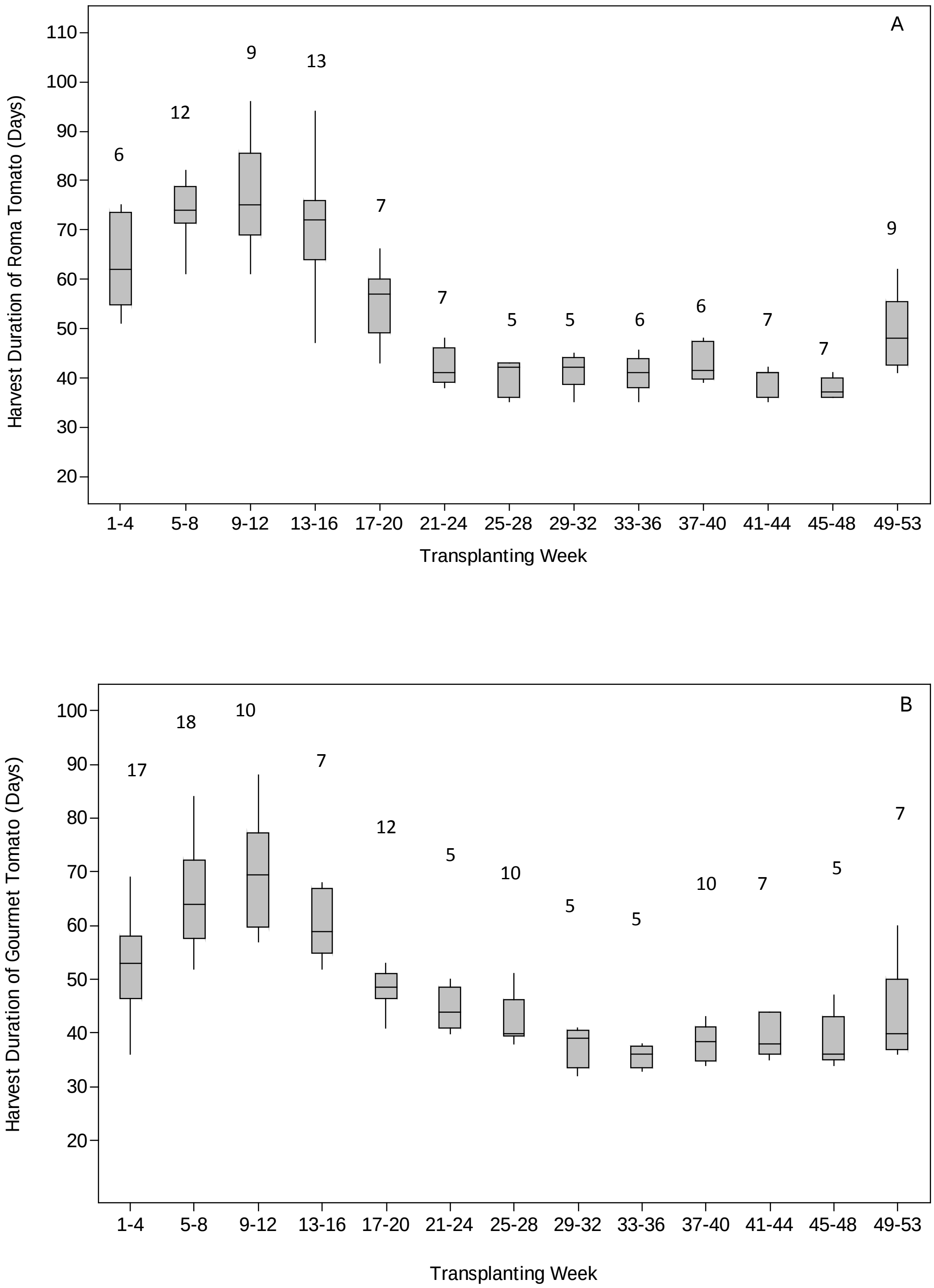


Figure 10: *Variation in harvest duration of Roma (A) and Gourmet (B) tomato transplanted in different weeks in 2008-2011. Median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles. The number on the top of the box represents the number of crops transplanted in those weeks. Coefficient of variation (CV) is given in the Appendix; Table 11.*

CROP YIELD

VARIABILITY

The yield of Roma and Gourmet tomato crops varied within and between the seasons for the crops transplanted in the period 2008-2011(Table 7). Several of the Roma and Gourmet crops transplanted in January and February in 2008 were notable for the high yields obtained. The crop yield data from January to June in 2009 were not accessible from the crop records obtained from the project industry partner.

YIELD TREND

The high degree of variation between crops within each transplanting week makes it difficult to confidently conclude any overall trend in yield exists from the crop record data. Based on daily mean data from the 2008-2011 records, the general trend of total yield of each variety was an upward trend for the crops transplanted in January to the beginning of March, where it peaked, and variable but steadily declining yield until the end of December, however, upon separation of the data, there were few generalisations in harvest pattern across the four years based on the records provided. The high variation in yield between crops is evident when data are expressed in box plots showing distribution in percentile ranges for crops transplanted in each 4 week block throughout the year (Figure 11). The yield variation was lower for crops transplanted in weeks 13-16 and 21-24 for Roma and weeks 29 to 36 for Gourmet. The yield was also significant for both crops. The lowest coefficient of variation (CV) was 6.27 and 5.61 in Roma and Gourmet tomato crops respectively (Appendix; Table 11).

The marketable yield of Roma and Gourmet tomato was variable, just like total yield. The same lack of consistent pattern was found for the marketable yield with around 11 percent less yield in each month than total yield of Roma tomato, whilst in the general yield of Gourmet tomato peaked for the crops transplanted in late March (~ day 90) and with lower mean yields at other times of the year. The marketable yield trend followed that of total yield but at an average of 10 percent less yield than on total yield in each month. There were no significant patterns across all transplanting times for the yield data, irrespective of the point at which yield appeared to peak or decline across the year except in 2009 for Roma and in 2010 for Gourmet tomato crops (Figure 12; Table 7).

The lowest coefficient of variation (CV) was 6.11 and 5.60 in Roma and Gourmet tomato crops respectively (Appendix; Table 11).

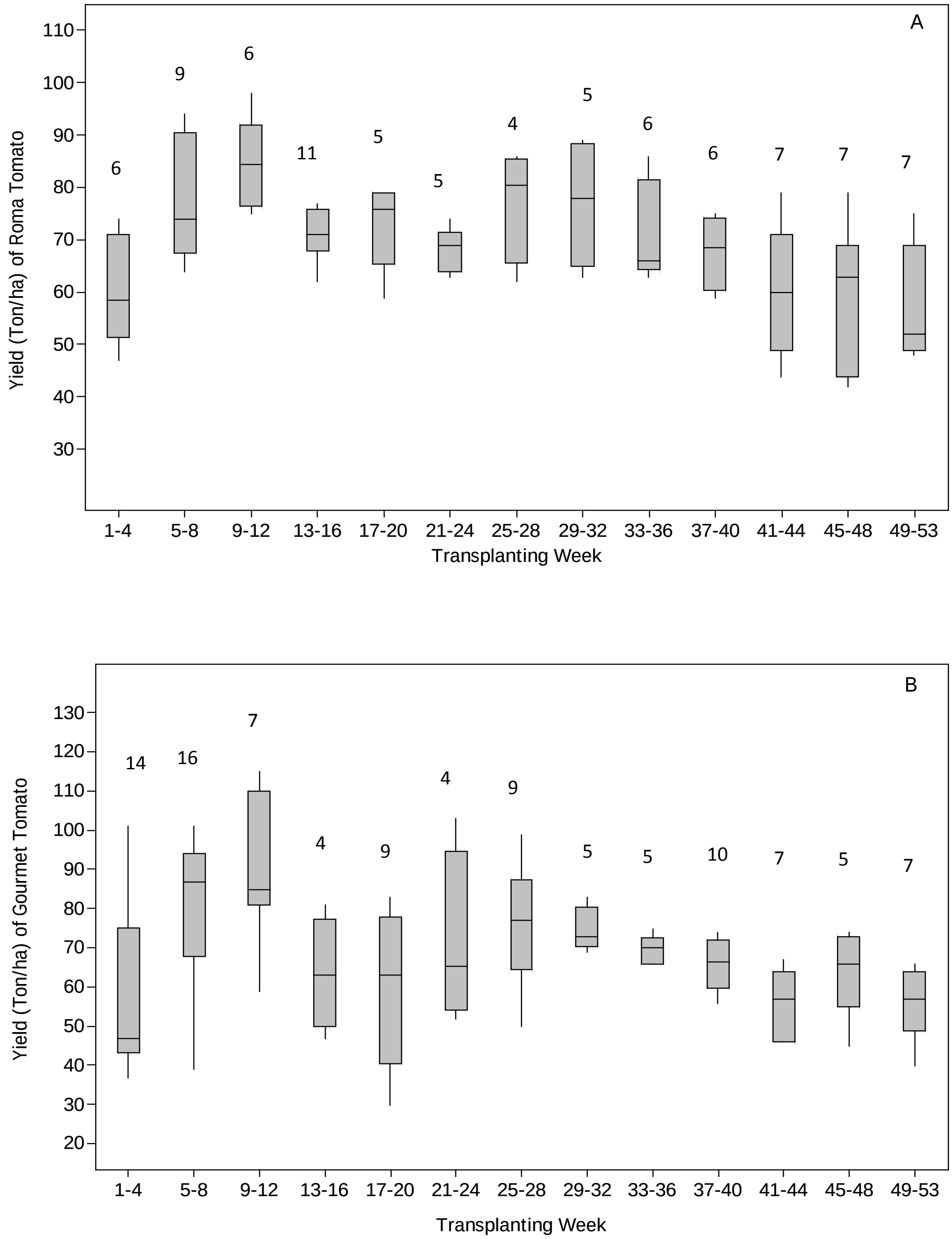


Figure 11: *Variation in raw yield of Roma (A) and Gourmet (B) tomato crops transplanted in different weeks in 2008-2011. Median values are indicated by the solid black line and box boundaries are the 25thand 75thpercentiles. The number on the top of the box represents the number of crops transplanted in specific weeks. Coefficient of variation is given in Appendix; Table 11.*

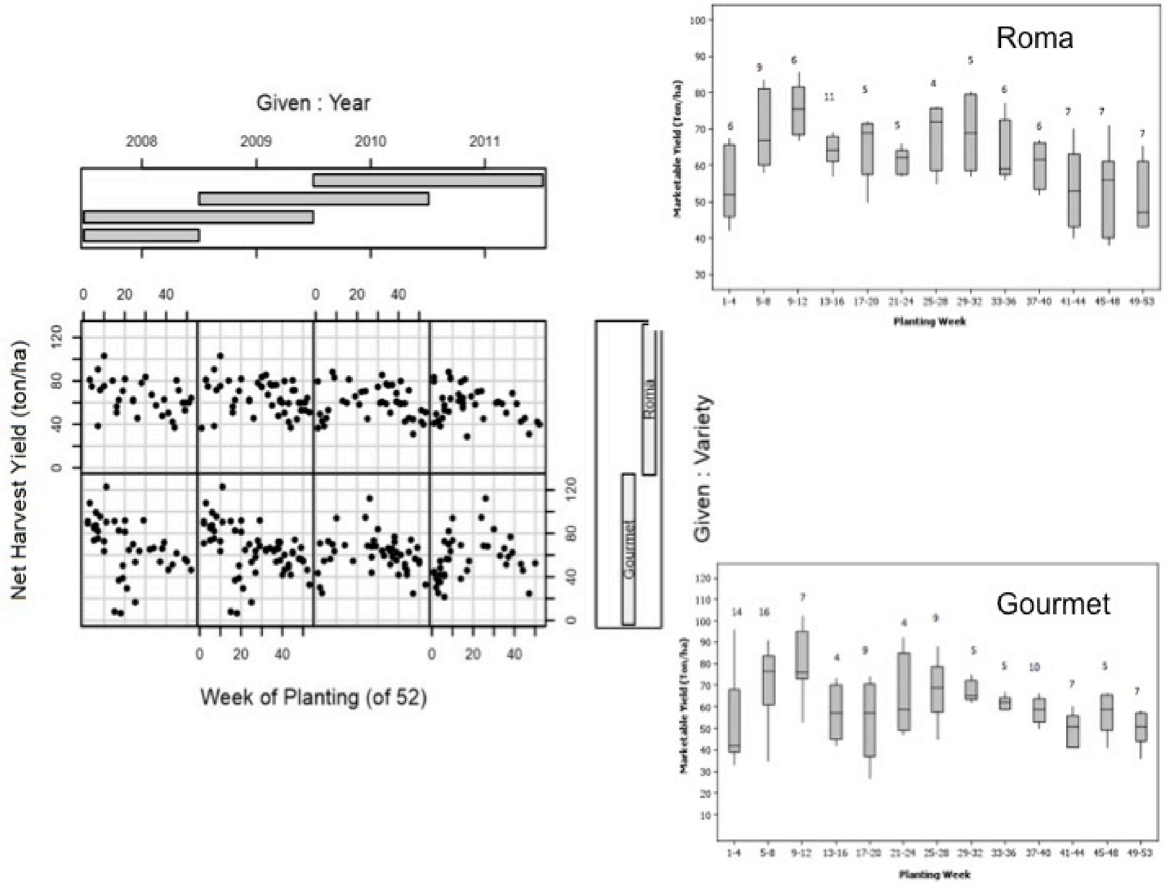


Figure 12: *The net harvest yield (marketable) of Roma and Gourmet tomato crops transplanted in January to December in 2008-2011 (left image).Variation in three-weekly rolling mean marketable yield in Roma (top right) and Gourmet (bottom right) tomato varieties in the same time period, where median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles. The number on the top of the box represents the number of crops transplanted in those weeks.*

MAIN FACTORS AFFECTING FIRST HARVESTING TIME

SEASONS AND SOILS

The analysis of crop data revealed that crop growing season and soil type had a significant influence on time between transplanting and first harvest time of Roma and Gourmet tomato crops(Table 5 and also Appendix Table 11 A). Not surprisingly, the crops transplanted in autumn and winter seasons took significantly longer (P = 0.000 for both Rom and Gourmet tomato) to mature to first harvest than crops transplanted in spring and summer seasons (Figure 13, Table 5). The time to first harvest took longer for both Roma and Gourmet tomato crops transplanted in autumn and winter seasons in 2008 and 2009 than in other years (Table 5).

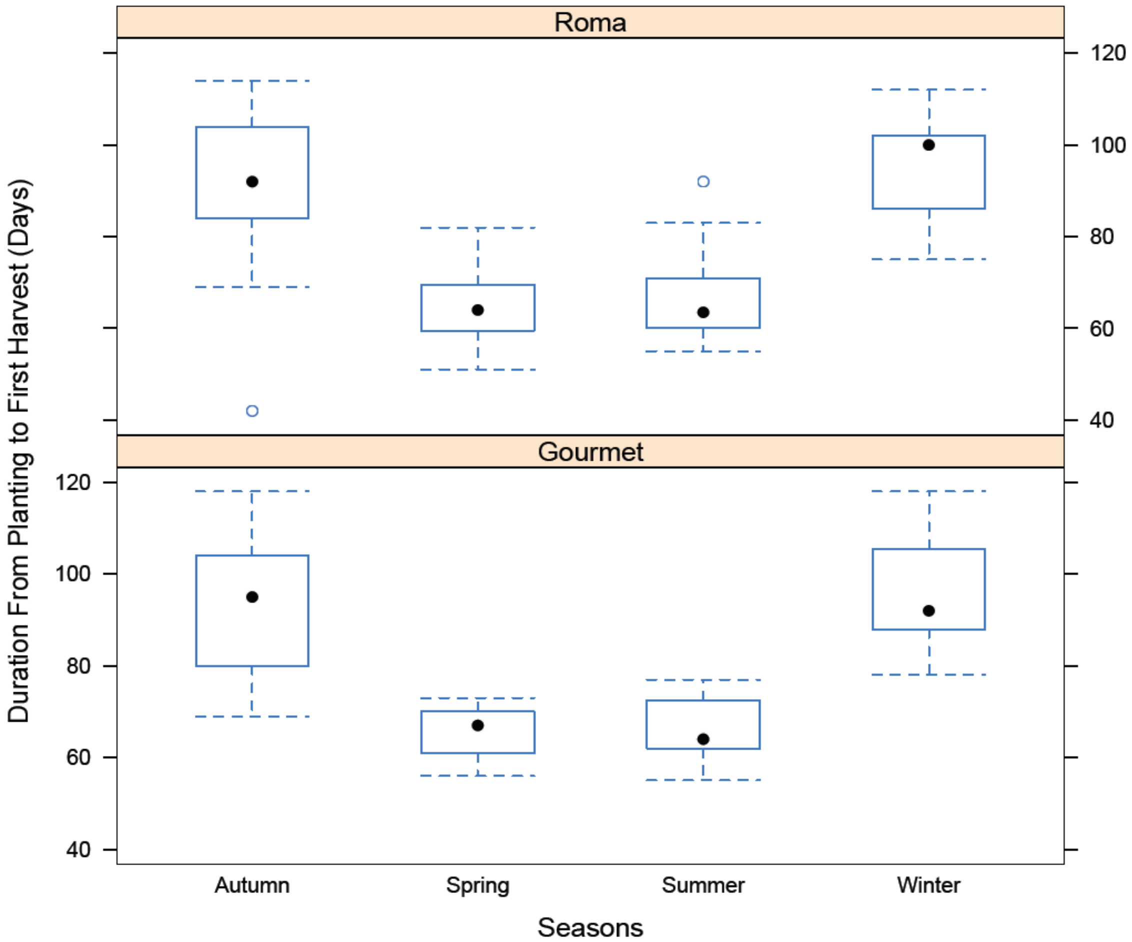


Figure 13: *Duration from planting to first harvest (days) in Roma and Gourmet tomato crops by seasons in year 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25thand 75thpercentiles and whiskers represents the distribution of the data.*

In addition, both Roma and Gourmet crops transplanted in clay soil required significantly longer than crops grown in loamy and sandy soils (Figure 14 and also Appendix Table 11 A), albeit that data were quite scant for sandy soils, only relating to crops surveyed in 2009 and 2010. The soil types have significant impact (P = 0.000 for both crops) on first harvesting days of both Roma and Gourmet tomato crops, but there is not enough replication of crops in all soils.

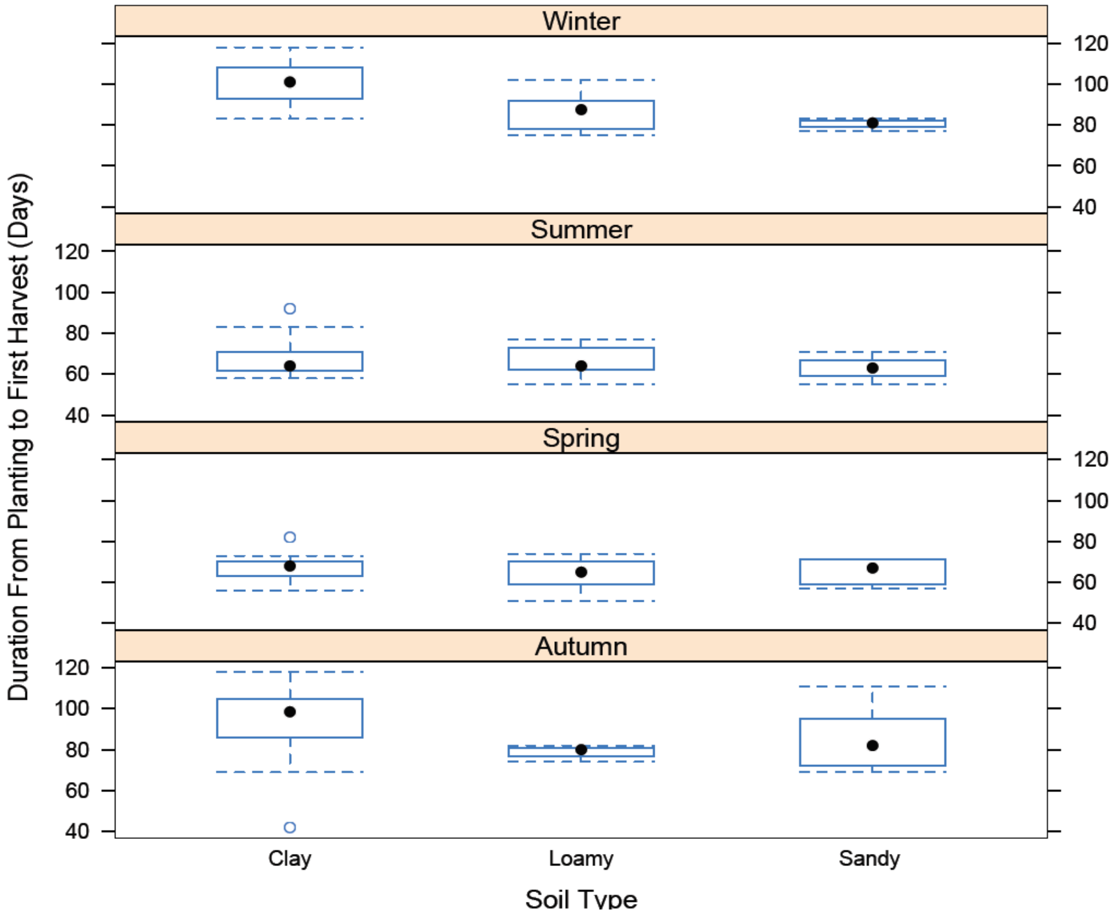


Figure 14: *Duration from transplanting to first harvest (days) in Roma and Gourmet tomato crops by seasons and soils for the year 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25thand 75thpercentiles and whiskers represents the distribution of the data.*

When seasonally aggregated data were analysed by using Minitab 16, the mean days from transplanting to first harvest in Roma ranged from 61.2 ± 2.7 days for crops transplanted in summer in 2009 to 107.4 ± 1.6 days for crops transplanted in winter in 2008, and in Gourmet from 61.9 ± 0.5 days for crops transplanted in summer in 2011 to 105.5 ± 3.7 days for crops transplanted in winter in 2008 (Table 5). First harvesting day was significantly higher in the crops transplanted in winter and autumn seasons in all years for both Roma and Gourmet tomato with the exception of 2009 in Roma tomato (Table 5). The highest coefficient of variation values were found for the autumn transplanted crops, reflecting the impact of reducing temperature as crops developed over winter on the rate of maturation of the tomato fruit.

Table 5: *The mean ± Standard error of mean (SE) and coefficient of variation (CV) of the first harvesting day of Roma and Gourmet tomato in summer, autumn, winter and spring seasons transplanted in 2008, 2009, 2010 and 2011. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s. Values followed with the same letters in each column of Roma and Gourmet tomato crops represent there was no difference.*

Crop	Season	2008			2009			2010			2011		
		Temp*(°C)	Harvesting	CV	Temp*(°C)	Harvesting	CV	Temp*(°C)	Harvesting	CV	Temp*(°C)	Harvesting	CV
Roma	Summer	30.1	70.8 ± 3.1b	15.5	30.3	61.2 ± 2.7b	10.0	29.1	64.5 ± 1.9b	8.6	30.7	64.4 ± 0.9b	3.2
Roma	Autumn	26.9	103.3 ± 3.3a	9.2	27.3	80.6 ± 9.5ab	29.1	27.1	87.4 ± 3.7a	11.4	26.7	86.4 ± 4.5a	13.8
Roma	Winter	22.4	107.4 ± 1.6a	3.3	23.7	87.1 ± 3.8a	10.7	22.9	94.0 ± 4.5a	11.7	N/A	N/A	N/A
Roma	Spring	27.4	66.1 ± 2.9b	13.4	27.7	62.8 ± 2.1b	9.5	26.6	65.5 ± 2.3b	8.6	N/A	N/A	N/A
Gourmet	Summer	30.1	71.8 ± 1.2b	6.5	30.3	64.7 ± 2.3b	10.2	29.1	64.7 ± 1.5b	7.36	30.7	61.9 ± 0.5b	3.0
Gourmet	Autumn	26.9	97.4 ± 3.9a	14.6	27.3	90.1 ± 4.5a	14.3	27.1	84.6 ± 5.9a	15.8	26.7	91.0 ± 16.0a	24.8
Gourmet	Winter	22.4	105.5 ± 3.7a	9.9	23.7	88.4 ± 2.0a	6.0	22.9	88.6 ± 2.9a	7.55	N/A	N/A	N/A
Gourmet	Spring	27.4	66.5 ± 2.4b	9.8	27.7	63.2 ± 1.6b	8.16	26.6	63.8 ± 3.6b	16.2	N/A	N/A	N/A

* the daily mean temperature of the season

MAIN FACTORS AFFECTING ON HARVEST DURATION

SEASONS AND SOILS

The harvest duration was significant in different seasons for both Roma and Gourmet tomato crops (Table 6). The duration of harvesting was significantly higher in the crops transplanted in autumn season on both Roma and Gourmet tomato except in 2011 (Figure 15; Table 6). Soil type had only significant effect on harvesting duration of Roma tomato (P = 0.001 and 0.168 for Roma and Gourmet tomato respectively: Appendix 11 A).

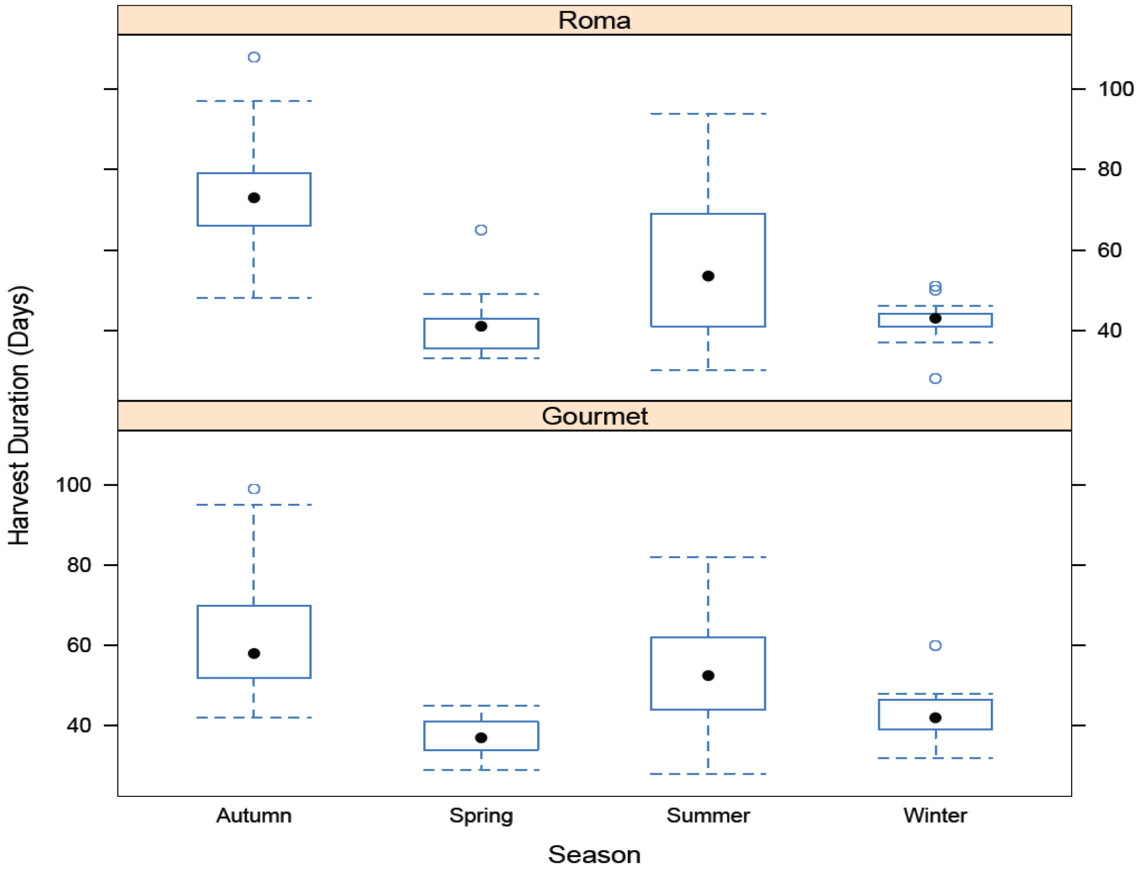


Figure 15: *Harvest duration (days) of Roma tomato transplanted in different seasons in 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25thand 75thpercentiles and whiskers represents the distribution of the data.*

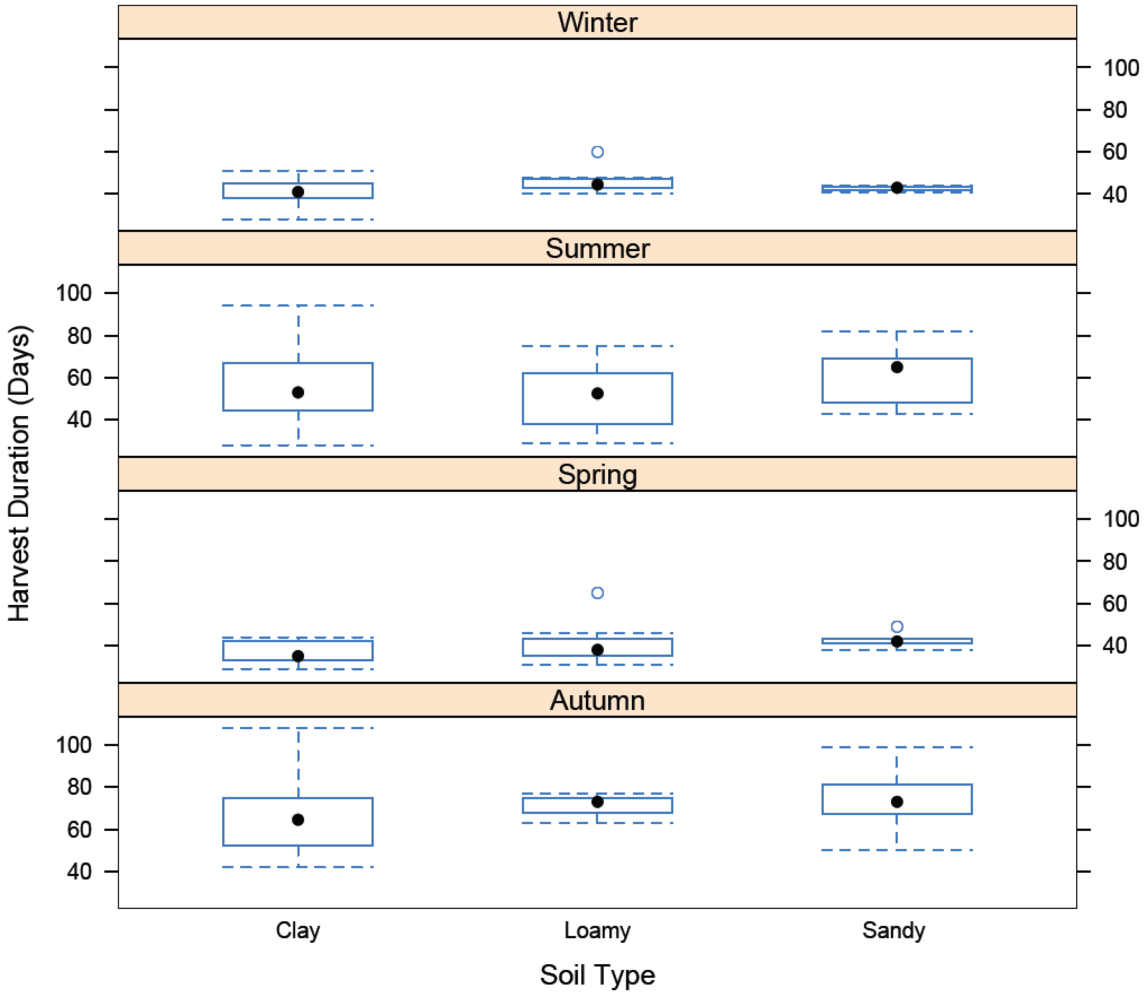


Figure 16: *Harvest duration of Roma and Gourmet tomato in different seasons and soils transplanted in 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25th and 75th percentiles and whiskers represents the distribution of the data.*

When seasonally aggregated data were analysed, the mean days of harvest duration of Roma tomato ranged from 39.2 ± 3.1 days for crops transplanted in winter 2008 to 77.3 ± 6.3 days for crops transplanted in autumn 2008; where as in Gourmet harvest duration ranged from 35.9 ± 1.1 days for spring transplanted crops in 2009 to 70.0 ± 2.2 days for autumn 2010 crops (Table 6). The crops transplanted in autumn had significantly higher harvest duration in all years for both Roma and Gourmet tomato crops. The crops transplanted in winter and spring seasons had the shorter harvest duration in all years on both crops. Harvest duration was observed to be more consistent in the crops transplanted in winter and spring seasons than in crops transplanted in summer and autumn.

Table 6: *The mean ± Standard error of mean (SE) and coefficient of variation (CV) of the harvest duration of Roma and Gourmet tomato in summer, autumn, winter and spring seasons planted in 2008, 2009, 2010 and 2011. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s. Values with the same letters in each column for Roma and Gourmet tomato represent there was no difference.*

Crop	Season	2008			2009			2010			2011		
		Temp*(°C)	Duration	CV	Temp*(°C)	Duration	CV	Temp* (°C)	Duration	CV	Temp*(°C)	Duration	CV
Roma	Summer	30.1	56.0 ± 4.7[b]	29.2	30.3	45.8 ± 5.8[b]	28.4	29.1	51.8 ± 6.4[b]	35.1	30.7	72.8 ± 6.2[a]	19.2
Roma	Autumn	26.9	77.3 ± 6.3[a]	23.2	27.3	63.1 ± 5.6[a]	21.9	27.1	71.0 ± 3.8[a]	14.3	26.7	73.1 ± 4.4[a]	17.3
Roma	Winter	22.4	39.2 ± 3.1[b]	18.1	23.7	41.5 ± 1.2[b]	7.2	22.9	45.5 ± 1.6[b]	8.8	N/A	N/A	N/A
Roma	Spring	27.4	41.1 ± 3.2[b]	23.9	27.7	39.3 ± 1.5[b]	11.1	26.6	41.8 ± 2.0[b]	11.8	N/A	N/A	N/A
Gourmet	Summer	30.1	51.6 ± 2.5[ab]	19.3	30.3	52.2 ± 6.0[ab]	32.9	29.1	48.4 ± 4.6[b]	30.0	30.7	57.2 ± 3.7[a]	21.5
Gourmet	Autumn	26.9	63.0 ± 4.5[a]	26.2	27.3	55.2 ± 2.7[a]	14.2	27.1	70.0 ± 2.2[a]	7.1	26.7	67.3 ± 15.8[a]	40.7
Gourmet	Winter	22.4	40.7 ± 2.2[b]	15.5	23.7	41.0 ± 1.0[b]	6.7	22.9	48.0 ± 3.1[b]	14.6	N/A	N/A	N/A
Gourmet	Spring	27.4	37.1 ± 2.2[b]	15.8	27.7	35.9 ± 1.1[b]	10.2	26.6	39.6 ± 1.3[b]	9.5	N/A	N/A	N/A

* the daily mean temperature of the season

MAIN FACTORS AFFECTING YIELD

SEASONS AND SOILS

The yield variation was observed on the crops transplanted in different seasons and soil types on both Roma and Gourmet tomatoes (Figure 17 and 18). The mean yield was not significantly different in Roma and Gourmet tomato crops transplanted in different seasons except in 2009 for Roma and in 2010 for Gourmet tomato respectively (Table 7). Soil types had no significant effect on yield in both Roma and Gourmet tomatoes (P = 0.692 and 0.718 for Roma and Gourmet tomato respectively: Appendix Table 11 A).

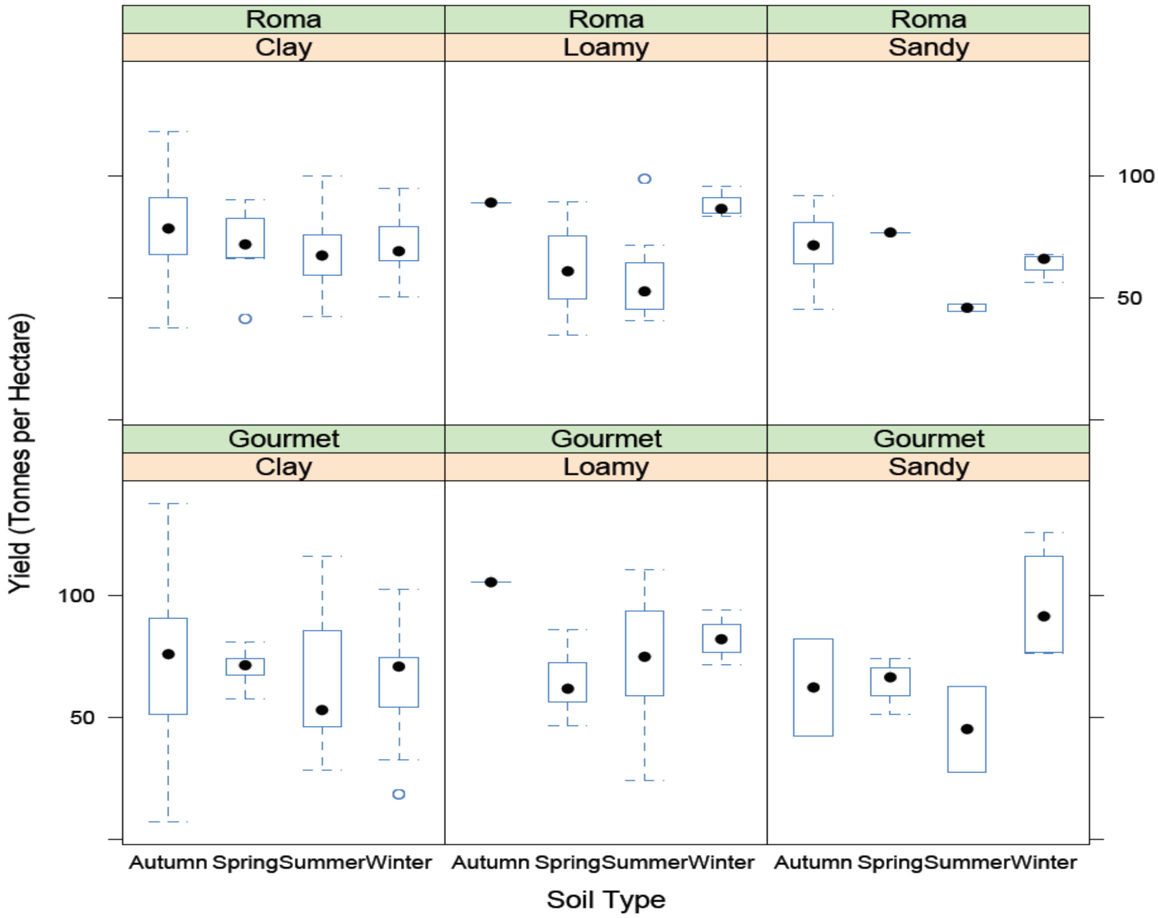


Figure17: *The yield (tonnes/ha) of Roma and Gourmet tomato in different soils and seasons transplanted in 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25thand 75thpercentiles and whiskers represents the distribution of the data.*

When seasonally aggregated data were analysed, the mean yield of Roma and Gourmet tomato were found to vary with season (Table 7). The yield of Roma tomato ranged from 52.3 ± 5.8 to 88.4 ± 3.7 tonnes per hectare for crops transplanted in summer and winter seasons in 2009 respectively; whereas in Gourmet it was 49.5 ± 5.1 to 95.6 ± 9.3 tonnes per hectare for crops transplanted in summer in 2011 and winter seasons in 2010 respectively (Table 7).

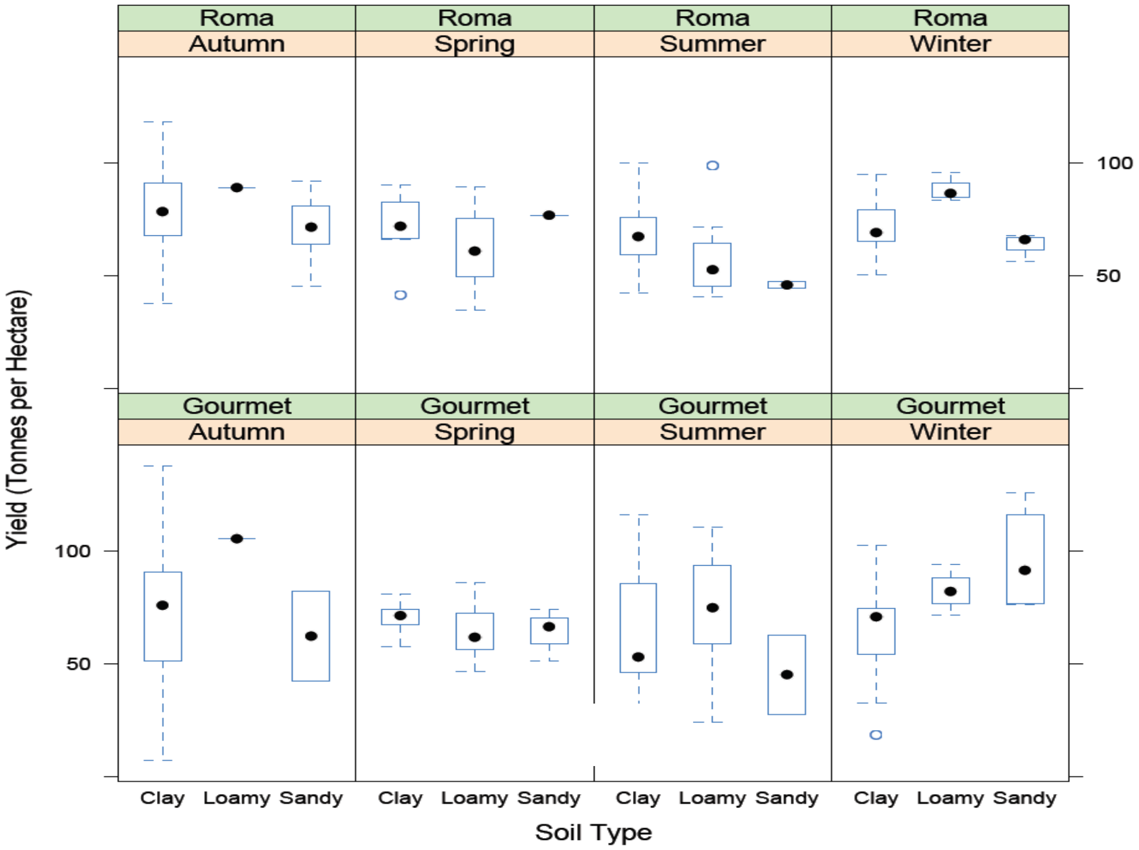


Figure18: *The yield of Roma and Gourmet tomato in different seasons and soils transplanted in 2008-2011. Median values are indicated by the black dot and box lower and upper boundaries are the 25th and 75th percentiles and whiskers represents the distribution of the data.*

Table 7: *The mean ± Standard error of mean (SE) and coefficient of variation (CV) of the yield (ton/ha) of Roma and Gourmet tomato in summer, autumn, winter and spring seasons transplanted in 2008, 2009, 2010 and 2011. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s. Values with the same letters in each column on Roma and Gourmet tomato represent there was no difference.*

Crop	Season	2008		2009		2010		2011	
		Yield	CV	Yield	CV	Yield	CV	Yield	CV
Roma	Summer	72.2 ± 4.95[a]	21.6	52.3 ± 5.8[b]	19.3	64.6 ± 7.4[a]	34.5	74.9 ± 5.9[a]	19.2
Roma	Autumn	81.4 ± 6.9[a]	24.2	N/A	N/A	74. 0 ± 3.9[a]	13.0	63.3 ± 6.4[a]	27.0
Roma	Winter	74.2 ± 6.3[a]	20.7	88.4 ± 3.7[a]	7.2	64.3 ± 4.0[a]	15.4	N/A	N/A
Roma	Spring	63.1 ± 5.8[a]	26.1	73.9 ± 4.7[a]	18.0	53.8 ± 6.1[a]	27.9	N/A	N/A
Gourmet	Summer	88.6 ± 4.9[a]	20.9	63.0 ± 7.4[a]	26.4	53.4 ± 6.7[b]	37.8	49.5 ± 5.1[a]	34.3
Gourmet	Autumn	72.7 ± 10.9[a]	53.9	N/A	N/A	78.6 ± 9.5[ab]	24.2	58.5 ± 12.1[a]	35.8
Gourmet	Winter	63.2 ± 9.3[a]	41.9	68.7 ± 5.6[a]	18.3	95.6 ± 9.3[a]	21.9	N/A	N/A
Gourmet	Spring	67.2 ± 3.9[a]	15.6	65.6 ± 4.0[a]	19.6	66.0 ± 3.8[b]	16.5	N/A	N/A

N/A= No crop yield record available of that season

DISCUSSION

The crops transplanted at different locations and soil types by SP Exports in the Bundaberg region in 2008 to 2011 were analysed in this research chapter to identify the variation between the crops and factors affecting harvesting time and yield as well as to provide reliable trends of harvesting and yield of Roma and Gourmet tomato crops. The harvesting time and yield assessments in the previous chapter on commercial crop monitoring demonstrated significant differences between crops. Environmental and crop management factors such as temperature, light, soil type, and crop establishment practices may contribute to the measured variation within a crop and between the crops transplanted at different locations and times, but assessments from only three crops used in Chapter 3 were not sufficient to identify the factors affecting harvesting and yield as well as to provide reliable trends of harvesting and yield. The seasonal trends analysed using commercial crop records in this Chapter 4 were consistent with the trends noted in the more detailed crop assessments in earlier research chapter, and also identified patterns in variability between crops within and between seasons. These trends provide a degree of confidence in predicting seasonal yield and crop timing parameters, but in addition they identified factors such as soil type that appear to impact on crop development rate.

Consistent with previous research in greenhouse (Peet et al., 1997; Adams et al., 2001; Uzun, 2006; 2007) and in field grown tomato (Perry et al., 1997), the time from transplanting to first harvesting time in crops displayed a strong seasonal trend which was consistent with early crop development rate being strongly influenced by temperature and also other environmental and management factors that are related with the location or site of the crop production. The crops transplanted in late autumn and in winter developed under lower temperature and required more days to harvest than crops transplanted in late spring and early summer were grown in comparatively higher temperature condition and were harvested earlier for both Roma and Gourmet tomato crops. The seasonal trend of harvesting time of the crops was clear, but significant crop to crop variability, and year to year variability, was also evident in the data. This variability was unlikely to be explained by temperature alone, highlighting the importance of identifying other factors impacting on crop development if accurate crop models are to be developed. Soil type was found to be a factor affecting timing of first harvest in field grown tomato crops. Crops transplanted in clay soil had a longer duration from transplanting to first harvesting than crops grown in loamy and sandy soils. Differences in soil water holding capacity and moisture release characteristics is a possible explanation of the influence on rate of crop development, with rate of soil drying previously shown to influence shoot growth in tomato (Hussain et al., 1999; Sharp et al., 2000) and in other crops (Morgan & Connolly, 2013) but, there are other independent or interacting factors with soil that also may have effect on first harvesting time of the tomato crops in each location. The industry method of prediction of first harvesting time i.e. day count method from transplanting to first harvesting time of the crops had prediction capacity of 78 and 84 % for Roma and Gourmet tomato respectively that indicates the requirement of improvement in prediction method of first harvesting time of tomato crops. Predicting the timing of the first harvest in field grown tomatoes is a key element of harvest scheduling for production companies managing large numbers of crops over multiple locations, and therefore the effect of soil type on early crop development is an area that warrants further investigation.

The seasonal trend of harvest duration was also consistent with temperature differences during the crop growing period. While most crops had harvest durations differing from the 3 week moving average trend line by less than 20%, a number of crop were harvested over a duration greater than 50% higher than the trend line. These differences did not appear to be related to temperature and suggest crop specific factor(s) may impact significantly on harvest duration. Seasonal trends were far less obvious for harvest duration than first harvesting time, with only a minor trend toward lower harvest duration in 2009 crops compared to other seasons. This again suggests that temperature is not a dominant driver of harvest duration in field tomato production.

The harvest duration was highest for both Roma and Gourmet crops transplanted in autumn where the crop harvesting was done in the comparatively cooler days in winter time. The crops transplanted in spring were found to have the lowest harvest duration due in part to the higher temperatures experienced when the crop harvesting was undertaken in the summer season. Generally, the coefficient of variation (CV) of harvest duration was high in the crops transplanted in summer season for both Roma and Gourmet tomato and possible reason might be the highly fluctuation in weather conditions i.e. temperature and rainfall. Tomato fruit ripening rate is known to occur more rapidly as temperature increases, and ripen fruit are present earlier on successive trusses when tomatoes are grown at higher temperatures in greenhouse production (Sawhney & Polowick, 1985; Zhang et al., 2005). In contrast to harvesting time, soil type did not significantly influence harvest duration, although a trend toward longer harvests in lighter soils was noted. Factors such as disease incidence and pest infestations, which have been observed to vary in frequency and severity between soil types, have the capacity to impact on the duration of fruit picking.

Crop yield was much more variable between crops than either time to first harvest or duration of harvest, most likely reflecting the greater range of factors that may affect yield that was consistent with the research finding in processing tomato (Patane and Cosentino, 2010) and greenhouse grown tomato crops (Lobell et al., 2009; Kleiber et al., 2014).The high variation in yield of each crops transplanted in different weeks and seasons in a year was consistent with the crop yield reported in the previous research chapter and high yield variability in tomato was also explained by Sadras et al., 2002 and Lobell et al., 2007. Yield tended to peak in crops transplanted in March for both Roma and Gourmet crops, reflecting the prevailing conditions in the months following transplanting being close to the optimum day and night temperature for tomato production. The yield trend generated from this research chapter may be useful for improving predictability of the tomato yield and similar research was also explained by McKeown et al., 2010 and Lee et al., 2011 for prediction of future yield of tomato.

CONCLUSION

A consistent level of variability within the season and also a consistent seasonal trend of first harvesting time and duration of Roma and Gourmet tomato crops transplanted in 2008 to 2011 indicate that temperature has the main role on ripening of the successive trusses for harvesting of the fruits. Soil types have also impact in first harvesting time of both tomato crops, but were consistent in all soils for harvest duration. The yield of both crops was highly variation within and between the seasons which indicate that besides temperature and soils; other factors may have impact on the yield. Yield was highly variable within seasons and with soil types which indicates that more research is required to identify the impact of temperature and soil factors and their interaction on the yield of field grown tomato.

CHAPTER 5

THE EFFECT OF TRANSPLANT SEEDLINGS AGE ON FLOWERING AND THE EFFECT OF PRUNING ON HARVESTING AND YIELD

ABSTRACT

Temperature has a dominant effect on the growth rate of commercially grown tomato crops, but does not explain all of the between-crop variability in the key crop growth and development parameters of flowering and harvesting time. The results presented in Chapter 3 showed large differences in the plant physiological age, measured as node number below the first truss, at which flowering commences. This difference may explain part of the variability in the time from transplanting to first harvest noted in field grown crops. Field tomato crops in Queensland, Australia are grown using transplanted, cell raised seedlings and it was hypothesised that the age of the seedlings at transplanting may influence the time of flowering and hence the time to first harvest in crops. The pruning practices adopted by the commercial growers were also examined to determine if they influenced harvesting time and yield of the tomato crops. In this Chapter, the results of a field trial examining flowering and fruit development patterns as well as pruning practices in plants grown from 22, 27 and 31 days old seedlings transplanted in the field on the same date are presented.

INTRODUCTION

Tomato crops may be established by direct seeding or transplanting of seedlings raised under nursery conditions. Direct seeding is often practiced in tomatoes grown for processing purposes (Hayslip, 1974). Direct seeding is also used in some region of USA for fresh grown tomatoes (Leskovar & Cantliffe, 1990) but in most modern production systems nursery raised seedlings are transplanted to establish field tomato crops. Nursery raised seedlings for transplanting are grown in multi-cell trays under controlled environment conditions to promote uniformity, and delivered to growers when field production sites are ready for crop planting. The use of tomato seedling transplants is standard commercial practice in Queensland, Australia. Increased uniformity in crops, higher seedling survival rates due to improved tolerance to early environmental and biological stresses, and early maturity of the crops (Liptay et al., 1982; Leskovar et al., 2011; Shinohara & Leskovar, 2014) are the main benefits for grower of using seedlings transplants for crop establishment.

The desired age of seedlings for transplanting may vary between productions locations, with younger seedlings often preferred when ideal planting conditions for the crop can be provided. Research has been conducted in different regions on 2 weeks to 15 weeks old tomato seedlings for production (Vavrina & Orzolek, 1993) with varying responses between production environments. Development of location and season specific recommendations for optimum transplant age appears appropriate for commercial field production. The preferred age of seedlings in Bundaberg, Queensland is 4 weeks old at transplanting, whereas it has been reported that in Florida and Northern states in the United States 5 week (10 cm tall) and 6 week (12 to 16 cm tall) old seedlings respectively (Leskovar et al., 1991) are preferred, while in other regions younger seedlings of 3-4 weeks old has been recommended (Leskovar et al., 1991; Orzolek et al., 1991). In Ghana, Africa, the growers prefer 4 week (25 days) to 5 week (30 days) old seedlings for transplanting (Agble, 1995). Older seedlings of 7-9 weeks may produce earlier yield (Liptay, 1987; Vavrina, 1991) but yield may be compromised.

Recommendations for ideal seedling age at transplanting are generally based on promoting uniform growth immediately after transplanting in order to achieve crop uniformity at harvest. While use of seedling transplants is known to reduce variability within the crop, and reduce the time between transplanting and harvest compared to direct seeded crops, the influence of the seedling age at transplanting on flowering and harvest dates is unclear. Variability in the flowering date of tomato plants within crops as well as between commercial crops, described in the previous Chapters, demonstrates that flowering date is affected by factors other than temperature and transplant variability as a source of variation in chapter 3. Within crop variability cannot be explained by transplant age, but plant to plant differences in time taken to overcome transplant shock may be involved. Studies in vegetables and other crops have demonstrated the importance of reducing transplant shock to ensure uniform growth (Flores-Nimedez et al., 1995; Sharma et al., 2005; Leskovar et al., 2011; Shinohara & Leskovar, 2014). As seedling age at transplanting could influence the degree of transplant shock experienced by plants (Murungu et al., 2006), the differences in within-crop variability between crops monitored in this project suggests transplant age or condition may be an important factor in predicting crop harvesting time. The variation of flowering and first harvest dates in all crops in Chapters 3 and 4 may be related to seedling age or condition of the seedlings at transplanting time as these affect root and shoot development (Leskovar & Cantliffe, 1990; Shinohara & Leskovar, 2014).

There are factors other than seedling age which may have a significant effect on flowering date in tomato crops. These factors include the transport and handling of seedlings from the nursery to field, and the level of transplant stress experienced by the seedlings during the transplanting operation and immediately after it. Seedlings kept at a low night temperatures of 10 to 13 degree Celsius before transplanting were reported to display enhanced early flowering and earlier fruit maturity (Wittwer & Teubner, 1957). As seedlings often need to be stored when a delay in transplanting occurs after transplants are received from the nursery, maintaining plants at a temperature of 10 to 13 degree Celsius for up to10 days has been recommended (Handenberg et al., 1986). Similarly, (Leskovar & Cantliffe, 1991) found that seedlings stored at 8 to 9 degrees Celsius for 2 or more days resulted in retarded shoot growth and early flower development. Seedling storage temperature may impact on the plants' capacity to commence rapid growth following transplanting. The root system of transplanted tomatoes seedlings that have not been stored outside the nursery prior to transplanting become very active within 3 days of field transplanting and commence nutrient uptake at that time (Tiessen & Carolus, 1963; Sumugat et al., 2011). Delays in the timing of the commencement of this rapid growth phase due to stress during transport, storage or transplanting may affect flowering date.

Research has been conducted to examine the effect of seedling age at transplanting on growth and development, as well as yield, of tomatoes and other crops. Contradictory results have been reported on the effect of transplanting seedling age on flowering and early harvest of fruits in tomatoes. In one study, 20 day old tomato transplant seedlings flowered earlier than 35 day old transplants, but 25 and 30 day old transplant seedlings reached harvest maturity earlier (Agble, 1995). In another study, younger transplants displayed reduced mortality rates at field establishment, increased growth rates after transplanting, and higher yield than older transplants (Ademiluyi, 2011). In contrast, Jankauskiene et al., (2013) reported that older transplanted seedlings flowered faster than younger transplants with 5-6 leaves. Seedlings ages of 4-5 weeks (Weston & Zandstra, 1989), 8-9 weeks (Chipman, 1961) and 9-10 weeks (Hoffman, 1929) have been recommended to produce early fruit, but the authors of these studies didn’t record the effect of transplant age on flowering time. Orzolek et al., (1991) found that fruit matured later in 3 - 4 week old transplanted seedling than in older seedling ages, contradicting the recommendation of Weston & Zandstra (1989). As mentioned above of the transplant seedlings age for the flowering times were not the same cultivars and locations that were used in this research site.

The specific impact of transplant age on flowering time has been examined in other crop species. Flowering was delayed when capsicum seedlings were transplanted at later stages of growth (Korodi, 1966). Harmon et al., (1991) described the optimal transplanting age of eggplant as between 35 and 49 days, suggesting that transplants younger or older than these ages would display delayed flowering.

The documented range of seedling transplant age responses in flowering time, harvest time and yield, as well as the variability in recommendations for transplant age for tomato, are not surprising given the many variables in transplant condition at transplanting and the field and environmental conditions under which the transplanting occurs. The optimum age of transplanting seedlings in tomatoes will obviously depend on environmental conditions and both soil factors and management practices used in the field. Most growers, through experience, have chosen the apparent ideal transplant age for the average conditions under which they grow their crops. However, often growers experience delays before planting of one or more days, and up to 2 weeks, after receiving from the nursery and have to plant seedlings that are older, and sometimes also younger, than the optimum. There is no recorded research on the effect of transplanting seedlings age in tomatoes in Queensland, Australia.

Following transplanting, the cultural practices employed during crop production will influence the rate of crop development and the timing of both flowering and first harvest of the crop. Field grown tomatoes are a labour intensive crop and several cultural practices are carried out manually at different stages of crop growth and development. Pruning is an important activity among these cultural practices, and refers to removal of selected side shoots from the main shoot. Pruning is practised to enhance the quality of fruit and increase crop yield by diverting nutrients to the flower clusters and developing fruits on the plant (Chen & Lal, 1999).

Much of the research examining the effect of pruning on tomato plant growth and development, as well as impacts on yield and fruit quality, has been carried out in greenhouse grown tomato crops. The pruning of the vegetative shoots improves the penetration of the light inside the canopy, thereby increasing photosynthesis efficiency which ultimately increases the yield of the crop (Rajewar & Patil, 1979; Mbinga, 1983; Ambroszczyk *et al.*, 2008). The pruning of the vegetative growth manipulates the balance between vegetative and reproductive growth, leading to improved fruit quantity and quality in glasshouse tomato crops (Arzani *et al.*, 2009; Hesami et al., 2012). Navarrete et al., (1997) described a negative correlation between vegetative growth rate and fruit yield in greenhouse tomato. Studies in greenhouse tomato explained that pruning improves the quantitative and qualitative characteristics of the fruits by allowing optimum light penetration inside the canopy of the plant (Preece & Read, 2005). The timing and extent of pruning is important in achieving a desirable balance between vegetative and reproductive growth of the tomato plant, and some research reports found that the quality and yield of tomato fruits were reduced by some pruning strategies in greenhouse (Resh, 2002; Kanyomeka & Shivute, 2005).

The standard pruning methods practiced in commercial field grown tomato crops differs from that used in greenhouse crops where semi-determinate and indeterminate type tomatoes are used in field and greenhouse crops respectively. Under field conditions, pruning is undertaken after flowering of the first truss and one lateral shoot is left below first truss initiated on the main shoot. All other lateral shoots below the first truss are removed in the pruning operation. The timing of this pruning operation in the field can vary by up to 2 weeks from the date that the flowering is first noted in a few plants in a field to the time when flowering is nearly completed in the first truss on the majority of plants in the field. Some growers may also implement a second pruning if growth of additional lateral shoots below the first truss, or vigorous lateral shoot growth above the first truss occurs after the first pruning. In greenhouse grown tomato crops all lateral shoots on the main shoot are removed and a pruning interval of 7-14 days is recommended as the optimum to support plant vigour and yield (Navarrete & Jeannequin, 2000). The removal of lateral shoots is designed to deliver a leaf area index of 2-3 $m^2.m^{-2}$ with the resulting light interception considered optimum for maximum production in the glasshouse (De Koning, 1996a). In contrast, no published research report or study was found on the appropriate timing of pruning and extent of lateral shoot removal in field grown tomatoes.

While greenhouse based pruning studies dominate the tomato literature, a limited volume of research work has been published on the effect of pruning on fruit quality and yield in field grown trellis tomato. Wurster and Nganga (1971) demonstrated that pruning improved the quality and size of tomato fruit, with pruned plants producing earlier fruit that were larger than non-pruned field grown tomato. Davis and Eaters (1993); and Richardson (2012) described that pruning is a cultural practice which influences the yield, whereas Navarrete and Jeannequin (2000) and Hesami et al., (2012) highlighted the benefits of pruning for fruit quality in field grown trellis tomato. Muhammad and Singh (2007a) also reported a significant increase in both the quality and the yield of field grown trellis tomatoes with pruning. As with greenhouse tomatoes, there have also been reports of pruning having deleterious effects on the quality and yield of field grown trellis tomatoes. Kanyomeka and Shivute, (2005) reported that pruning resulted in low quality production and yield losses. Sikes and Coffey (1976) reported earlier yields from pruning, but with a reduction in total yields. Olson (1989) also found significant reduction in yields with heavy pruning in field grown tomato, but fruit size increased as the degree of pruning increased.

Pruning has also been noted to have an effect on the occurrence of pests and diseases in tomato crops. Dullahide et al., (1983) reported that pruning can spread virus diseases in field grown tomato crops and this can result in significant yield reductions. Pruning can also have beneficial effects on crop pest and disease status, with Saunyama and Knapp (2003) demonstrating that pruning is effective in reducing the incidence of pest problems in field grown trellis tomato crops. Similarly, Kanyomeka and Shivute (2005) explained that pruned tomatoes are less prone to pest attack than those which were not pruned in the crops grown in greenhouse. Pruning therefore has the potential to deliver both positive and negative impacts on tomato crops grown in the field as well as greenhouse tomato crops.

In the previous research chapters 3 and 4, temperature and soil type were identified as important environmental and edaphic factors affecting flowering time, and first harvest date of field grown tomato. Cultural practices adopted by the commercial tomato growers were also considered likely to have affected the timing of harvest and yield of field grown tomato crops, with pruning considered one of the most important managerial or cultural factors in production. The potential for pruning to impact on timing of harvest, as well as yield, in field grown trellis tomato crops is of obvious significance in identifying key determinants of crop development under production conditions in the sub-tropical region in Queensland, Australia.

The aim of this study was to assess the effects of transplant seedlings age on flowering time of the first truss and the effects of different pruning strategies on harvesting time and yield in field grown tomato crops.

MATERIALS AND METHODS

SITE AND CLIMATIC CONDITION

The research work reported in this chapter was carried out at the Queensland government department of agriculture, fisheries and forestry Bundaberg research facility in Queensland, Australia. The research facility is located at latitude - 24.85° and longitude 152.40 ° east. The soil type in which the trial crop was grown is classified as red ferrosol (Isbell, 2002). Monthly weather data were collected from the Bundaberg Aero weather station, situated at latitude - 24.89 ° and longitude152.32 ° east (Table 1).

Table 1: *Monthly weather data collected from the Bundaberg Aero[@] close to the research station in 2012.*

Parameters		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	29.6	30.4	29.1	27.6	24.5	21.4	21.7	23.8	25.7	27.1	29.1	31.7
	Min*	20.8	21.3	20.0	17.0	13.2	12.1	10.9	9.3	13.0	14.9	17.6	20.0
Rainfall	mm	263.8	74.0	241.4	37.2	27.6	183.0	89.4	11.4	18.0	27.0	38.2	47.6
Relative Humidity (%)	9am	69.0	71.0	71.0	72.0	71.0	78.0	73.0	65.0	60.0	56.0	58.0	54.0
	3pm	64.0	61.0	54.0	57.0	54.0	63.0	56.0	41.0	48.0	51.0	53.0	51.0
TCSR+	MJm^{-2}	658.0	635.4	552.5	500.2	422.4	322.5	388.5	536.6	619.1	758.1	858.6	947.5

**Maximum and minimum temperature was based on mean of maximum and minimum temperature of the month.*

+ Total cumulative solar exposure (TCSR) was based on the cumulative solar radiation of the days on each month.

@Justification is given in Chapter 2 on the use of Bundaberg Aero data

EXPERIMENTAL DESIGN

A randomised block design was used to see the flowering time of the first truss of 22, 27 and 31 days old transplanted seedlings (three treatments). The trial consisted of three rows of plants and each row was ninety two meters long. A one metre buffer zone was left at each end of each row and the remaining ninety metres was divided into three blocks, resulting in a total of 9 blocks within the three rows. Each block was divided into three plots for the seedlings age treatments. Each of these treatments had nine replicates in total. The treatments were allocated randomly with in each block. Plant to plant spacing of the seedling was kept at 45 cm and each plot contained a total of twenty two plants. Twenty plants were selected from each plot of transplanted seedlings age groups for the flowering time of the first truss.

Pruning treatments were applied at the time of flowering of the first truss or after to see the effect of pruning strategy on harvesting time of the trusses. Three treatments of transplant seedlings age (22, 27 and 31 days old), two regimes of pruning time i.e. early and late and two regimes of pruning intensity i.e. light and heavy; a total of 12 treatments were used in the trials (three transplanting seedlings age of 22, 27 and 31 days old treatments and 4 pruning treatments of early/ light i.e.1:1, early/heavy i.e.1:2, Late/light i.e.2:1, Late/heavy i.e.2:2). This experimental design to see the effect of pruning strategy on harvesting time of the trusses is called a Linear Mixed Effects Model. Each plot of transplanted seedlings age groups was divided into four sub plots representing five plants for each of the four pruning treatments (Figure 1). Several plants were transplanted as the guard plants at the end of each row and between the transplanted seedlings age treatments in each block. Plants were pruned either at the time of first truss flowering (standard commercial practice) or at the time of second truss flowering, and pruned according to normal practice used by commercial tomato growers (i.e. keep one side shoot just below first truss and remove others below that side shoot) or a more severe pruning where only one side shoot was left just below second truss and all others below that side shoot were removed. The crop management practices were done as mentioned earlier in Chapter 2 of this thesis except for pruning treatments.

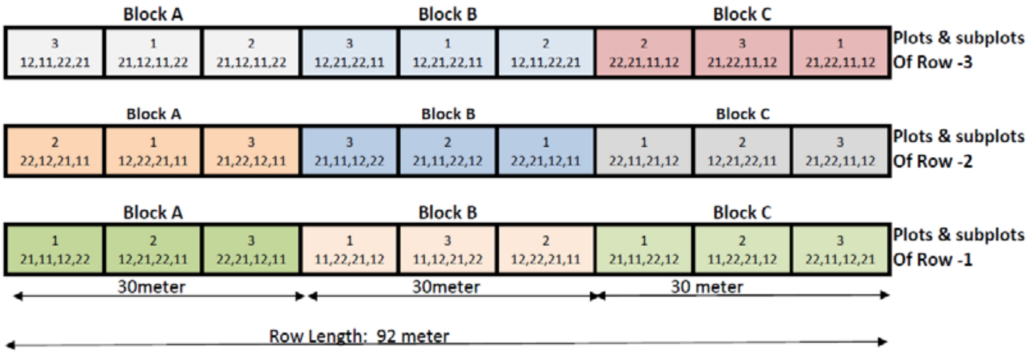


Figure 1: *Diagram of the rows, blocks, plots and subplots in the research field to see the effect of transplant seedlings age on flowering time of the first truss and also to see the effects of pruning strategy on harvesting time of field grown Roma tomato in Bundaberg research station in 2012. A, B and C represent the blocks in each row for the replication of the treatments. The numbers 1, 2 and 3 in plots in each block of the row represents the 22, 27 and 31 days old transplanted seedlings respectively. The subplots 11, 12, 21 and 22 represent the pruning treatments randomly allocated in each plot.*

MEASUREMENT OF THE TRANSPLANTED SEEDLINGS BEFORE TRANSPLANTING

Five representative seedlings from each age group were selected for measurement of developmental parameters at the time of planting of the trial. The number of leaves and internode lengths were measured, and total leaf area calculated from scanned images of the leaves. The root system of these seedlings was cleaned of potting mixture by rinsing in tap water, weighed and then dried at 40 ° Celsius till constant dry weight was received after fully dehydration and measured and recorded the dry weight. The measured parameters are presented in Table 2.

Table 2: *The height, leaf number, leaf area, dry weight and length of the nodes of 22, 27 and 31 days old seedlings of Roma tomato before transplanting in 2012. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters in each row represent there was no difference.*

Parameters	22 day old seedlings	27 day old seedlings	31 day old seedlings
Height (mm)	94.6 ± 6.76^{b}	111.6 ± 4.26^{b}	199.4 ± 1.91^{a}
Leaf number	6.0 ± 0.00^{b}	6.4 ± 0.24^{ab}	6.8 ± 0.20^{a}
Leaf area (cm^2)	19.33 ± 1.46^{b}	20.07 ± 1.50^{b}	38.48 ± 2.17^{a}
Dry weight(gm)	0.31 ± 0.01^{b}	0.39 ± 0.01^{b}	0.56 ± 0.03^{a}
Base-cotyledon*	45.8 ± 4.27^{b}	45.6 ± 1.20^{b}	64.8 ± 1.77^{a}
1st inter node*	33.8 ± 1.42^{b}	32.6 ± 1.43^{b}	80.2 ± 1.71^{a}
2nd inter node*	5.4 ± 2.24^{c}	13.4 ± 2.08^{b}	37.4 ± 2.01^{a}
3rd inter node*	7.4 ± 0.50^{a}	13.4 ± 2.82^{a}	11.6 ± 2.06^{a}
4th inter node*	1.0 ± 0.00^{b}	3.6 ± 0.74^{a}	2.4 ± 0.24^{ab}

**Internode length in millimetre (mm)*

CROP MANAGEMENT PRACTICES

The trial was transplanted on 12th April, 2012 and the plants were assessed regularly to document plant development. The Chapter will focus on effect of transplanting age on flowering time and effect of pruning on harvesting time, therefore data collection were done in this aspects for the analysis. Crop management practices were adopted as in Chapter 2.

MONITORING PARAMETERS OF THE PLANTS

Plant monitoring involved the assessment of a range of parameters on each of the twenty treated plants in each plot. The recorded parameters and data collection procedures are described below.

PLANT HEIGHT

Plant height was measured by measuring scale from the ground level to top of the plant on every alternate day commencing one week after transplanting of the tomato seedlings and continued until flowering time by using measuring scale from the ground level to the top of the plant. Two plants were selected in each plot for height measurement, i.e. eighteen sample plants to measure the plant height from nine replications for each age group.

FULLY EXPANDED LEAVES

The number of fully opened leaves on each sample plant was counted and recorded until flowering time on those plants which were used for measurement of plant height. The leaf was defined as fully opened when all the leaflets were close to ninety degrees to the main leaf blade. Leaf number was assessed on the main shoot as well as on all the side shoots of the sample plant.

CANOPY AREA

Canopy area was measured using digital images taken in the field. One sample plant was selected for each treatment in each plot and digital images were collected from each sample plant at weekly intervals until flowering time. Leaf area was calculated using Adobe Photoshop CS 5 to determine number of green pixels in each digital image. A 40 cm^2 calibration standard was included in each digital image to allow conversion of pixels to leaf area.

GROWTH AND DEVELOPMENT OF THE SIDE SHOOTS

The growth of all the side shoots from the leaf axils below the first truss was measured at every 2 days. Two sample plants were selected on each plot which was used for measurement of plant height and to measure the growth of side shoots until flowering time.

FLOWERING TIME OF THE FIRST TRUSS

Flowering time of the first truss (date that the first flower on the truss reached anthesis) was recorded in twenty plants in each block of transplanted seedlings age group treatments. The plants were monitored every alternate day after truss formation. When the truss was visible and flowering was imminent, monitoring was carried out every day shortly after midday to accurately determine flowering date. The flowering time of the first truss of each plant was recorded when the first flower of the first truss was fully opened.

SHOOT DRY WEIGHT OF DIFFERENT PRUNING LEVELS

One sample plant was randomly selected on each subplot (pruning treatment) to measure the shoot dry weight. The shoots which were removed at the time of pruning from different pruning treatments were collected in paper envelope and kept dried at 40 ° Celsius till constant dry weight was received after fully dehydration in drying oven and the dry weight was measured and recorded.

NODE NUMBER OF THE FIRST TRUSS

The position of the node number of the first truss on each sample plant was counted and recorded at the time of first truss flowering. Node number one was counted as the first true leaf node and subsequent nodes were counted to the leaf below the first truss.

HARVESTING TIME OF THE TRUSSESS AND FRUITS WEIGHT

The ripened fruits were harvested based on the colour development of the fruits. The fruits were ready to harvest when they reached at least half colour of the surface shows tannish yellow, pink, or red colour (Bagshaw et al., 1997). The first harvesting time of the plant was recorded as the date when the first fruit was harvested from the first truss. The harvesting time of the second to sixth truss was recorded when first fruit was harvested from the respective truss. The number and weight of harvested fruits were measured from the first and second trusses for all pruning treatments on 27-day-old transplanted seedling. Only 27-day-old seedlings and their pruning practices (1: 1) were chosen for this assessment as 27 days old transplant is the age that is normally used on commercial transplanting and this is the limitation of the study. Three plants were selected from the 27 days old seedling on each row from the early and light pruning (1:1) treatment to measure the total fruits and weight for each sub sequential harvesting.

STATISTICAL ANALYSIS

The one way analysis of variances of canopy growth, seedlings height, leaf area, and visible truss (first and second truss), was performed on each day collected data and also verified by two-way Analysis of Variance (ANOVA) in different transplanted seedlings age groups in

Minitab version 16. The node and leaf numbers at flowering time of the first truss, flowering time of the first truss and fruit yield of first truss, second truss and other trusses was also performed by one way analysis of variance in Minitab. The comparisons of the different measured data were performed by one-way and/or general linear model (GLM) analysis of variance in Tukey's method at 95 percent confidence interval and all the statistically significant findings are reported at $p \leq 0.05$ in Minitab 16. Transformation of the data was performed by using square root in excel and/ or by Johnson transformation in Minitab for normality and homogeneity of the variances in some measured data.

Of particular interest was the effect of the seedling ages and pruning treatments on duration to first harvest. In order to obtain estimates on how the seedling age at transplant and pruning treatment affected time to first harvest in each truss, a Linear Mixed Effects Model was used by employing the package *lme4* in R 3.1.1. Due to the fact that the data were not a balanced design (plants die or do not always send out a fifth or sixth truss, for instance), it was more appropriate to use a linear mixed effects model rather than a traditional split-plot design with a fixed-effects ANOVA for the harvest data. Further, the growth and subsequent harvest parameters of a truss is presumably dependant on the truss (es) before it, and a linear mixed effects model allows for more relaxed assumptions around the data.

The fixed effects in the model were seedling age, pruning treatment and truss number, whilst block and row were random factors. This full model was compared against reduced effects models using and analysis of deviance from the full model. For Roma tomatoes, the full model was associated with the lowest AIC, and had the lowest deviance (Appendix 15 A)

Correlations between fixed effects were calculated in order to determine if there was a relationship between levels of a factor, or between factors (See appendix 15B). Unsurprisingly, there was a moderate degree of correlation between trusses. There was also some correlation between pruning regimes. Thus, there was some correlation between different *levels* of two of the fixed factors, but not *between* different fixed factors.

RESULTS

CANOPY AREA ON ROMA TOMATO

The total canopy area (Figure 2A) on 31 day old seedlings was significantly wider than 22 and 27 day old seedlings before transplanting and the same trend existed until 12 days after transplanting. There was no statistically significant difference in the area of canopy at 16, 18, 20 and 22 days after transplanting on all age groups. The canopy area displayed a period of rapid growth at 22 days after transplanting on all three age groups.

The rate of daily canopy expansion (Figure 2 B) was not significantly different between all transplanted seedlings age groups between eight days and twenty two days after transplanting. The daily rate of canopy expansion was lower until eight days after transplanting on all seedlings age groups but increased rapidly at ten days after transplanting. The daily expansion rate was lower at eighteen days after transplanting on 31 day old seedlings.

The relative expansion rate of canopy (Figure 2 C) varied significantly at eight days and sixteen days after transplanting in 22, 27 and 31days old seedlings. The relative growth rate of canopy was not significantly different at ten days and followed the same trend at 12, 18, 20 and 22 days after transplanting.

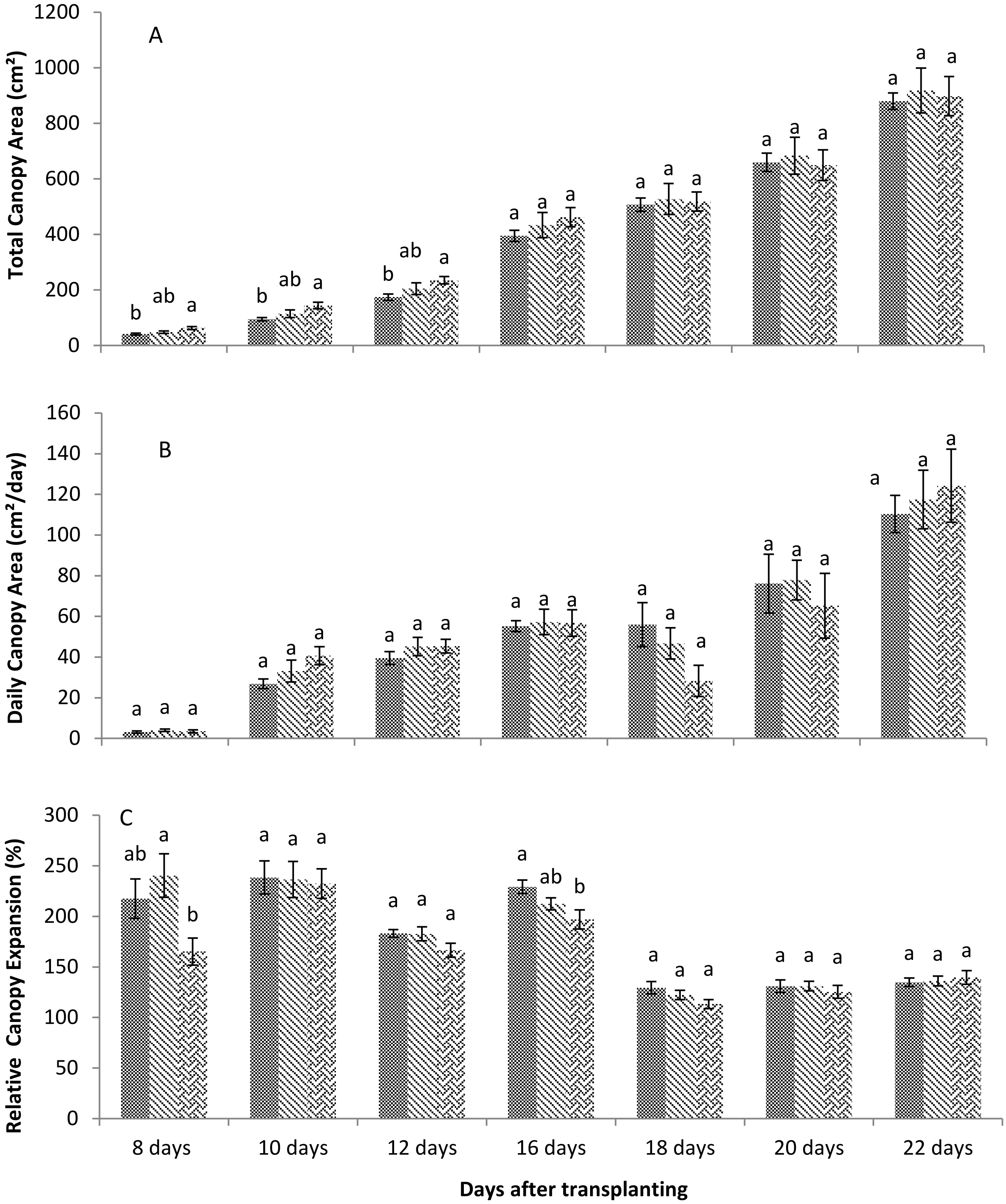


Figure 2: *The total canopy area (A), and daily (B) and relative (C) canopy area expansion on 22, 27 and 31 days old seedlings at 8, 10, 12, 16, 18, 20 and 22 days after transplanting of Roma tomato transplanted in 2012.The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Markings with the same letters represent there was no difference. In the figure, the legend for 22 days seedlings for 27 days seedlings for 31 days seedlings*

PLANT HEIGHT BEFORE FLOWERING ON ROMA TOMATO

The total height of the transplanted seedlings was significantly higher for 31 days old seedlings than other aged seedlings before transplanting, and same trend was found from 8 to 20 days after transplanting (Figure 3 A). There was no significant difference in the plant height between 22 and 27 days old seedlings before and also after transplanting (Figure 3 A).

The daily extension rate of the transplanted seedlings height was found to be significantly higher for 21 and 27 day old compared to 31 day old transplanted seedlings at eight days after transplanting (Figure 3 B). The daily extension rate in seedling was highest at 14 days after transplanting for all three seedlings ages. There were no significant differences in daily extension rate of the transplanted seedlings except 8 days after transplanting.

The relative extension rate of the transplanted seedlings height varied significantly between treatments at eight days after transplanting (Figure 3 C), with 22 day old seedlings displaying the highest and 31 day old seedlings the lowest relative extension rate. While a significant difference was also found at 14 days after transplanting, the overall trend was no significant differences in relative extension rate between the treatments after the initial period of transplanting adjustment.

DEVELOPMENT OF FLOWERING TRUSS

There was no visible truss development until ten days after transplanting (Figure 4 A). Differences between treatments in the percentage of plants with first truss visible were only significant at 18 days after transplanting. There was a trend towards the first truss percentage being higher in 22 day old seedlings than the other age groups at 12 days and 14 days after transplanting.

The development of the second truss was first observed at fourteen days after transplanting for all age groups (Figure 4 B). The percentage of plants with a visible second truss was not significantly different between treatments until eighteen days after transplanting, and was found to be significantly higher at 20 and 22 days after transplanting in 22 days old seedlings when compared with other treatments.

PLANT DEVELOPMENT MEASUREMENTS

The mean node number position of the first truss on the main shoot was 7.7 ± 0.04^{c}, 9.2 ± 0.05^{a} and 8.8 ± 0.04^{b} for 22, 27 and 31 day old transplanted seedlings respectively, and these values were significantly different from one-another (P = 0.000 & DF = 107). The number of fully open leaves produced before flowering of the first truss on the plants was 9.1 ± 0.07^{c}, 10.3 ± 0.08^{a} and 9.9 ± 0.09^{b} on 22, 27 and 31 day old transplanted seedlings respectively, and also differed significantly(P = 0.000 & DF = 107).

SHOOT DRY WEIGHT ON DIFFERENT PRUNING LEVELS ON ROMA TOMATO

The dry weight of pruned shoots was significantly different between pruning treatments (Figure 5). As expected, dry weight of pruned shoots was significantly higher in plants pruned at the time of second truss flowering (late/light i.e. 2:1 and late/heavy i.e. 2:2) than those pruned at flowering of first truss. No significant differences were found between transplant seedlings age within the treatments. A trend towards higher side shoot weight in transplants pruned to leave a single side shoot below the second truss compared to those pruned to leave a single side shoot below the first truss was noted, and this would be consistent with more side shoots being removed in the former treatment.

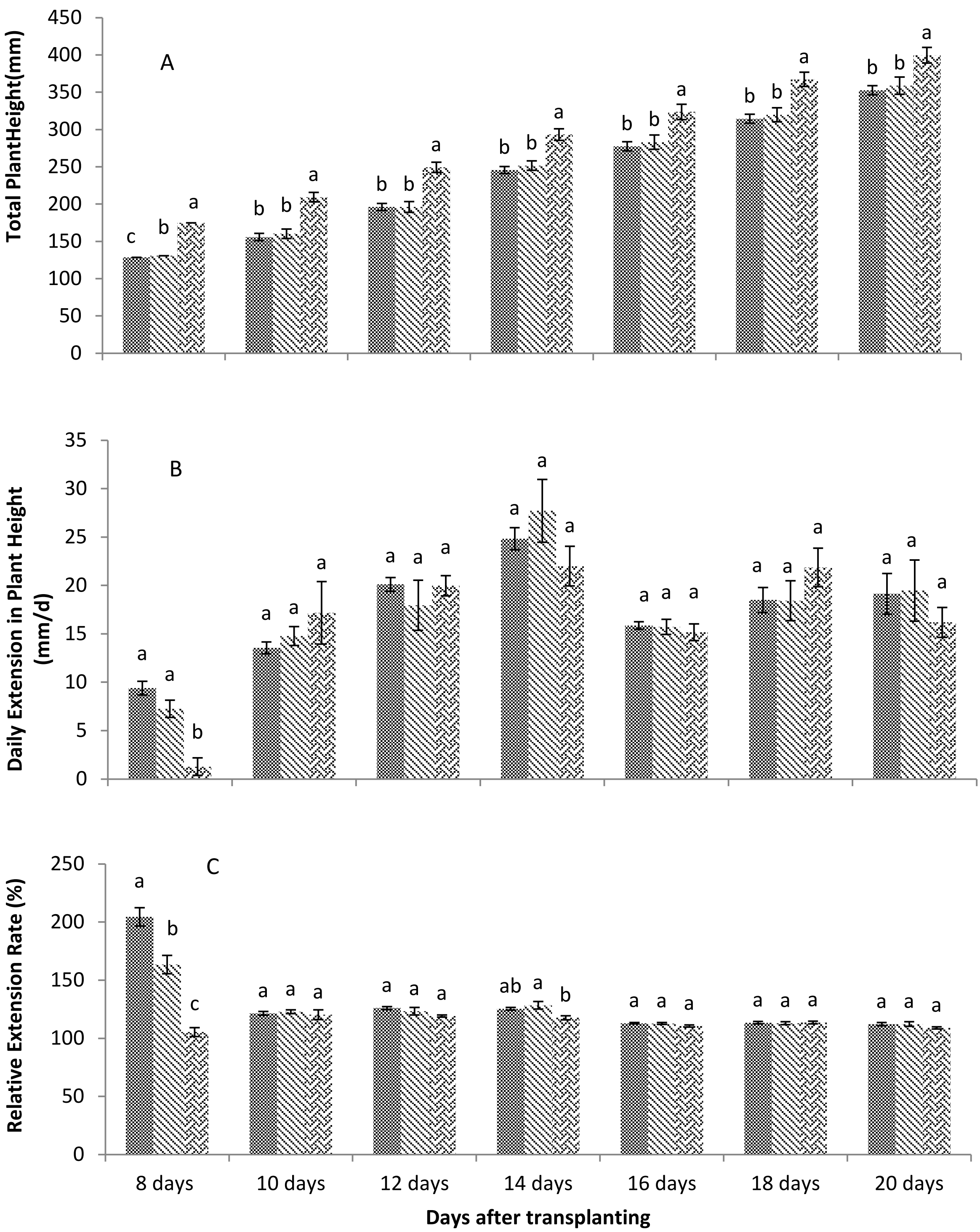


Figure 3: *The total plant height (A), daily (B) and relative (C) extension rate on 22, 27 and 31 days old seedlings at 8, 10, 12, 16, 18 and 20 days after transplanting of Roma tomato transplanted in 2012.The data presented here are the mean values ± SE, which were analysed at the significant levels of $P \leq 0.05$ at Tukey,s. Markings with the same letters represent there was no difference. In the figure, the legend for 22 days seedlings for 27 days seedlings for 31 days seedlings*

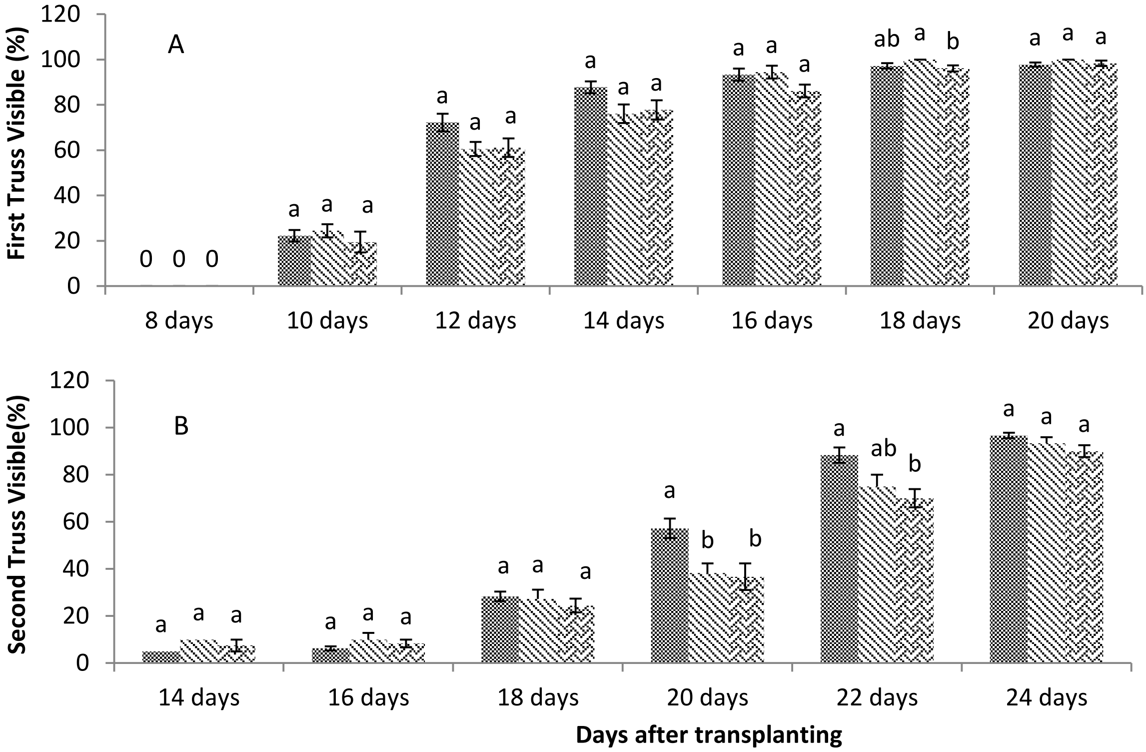


Figure 4: *The percentage of plant with first (A) and second (B) visible trusses on 22, 27 and 31 days old seedlings at 8, 10, 12, 16, 18, 20, 22 and 24 days after transplanting of Roma tomato transplanted in 2012.The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters represent there was no difference. In the figure, the legend for 22 days seedlings for 27 days seedlings for 31 days seedlings*

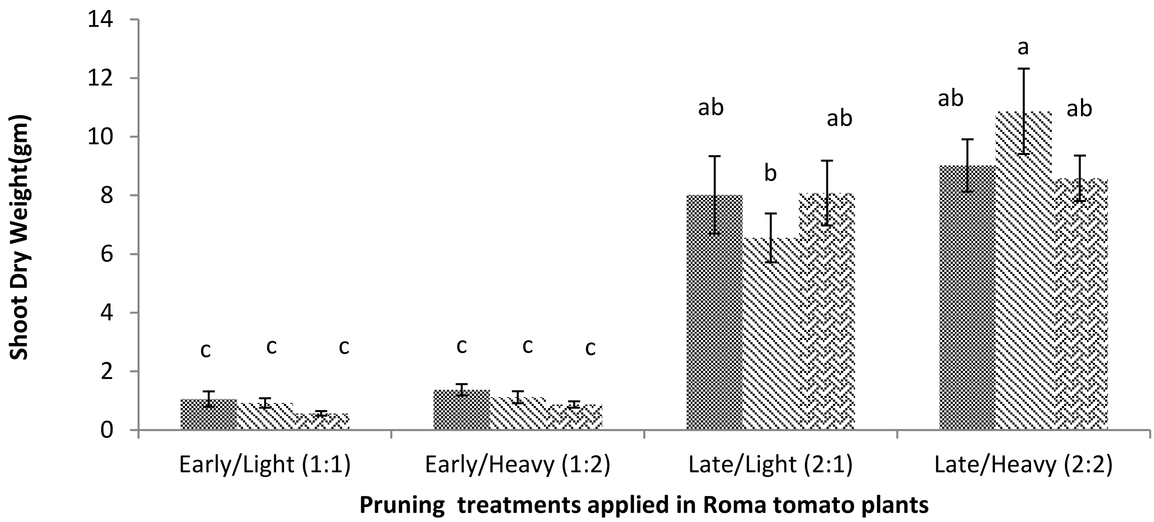


Figure 5: *The shoot dry weight (gm) at different pruning treatments applied in Roma tomato plants transplanted in 2012, Bundaberg. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters represent there was no difference. In the figure, the legend for 22 days seedlings for 27 days seedlings for 31 days seedlings*

FLOWERING TIME OF THE FIRST TRUSS

The mean flowering time of the first truss on the main shoot was 22.1 ± 0.18[b], 22.9 ± 0.27[a] and 22.7 ± 0.19[ab] for 22, 27 and 31 day old transplanted seedlings respectively, and the flowering time of the first truss was significant (P = 0.035, F = 3.46 & DF = 107). The pruning experiment was done at the time of flowering time of the first truss or after in all transplanted seedlings age groups; therefore pruning treatments had no effect on the time of first truss flowering.

HARVESTING TIME OF THE TRUSSES

The variation of harvesting time of the first to sixth trusses was observed in different transplanting seedlings age groups imposed by pruning treatments (Table 4). The harvesting time of the first truss was significantly earlier in 22 days old seedlings in pruning regime of late and heavy pruning (2:2). The result also showed that the harvesting time of the first and second truss was earlier in heavy pruning whereas third to sixth truss; it was in light pruning.

Table 4: *The harvesting days of the trusses on 22, 27 and 31 day old transplanted seedlings at different pruning levels on Roma tomato transplanted in 2012. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters in the row represent there was no difference.*

	22 Days Seedling				27 Days Seedling				31 Days Seedling			
Truss	1:1	1:2	2:1	2:2	1:1	1:2	2:1	2:2	1:1	1:2	2:1	2:2
First	^{ab}87.3 ± 0.7	^{ab}86.2 ± 0.8	^{ab}87.7 ± 0.8	^{b}85.8 ± 0.7	^{ab}88.4 ± 0.8	^{a}88.7 ± 0.9	^{a}89.2 ± 0.9	^{ab}86.8 ± 0.9	^{ab}88.4 ± 0.8	^{ab}87.3 ± 0.8	^{a}89.3 ± 0.8	^{ab}87.9 ± 0.8
Second	^{ab}103.8 ± 0.7	^{b}101.4 ± 0.5	^{ab}104.4 ± 0.5	^{b}101.6 ± 0.6	^{a}105.6 ± 1.0	^{ab}103.1 ± 1.0	^{a}106.2 ± 0.9	^{ab}103.6 ± 0.9	^{a}105.9 ± 0.6	^{ab}103.8 ± 0.7	^{ab}105.5 ± 0.6	^{ab}104.0 ± 0.8
Third	^{abc}116.0 ± 1.0	^{abc}117.5 ± 1.3	^{abc}116.8 ± 1.0	^{abc}116.3 ± 1.1	^{ab}118.8 ± 0.8	^{a}119.7 ± 1.3	^{ab}119.7 ± 0.9	^{abc}116.8 ± 1.1	^{c}114.4 ± 1.1	^{abc}118.5 ± 1.3	^{abc}116.0 ± 1.2	^{bc}115.9 ± 1.2
Fourth	^{d}123.3 ± 1.0	^{abcd}126.7 ± 0.9	^{d}124.3 ± 0.9	^{abcd}127.5 ± 0.8	^{d}124.4 ± 0.7	^{ab}129.0 ± 1.0	^{cd}124.7 ± 0.8	^{abcd}127.0 ± 0.8	^{d}124.3 ± 0.9	^{a}130.1 ± 1.0	^{bcd}125.7 ± 1.0	^{abc}129.4 ± 1.0
Fifth	^{e}129.2 ± 0.8	^{abcde}133.5 ± 0.9	^{de}129.6 ± 1.0	^{abcd}133.5 ± 0.8	^{cde}130.4 ± 0.7	^{abc}134.2 ± 0.9	^{bcde}130.8 ± 0.8	^{abcd}132.4 ± 1.0	^{e}129.6 ± 1.0	^{a}135.4 ± 1.1	^{bcde}131.4 ± 1.0	^{ab}134.9 ± 0.8
Sixth	^{d}133.6 ± 0.8	^{abcd}136.4 ± 0.8	^{d}133.1 ± 0.8	^{abc}138.1 ± 0.8	^{cd}134.2 ± 0.9	^{abc}137.7 ± 0.9	^{d}132.7 ± 0.7	^{abcd}136.6 ± 0.9	^{bcd}134.3 ± 0.9	^{ab}138.4 ± 1.0	^{abcd}135.4 ± 1.0	^{a}139.4 ± 0.9

All factors in the linear mixed-effects models of Roma tomatoes had a significant effect on time to first harvest. Increasing the age of seedlings at transplant added on average 0.15 of a day to the time to harvest, whilst early / light (1:1) pruning decreased the time to harvest by almost two days. The average time to first harvest on truss one was 84 days, with an extra 16 days elapsing before fruits could be harvested on truss 2, and a further 15 days to harvest truss three. Thirty-eight days after harvesting truss 1, truss 4 was ready for harvest, with trusses 5 and 6 bearing harvestable fruit within the next ten days (Table 4A).

Table 4A: *The analysis of harvesting trusses by linear mixed-effects model on Roma tomato transplanted in 2012, in Bundaberg.*

Fixed Effects	Estimate	Standard Error	t-value
Intercepts	84.7056	1.2316	68.78
Seedling Age	0.1512	0.0287	5.27
Truss-2	16.3520	0.3527	46.37
Truss-3	29.5333	0.3555	83.07
Truss-4	38.5985	0.3584	107.70
Truss-5	44.3054	0.3604	122.94
Truss-6	48.0194	0.3525	132.47
Pruning Regime Early/Light(1:1)	-1.9652	0.2935	-6.70
Pruning Regime Early/Light(2:2)	-0.5554	0.3002	-1.85
Pruning Regime Early/Light(2:1)	-1.2940	0.2957	-4.38

Variation in time to first harvest in each truss for Roma tomatoes is shown in figure 5 A below. Before these trusses are harvested, increased seedling age at transplant delays harvesting in both roma and gourmet crops, whilst pruning (especially early, light pruning) decreases time to harvest by up to two days for each truss.

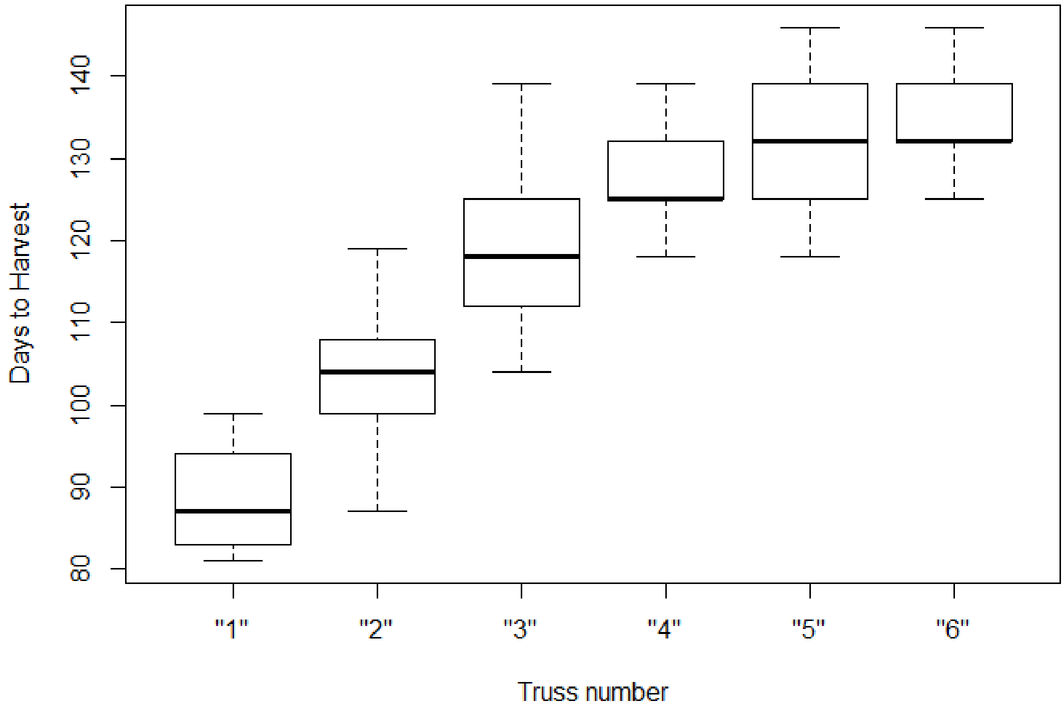


Figure 5 A: *Variation in harvesting days of first, second, third, fourth, fifth and sixth trusses on Roma tomatoes transplanted in 2012. Median values are indicated by the solid black line and box boundaries are the 25thand 75thpercentiles.*

FRUIT NUMBER AND WEIGHT

There are no significant differences except for fruit number and weight in other trusses (Table 5). The number and weight of harvested fruits from the remaining trusses were significantly higher in pruning treatments level early/light i.e. 1:1 (the level normally practiced on commercial tomato crops) than in other pruning treatments.

Table 5: *Number of fruits and weight of the first and second as well as in other trusses on 27 days old transplanted seedlings at different pruning levels on Roma tomato transplanted in 2012. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters in each row represent there was no difference.*

	Pruning Levels			
Parameters	Early/Light(1:1)	Early/Heavy(1:2)	Late/Light(2:1)	Late/Heavy(2:2)
Fruits in first truss	7.2 ± 0.2^{a}	7.5 ± 0.1^{a}	7.7 ± 0.18^{a}	7.3 ± 0.1^{a}
Fruits weight in first truss*	0.63 ± 0.02^{a}	0.70 ± 0.01^{a}	0.66 ± 0.02^{a}	0.64 ± 0.01^{a}
Fruits in second truss	6.9 ± 0.5^{a}	6.9 ± 0.5^{a}	7.1 ± 0.5^{a}	6.7 ± 0.5^{a}
Fruits weight in second truss*	0.53 ± 0.02^{a}	0.53 ± 0.02^{a}	0.53 ± 0.19^{a}	0.52 ± 0.15^{a}
Fruits in other trusses	168.6 ± 6.8^{a}	128.0 ± 5.2^{bc}	158.0 ± 9.0^{ab}	125.3 ± 6.9^{c}
Fruits weight in other trusses*	7.17 ± 0.63^{a}	4.31 ± 0.42^{b}	6.04 ± 0.24^{ab}	4.63 ± 0.30^{b}

* *The weight of the fruits in kilogram*

DISCUSSION

The variability in growth and flowering time of different ages of transplanted tomato seedlings, as well as variation in harvesting time and yield by pruning treatments, was recorded in the research described in this chapter. The flowering time of the first truss was significantly earlier at lower node position in 22 day old transplanted seedlings of field grown tomato plants. Flowering time may be related to the time of harvest of the crops; therefore seedling age may be considered as a possible factor influencing the time to harvest of field grown trellis tomato crops. While transplanted seedlings age and the pruning treatments induced statistically significant changes, the scale of these changes, 1 or 2 days earlier on flowering or harvesting time of the crops, are unlikely to have any meaningful impact from a commercial crop management perspective.

The flowering time of the tomato plants displayed a positive relationship to harvesting time of the fruits; therefore, earlier flowering of younger transplanted seedlings corresponded to earlier harvesting of the crops. Earlier flowering of the younger transplanted tomato seedlings was also observed by Korodi, 1966; Adelana, 1983; Agble, 1995; Salik et al., 2000; and, Ademeluyi, 2011, but conflicting result was observed by Jankauskiene et al., 2013.

Tomato seedlings require a certain amount of thermal time to reach floral initiation. Schmitz and Theres, (1999) described that after formation of 7-11 phytomers (leaves), the shoot apical meristem from the primary shoot is transformed into inflorescences. Wetzstein and Vavrina (2002) described that the shoot tips of normal tomato seedlings at18 days after sowing had vegetative, non- reproductive, dome-shaped shoot apices and the shoot apex become reproductive only at 35 to 42 days after sowing. The transplanted seedlings in all age groups in this research had only 6 phytomers/leaves i.e. less than in Schmitz and Theres findings and all seedlings were also younger than Vavrina research findings which indicate that there is less possibility to develop the visible inflorescences at transplanting time. The visible inflorescences were observed at 10 days after transplanting even in younger transplants which clearly indicates that there are some factors responsible for early flowering at lower nodes on younger transplanted tomato seedlings or delayed flowering in older seedlings.

There are some possible reasons of earlier flowering at lower nodes in younger transplanted seedlings. One of the possible reason of early flowering at lower nodes in younger transplanted seedlings may be the earlier field establishment of younger transplanted seedlings and similar research were also described by Nicklow & Minges, 1962; Vavrina, 1998; Leskovar et al., 1991; and Ademiluyi, 2011. We do not have data to support this argument.

The environmental stress on transplanted seedlings before establishment of the root system in the soil may be another possibility to explain early flowering at lower nodes on young transplanted tomato seedlings. Normally, the root system of transplanted tomatoes seedlings becomes active within 3 days of transplanting and starts to take up soil nutrients (Tiessen & Carolus, 1963; Sumugat et al., 2011). Root derived signals associated with exposure to root stress and/or partial root zone drying before full establishment of the root system may enhance inflorescence development in the young transplanted seedlings due to early field establishment of the root systems of young transplanted seedlings than old transplanted seedlings. A similar finding of early flowering of the transplanted tomato seedlings at lower nodes attributed to stress and/or partial root zone drying was described by Bindon et al., 2008, and Posades et al., 2008 in field grown tomato crops.

Another possibility of explaining the early flowering at lower nodes on young transplanted tomato seedlings is that the environmental regulated stress signalled to the flowering genes that controls the floral identity of the meristem in tomato (Allen & Sussex, 1996; Dielen et al., 1998; Quinet et al., 2006). Another possibility may be the interaction of the daily light energy integral and chlorophyll content of the leaves. Flowering time of the tomato plant mainly depends on the daily radiation energy received by the plant (Dielen et al., 2004) and younger transplanted seedlings have been shown to have a higher chlorophyll a: b ratio than old transplants (Leskovar et al., 1991), which may result in a high photosynthetic rate that supplies adequate sugars to the meristem to constitute an essential signal for early flowering. The early flowering at lower nodes on young transplanted seedlings, whether through environmental stress on the seedlings or other alternative mechanisms, need to be consider for future research in field grown tomato crops.

Pruning significantly affected time to harvest and yield of tomato crops. The amount of pruning was found to significantly impact on time to harvest and yield of the crops transplanted on different seedlings age. Fruit growth and maturation time depend on availability of assimilate, with competition for assimilates that impact on tomato fruit growth (Ho, 1984; Picken, 1984; De Koning, 1989; and Bertin, 1995). Heavy pruning of field grown tomato plants greatly reduces the number of vegetative shoots and inflorescences which are also the main sink organs of the plant. The assimilate produced in the plants translocated through the one common pool to the fruits which are the main sink organs in heavy pruning treatments resulting an increased growth rate of the fruits on these trusses and earlier maturity. Earlier harvesting following pruning of tomato crops has been previously described by Wurster & Nganga, 1971; Sikes & Coffey,1976; Bangerth & Ho, 1984; De Koning,1989; Boote et al., 2012; Osoria et al., 2014. The impact of pruning on the harvesting time of the successive trusses has not been described by the earlier researchers in field grown tomatoes. The increased competition for assimilate between the other trusses and growing vegetative shoots from the axils of leaves delayed growth and maturity of the fruits on these heavy pruned plants are likely to have contributed to the later harvesting which are the later opening ones noted in this trial. A similar research result was also found by Li et al., 2015 in greenhouse tomato crops. The competition for assimilate between the vegetative organs and fruits is low due to high source-sink ratio on third to sixth trusses that influenced faster growth and maturity of the fruits that has impact on early harvesting of the trusses in the pruning treatments of early/light (1:1). The result was also consistent with the explanation of the earlier researchers in greenhouse tomato (De Koning, 1989; Boote et al., 2012; Osoria et al., 2014).

The analysis of the crop yield data showed that pruning treatments levels didn’t have any significant differences on the numbers and weight of the fruits on the first and second trusses but significant differences were observed on the remaining trusses of field grown trellis tomato crops. The optimum source-sink ratio in the field tomato crops is important factor for the distribution of assimilate to the fruits that have impact on yield. The lighter pruning at an early stage of growth and development of the crops is normally practiced in commercial tomato crops to maintain source-sink ratio for the optimum production. The removal of the lateral branches by heavy pruning in field grown trellis tomato crops greatly reduces the number of fruits that impact on yield reduction. The pruning practices to maintain optimum source-sink ratio of 0.5 (De Koning, 1994; Boote et al., 2012) by removing all the lateral shoots at 7-14 days interval (Navarrete & Jeannequin, 2000) that maintained leaf area index at 2-3 for optimum production in greenhouse tomato crops was also explained by De Koning, 1996a; Ho, 1996 and Ambrosszczyk et al., 2008; Osoria et al., 2014. This information is relevant for the tomato growers to maintain the appropriate vegetative and generative organs of the tomato plants by adopting the suitable pruning strategy. This research studies also validates the grower pruning practices adopted in commercial field grown tomato crops in this region.

CONCLUSION

The younger transplanted seedlings displayed significantly earlier flowering time at a lower node position than older transplanted seedlings. The environmental stress before establishment of the root system in the soil and or partial root drying,regulating a stress signal to the flowering genes which controls the floral identity of the meristem, may be one possible reason for early flowering of younger transplanted seedlings. The interaction of the daily light energy integral and chlorophyll content of the leaves may be another possible reason for it. The analysis of the data also showed that the pruning treatments on different transplanted seedlings age groups have the significant effect on harvesting time and yield due to the source-sink ratio of the vegetative and generative sink organs of the field grown tomato crops. The heavier pruning treatment induced significantly earlier harvesting time of the plants on younger transplanted seedlings, whereas the early/light pruning treatments influenced significantly higher yield of the crops. Although seedlings age at transplanting and the amount of pruning induced statistically significant impacts on flowering and/or harvesting time of the plants, the scale of the response at only 1 or 2 days difference is not a meaningful impact from a commercial crop management perspective.

CHAPTER 6

THE SOURCE -SINK INTERACTION IN FIELD GROWN TOMATO

ABSTRACT

The research work reported in this chapter was carried out to find the effect of branching pattern on carbon partition and the effect of fruit loads on photosynthesis in commercially field grown Gourmet tomato crops in Bundaberg, Australia. The crop monitoring was conducted on five replicated plots; each plot containing 20 selected sample plants for the four treatments. The fresh and dry weight of the first and other (2-6 fruits) fruits of the first truss at different growth stages of the fruit and growth rate of the first fruit were measured to assess the dry matter partitioning to fruits. Quantum yield of the leaves on different treatments was also measured to assess the relationship between fruit loads and photosynthesis rate of field grown tomato plants. The study had found that the branching patterns of field grown trellis tomato affect significantly higher on assimilate partitioning to the first fruit of the first truss only at maturity stages and also significantly earlier on time to first harvest of the crops. The fruit load on different branching patterns of commercial field grown trellis tomato had no any significant impact on the photosynthesis rate of the plants but, significant impact was observed only by manipulating fruitless plants after top shoot pruning of the plants.

INTRODUCTION

Temperature and light influence the rate of maturation of tomato fruit and crop yield through the processes of photosynthesis and carbon partitioning within the plant. Greenhouse tomato crop yield models work well in part because temperature and light levels can be controlled, and because side shoots are removed so fewer sinks exist to influence carbon partitioning. Adams and Valdes (2002) explained that high temperature enhanced fruit ripening. This author also found that the number of harvested fruit and the yield of tomato crops grown in greenhouse conditions were significantly and positively correlated with air temperature and solar radiation, but the correlations were strongest with solar radiation (Higashide, 2009). McAvoy et al., 1989 explained that the yield of tomato fruits mainly depends on the cumulative solar radiation received by the plants from flowering to harvesting. Even the weekly yields of greenhouse tomato crops can be predicted based on the cumulative solar radiation received by the plants before harvesting (Hisaeda & Nishina, 2007).

Temperature and light also influence the sink –source ratio of tomato crops. The temperature has direct effects on the ratio of vegetative to generative sink strength in glasshouse tomato (De Koning, 1994; Heuvelink, 1996). High temperature before anthesis has a negative effect on pollen release, resulting in higher levels of flower and fruit abortion (Peet et al., 1998; Sato et al., 2000); it also enhances early fruit growth rate due to the increase in assimilate partitioning to fruits (De Koning, 1989) which results in early harvesting of the tomato fruits. Cockshull *et al.,* (1992) described that shading levels of up to 25 % light loss led to a similar proportional yield loss in greenhouse tomato crops. It was also explained that fruit set was reduced significantly under low light conditions in winter season due to high competition for carbon between source and sink organs (Ho, 1984) and not much produced anyway.

Temperature and light are the main parameters of photosynthesis process but also influence translocation and partitioning of assimilates to the sink organs of the plants. It was explained that during the diurnal cycle assimilates in mature cucumber leaves were exported within 2 hours of the commencement of the dark period at 20 °C air temperature and 4 hours at 16 °C, but export was strongly inhibited at 10 °C (Toki *et* *al.*, 1978). Other authors have concluded that the exported proportion of carbon from source leaves is stable under different temperature and light regimes, but the amount of carbon per unit area that is exported mainly depends on the carbon pool (Nishizawa et al., 2009) which is predominantly determined by light intensity (Grodzinski et al., 1999). The amount of carbon exported from leaves increased in plants grown under 414 $\mu mol.m^{-2}.s^{-1}$ light intensity conditions compared to 166 $\mu mol.m^{-2}.s^{-1}$ in tomato seedlings (Nishizawa *et al.*, 2009). Bruggemann *et al.*, (1992) described that tomato plants grown at low temperature (6-10°C) and light levels (60–100 $\mu mol.m^{-2}.s^{-1}$) displayed feedback inhibition of photosynthesis due to internal sugar accumulation in the leaves, which significantly decreased the photosynthetic capacity of the plants. Fluctuations in ambient temperature between12 and 27 degrees Celsius in field conditions have been noted to induce large plant growth and development response (Philip, 2013), most likely resulting from the physiological mechanisms noted above. The wider variation in temperature under field compared to greenhouse conditions introduce more complexity in prediction of assimilates production and partitioning as well as the yield of field grown crops.

Assimilate partitioning patterns are also affected in tomato production through the physical manipulation of sinks. Pruning experiments revealed significant effects on rate of fruit ripening and yield suggesting carbon partitioning patterns in field grown tomato, where shoot number and timing of truss initiation are more variable than in greenhouse crops, are more complex than in greenhouse tomatoes. The multiple shoot structure in field grown plants is generated through early removal of lateral shoots from lower nodes and top pruning of the shoots before harvesting of the fruits which removes vegetative sinks. In contrast, in greenhouse crops all side shoots of the main shoots are removed at 7-14 day intervals and the terminal shoot tip is never pruned, with improvements in plant vigour and yield (Navarrete etal.,1997), and maintenance of proper balance between source and sink strengths of the plant for the yield (Ho, 1996), given as advantages of this pruning system. In the earlier chapters of the thesis, it was found that time to harvest of the first and second truss was significantly earlier in plants that were more heavily pruned whereas time to harvest was significantly delayed for the third to sixth trusses of the field grown tomato plants. Earlier maturity of the fruits following pruning has also been reported by Sikes and Coffey (1976), but effects on remaining trusses on the plant have not previously been documented. It was observed that fruit number and weight in the first and second trusses was not significantly affected by the pruning treatment but significantly lower were recorded in others trusses between the different pruning levels. Previous studies have documented a significant reduction in yields with heavy pruning in field grown tomato and a corresponding increase in fruit size as the degree of pruning increased (Olson,1989), but the impacts on individual trusses were not described. Richardson (2012) described that the pruning in field grown trellis tomato increased the quality of the fruits and marketable yield of the crops. While previous studies have focussed on optimum pruning practices for crop yield in field grown tomato, little information has been generated at the individual fruit or truss level, but this knowledge is important in understanding the effects of treatments on assimilate partitioning patterns for predictive model development.

Sink–source relationships are complex and difficult to quantify (Marcelis, 1993), especially in field grown trellis tomato grown under fluctuating environmental conditions and with many vegetative and generative sinks associated with the branching structure of the semi-indeterminate tomato crops. The changes in sink activity with developmental stages add additional complexity (De Koning, 1994). The translocation patterns of assimilates is vary (Watson & Casper, 1984) and changes over the different stages of growth and development of the plant (Marquis, 1996). A fruit truss develops after each three leaves (phytomers) in indeterminate tomato plants grown in greenhouse conditions (Heuvelink, 1995a) and the generative sink strength of the fruit truss is proportional to the number of fruits in each truss, but it is different in field grown tomato crops due to the branching patterns and new shoots development from each leaf axil. In greenhouse tomato crops, the three leaves and internode between two trusses is considered as a vegetative unit and its average sink strength was 2.96 times higher than the average sink strength of a fruit (De Koning, 1994; Heuvelink, 1997). This consistent pattern is not observed in field grown tomato, with fruits on upper section of the trellis crops generally significantly smaller than those formed at lower node positions and often of less than marketable size suggesting resource constraints (carbohydrate) for the fruit growth.

Evidence from other species indicates that increasing sink strength leads to an increased rate of photosynthesis of the plant and also in nearby leaves. Gonzalez-Real et al., (2009) described that the leaf photosynthesis capacity of the nearby leaf in fruit shoot is mainly driven by the sink demand of the most proximal fruit in pepper plants. Urban *et al*. (2003) described that the leaves close to developing fruits exhibit increased photosynthetic capacity compared to the remaining leaves of the tree. Hansen (1967; 1969) described that the leaves close to the fruits supply much of assimilate for fruit development in apple tree and more assimilate translocated to the fruiting branches compare to non-fruiting branches, but it is not known whether this response occurs in field grown trellis tomato. If it does, the effect of branching on leaf area index/effective photosynthetic capacity might be less critical to rate of fruit maturation and yield.

Effects of fruit load on photosynthesis and carbon partitioning in pruned plants under greenhouse conditions have demonstrated the importance of truss/fruit number on rate of maturation of fruit. Fruits are the dominant sink in tomato plant (Hurd et al., 1979; De Koning & De Ruiter, 1991) and the enhanced fruit growth was observed at the expense of vegetative growth in pruned plants. Fruit size increases and earlier maturation occurs at a small sink-source ratio compare to large ratio. Marcelis and Heuvelink (1997) reported that tomato fruits grown on plants with seven fruits per truss reached only 70 % of the final dry weight of fruits grown on plants with one fruit per truss. Tanaka and Fujita (1974) found that when trusses were pruned to one or three fruits the final plant dry weight was reduced by 20% compared to six fruits per truss. Complete fruit removal decreased leaf photosynthesis rate by approximately 50%. Heuvelink and Buiskool (1995) described that partial fruit pruning (sink removal) did not influence canopy light utilization efficiency but partitioning of assimilates between fruits and vegetative parts was greatly affected. The effect of low sink demand (i.e. low number of fruits per truss) on reduction of photosynthetic rate in greenhouse tomato crops was attributed to accumulation of assimilates on the leaves (Tanka & Fujita, 1974; Marcelis, 1991; Qian et al., 2012).

Branches can act as semi-independent structures in terms of source/sink relations. Generally, the branches of a plant are neither fully dependent nor universally interdependent, (Watson & Casper, 1984). The branches in capsicum (Steer & Person,

1976) and groundnut (Khan & Akosu, 1971) function semi-autonomously for assimilate partitioning. Steer and Person (1976) described that the young growing fruits on the axillary branches of capsicum plant receive carbon from the main branch only in their initial development phases but, when the size of axillary branch increases, it becomes independent from the main branch and the leaves supply the carbon to the mature fruits only within the branch. Khan and Sagar (1966) studied greenhouse tomato crops and described that the first truss is a major sink for assimilates from all leaves above or below the truss and later when the fruits of the truss matures, and the leaves closest to the truss become its most important supplier.

Branching creates a denser canopy so leaf area index/effective photosynthetic capacity is influenced by the pruning and training strategies in any trellised crop. Normally, the pruning of the selected side shoots in field grown tomato crop is practiced at an early stage of growth and development in order to manipulate the plant canopy structure and increase the marketable yield. Ninemets (2007) described that the light absorption from the leaves of the plant is an important factor for determining crop yield which is mainly dependent on plant architecture and canopy structure. Ambroszczyk *et al., (*2008) described that pruning in greenhouse tomato is also important to maintain optimum leaf area index and improve light penetration inside the plant canopy to increase the photosynthetic efficiency and the crop yield. The vegetative growth associated with the side shoots in the tomato crops are also a powerful sinks of assimilates and pruning of these vegetative shoots allows diversion of assimilates to the fruits.

Research needed to address questions on photosynthetic rate, fruit maturation rate and yield in field grown tomatoes to help predict impacts of timing and type of pruning regime on crop yield and time to harvest. The objective of this research was to describe the effect of branching pattern on carbon partition and the effect of fruit load on photosynthesis in field grown trellis tomato crops.

MATERIALS AND METHODS

SITE DESCRIPTION

The research was carried out in commercial field grown tomato crops on a light sandy loam i.e. kandosol (Isbell, 2002) in Bundaberg, Australia. The Gourmet crop type was used in the experiment and the experimental site was located at - 24.98 ° latitude and 152.31 ° E longitude. The weekly weather data from transplanting to the first harvesting time of the tomato crop (transplanting weeks 26-39) was collected from Bundaberg Aero Club (Latitude - 24.89 ° and longitude152.32 ° East) in 2013 (Table 1).

Table 1: *The weekly weather data from transplanting to the first harvesting of the Gourmet tomato crop (transplanting weeks 26-39) from Bundaberg Aero Club[@] in 2013.*

2013 Transplanting Week		26	27	28	29	30	31	32	33	34	35	36	37	38	39
Temperature (°c)	Max*	21.6	23.3	22.9	24.2	22.4	24.2	25.7	26.0	24.9	26.4	25.6	28.4	30.0	29.6
	Min*	9.8	14.2	13.2	13.6	11.4	10.4	7.6	13.2	7.5	11.1	13.0	13.2	17.3	16.1
Rainfall	mm#	0.0	9.2	1.2	4.4	0.2	0.8	0.0	0.2	0.4	0.0	1.8	1.2	0.0	0.0
Relative Humidity (%)	9am	65	79	78	81	71	67	54	65	41	69	59	61	54	60
	3pm	47	67	58	61	56	50	33	47	28	42	44	45	50	56
TCSR+	MJ/h	103	102	106	110	107	125	149	149	163	160	163	165	183	189

[*] *Maximum and minimum temperature was based on mean of maximum and minimum temperature in each transplanting week respectively.*

[#] *Cumulative rainfall (mm) in each transplanting week*

[+] *Total cumulative solar radiation (TCSR) was based on the cumulative solar radiation of the days in each transplanting week.*

[@] *Justification for the use of data is given in Chapter 2*

EXPERIMENTAL DESIGN

The experiment was conducted on four, 40 meter long, rows in a commercially grown Gourmet tomato crop. The plants were closely monitored and individual plants were selected for sampling based on uniformity in flowering date. The monitoring and sampling was conducted on five replicated plots; each plot containing 20 sample plants for the control and three treatments i.e. one sample plant in each sampling date for these treatments (28, 38, 48, 58 and 64 days after flowering of the first truss). All plants were initially pruned following commercial tomato growing practices where all lateral shoots were pruned and only one side shoot below first truss of the main shoot retained. Five plants were selected for each treatment in a plot. There were three treatments and one control in the experiment and the treatments were randomised in each plot. Treatments were as follows:

- Control: No further pruning applied (C)
- Lowest lateral shoot pruned directly above the first truss on the shoot (AT). The shoot above the first truss of the side shoot below the first truss of the main shoot is pruned for this treatment.
- Lowest lateral shoot pruned below first truss position to leave only three nodes/leaves on the shoot (BT). The shoot only with three leaves is kept and pruned above it on the side shoot below the first truss of the main shoot for this treatment.
- Lateral shoot directly below the first truss of the main shoot removed (RSS). The side shoot below the first truss of the main shoot is removed for the preparation of this treatment.

METHODOLOGICAL APPROACH

The crop was monitored frequently when the plants were close to the flowering time. Three hundred plants were selected from the four rows of transplanted seedlings. These plants were selected as they all flowered (anthesis of the first flower on the first truss) at 28 days after transplanting. Commercial pruning was applied to all plants at this time.

One hundred plants from those pre-selected sample plants were selected again as the sample plants at 56 after transplanting (28 days after first truss flowering) when the flower of the first truss of the first side shoot was observed. The pruning treatments were applied at this time. The first truss on the main shoot of each plant was pruned to retail six fruit on the truss. Crop monitoring involved the assessment of a range of parameters on each sample plant.

MEASUREMENT OF THE DRY WEIGHT OF THE SHOOTS RECEIVED FROM THE PRUNING

The shoots removed by commercial pruning from 25 randomly selected plants were oven dried at 80 degrees Celsius until constant dry weight was attained and dry weight recorded. Again, the shoots removed by pruning at the time of main treatment impositions at 56 days after transplanting (28 days after first truss flowering) were also oven dried and the dry weight was recorded.

FRESH AND DRY WEIGHT OF THE FIRST TRUSS FRUIT

The first truss was harvested at different sampling times at 28, 38, 48, 58 and 64 days after flowering of the first truss of the main shoot (destructive sampling time of the first truss of the main shoot of the research trial). The first recorded fresh and dry weights of the fruits were at 22 days after flowering of the first truss of tomato and it was considered as a control treatment. All the treatments were prepared at 28 days after flowering of the first truss of the main shoot. Five plants in each treatment in a plot were randomly selected for harvesting at different sampling times and tagged as plant number 1-5. The first truss was harvested from those pre-selected sample plants and fresh weight of the first fruit and other 2-6 fruits of that truss were recorded and the fruits were kept in oven for drying at 80 degree Celsius until constant dry weight was received.

MEASUREMENT OF THE PHOTOSYNTHETIC QUANTUM YIELD OF THE LEAVES

The photosynthetic quantum yield (QY) values was measured in the leaf below first truss of the main shoot and recorded at 43, 48, 52, 57, 58, 63 and 64 days after flowering of the first truss in fifth (last) sample plant on each treatment. QY was measured using **FluorPen** (FP100-Photon System Instrument; made in Czech Republic). The quantum yields on the second leaf of the first side shoot on control, AT and BT treatment of the same plant was also measured. One treatment was added by removing all the fruit trusses of the first plant of RSS in five replications after harvesting of the first truss at 28 days after flowering to measure the quantum yield that did not have any fruits or trusses as RSS-no truss (RSS-NT).

MEASUREMENT OF THE GROWTH RATE OF THE FIRST FRUIT OF THE TRUSS

Fluctuations in the diameter of the first fruit on the first truss were recorded at 30 minutes intervals in a single plant in each treatment using stem micro-variation sensors (**PM-11Phytomonitor**). Relative humidity, air and soil temperature data were also recorded. The measurements were taken between 33 and 52 days after flowering of the first truss and recorded for analysis by using micro-variation sensors of the PM-11 Phytomonitor**.** The fruit diameter remained relatively constant at later stages of the measurement and the assessment was stopped at 52 days after flowering.

STATISTICAL ANALYSIS OF THE DATA

Statistical analysis was performed to quantify the variation in dry weight and dry matter percentage of the fruits of the first truss and quantum yield of the leaves. One way analysis of variance of dry weight of pruning shoots, harvesting day, fresh and dry weight as well as dry matter percentage of the first fruit of different treatments was performed in Minitab version 16. The analysis of variances (ANOVA) of dry weight of fruits and quantum yield at each measurement day of the treatments was also done by using one way ANOVA whereas two ways ANOVA was used to verify the differences between the measurement days of these parameters on the treatments. The comparisons of the different measured variables were performed by one way analysis of variance in Tukey’s method at 95 percent confidence interval and all the statistically significant findings are reported at $p \leq 0.05$. Analyses were also performed using R version 3.1.1. Variation in dry weight of the first and others 2-6 fruits of the first truss in different treatments and fruit diameter flux was described using exploratory co-plots and box-plots in R, followed by piece-wise regressions to describe comparative differences between fruits and dry weight in treatments. Transformation of the data was performed by square root transformation method in excel as well as by Johnson transformation in Minitab version 16 where normality assumption and homogeneity of variance of the data were violated in the study.

RESULTS

The dry weight of the pruned shoots, time to harvest of the first truss and the fresh and dry weight of the first fruit varied significantly between treatments (Table 2). The dry weight of the pruned shoots was significantly high in the RSS treatment (weight of the entire first lateral shoot) and low in the AT treatment (weight of lateral shoot above the position of the first truss on that shoot). Significant differences on fresh weight as well as dry weight of the first fruit at the time to harvest and harvesting time of the first truss between treatments show that effects on source strength and/or sink capacity were likely to have been generated by the treatments. The fresh and dry weight of the first fruit of the first truss was significantly high in RSS and BT but low in AT and Control treatments. There was no significant difference on the dry matter percentage of the first fruit at harvesting time.

Table 2: *Time to flowering & harvesting (days) after transplanting and fresh and dry weight (gram) of the first fruit of the first truss, dry weight of pruned shoot at treatment preparation and dry matter percentage of Gourmet tomato in different pruning treatments transplanted at 27th June in 2013 in Bundaberg**.** The data presented here are the mean values ± SE, which were analysed at the significant levels of $P \leq 0.05$ at Tukey,s. Values with the same letters in each vertical column represent there was no difference.*

Treatment	Flowering Day	Dry Weight (g) of Pruned Shoot	Time to Harvest	Fresh Weight(g)	Dry Weight (g)	Dry Matter (%)
Control	24	N/A	91.6 ± 0.4^{a}	137.70 ± 12.80^{b}	7.40 ± 0.49^{b}	5.4 ± 0.2^{a}
AT	24	3.19 ± 0.53^{c}	90.4 ± 1.2^{ab}	138.64 ± 5.00^{b}	7.57 ± 0.25^{b}	5.4 ± 0.1^{a}
BT	24	8.80 ± 1.35^{b}	90.0 ± 1.1^{ab}	176.91 ± 5.77^{a}	9.56 ± 0.32^{a}	5.4 ± 0.1^{a}
RSS	24	17.47 ± 1.04^{a}	87.6 ± 0.7^{b}	202.21 ± 7.58^{a}	10.54 ± 0.19^{a}	5.2 ± 0.1^{a}

DRY WEIGHT OF THE FRUIT OF THE FIRST TRUSS

The dry weight of the first fruit increased with time after flowering of the first truss (Figure 1). Dry weight increased approximately linearly until 48 days in all treatments, but the rate of increase was slightly lower in the control and BT treatments. The former treatments also increased between days 48 and 58 while the later 2 treatments displayed only a slight increase in the same time period. Growth in all treatments was low between days 58 and 64. Significant differences between treatments existed at 64 days after flowering, but there were no significant differences between treatments in the dry weight of the first fruit at sampling dates at 38, 48,and 58 days after flowering of the first truss(Table 4).

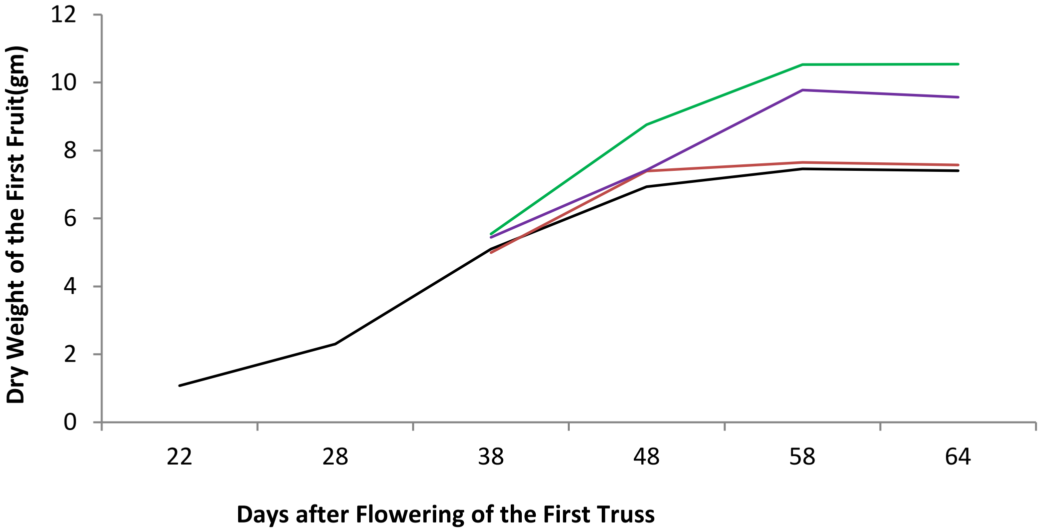


Figure 1: *The dry weight (g) of the first fruit at 22, 28, 38, 48, 58 and 64 days after flowering (DAF) of the first truss on control, AT, BT and RSS treatments on commercial Gourmet tomato crop transplanted in 2013 in Bundaberg. In the figure the legend ―― for dry weight of the first fruit on control, ―― for dry weight of the first fruit on pruning the shoot above truss of the first side shoot (AT), ―― for dry weight of the first fruit on pruning the shoot below the truss of the first side shoot (BT) and ―― for dry weight of the first fruit on removing the first side shoot below the first truss (RSS).*

The dry weight of the first fruit and the remaining 5 fruits of the first truss (2-6 fruits) varied with fruit maturity stage in the different treatments (Figure 2). Weight of the first fruit (1.07 gm) was significantly high than mean weight of the remaining 5 fruits (0.91 gm) of the first truss at 22 days after flowering (Table 4). Patterns of weight change over time varied between treatments from day 28 when treatments were imposed. The dry weight of the first fruit on BT and RSS was significantly high than other treatments at days 38, 48, 58 and 64 after flowering (Table 4) .

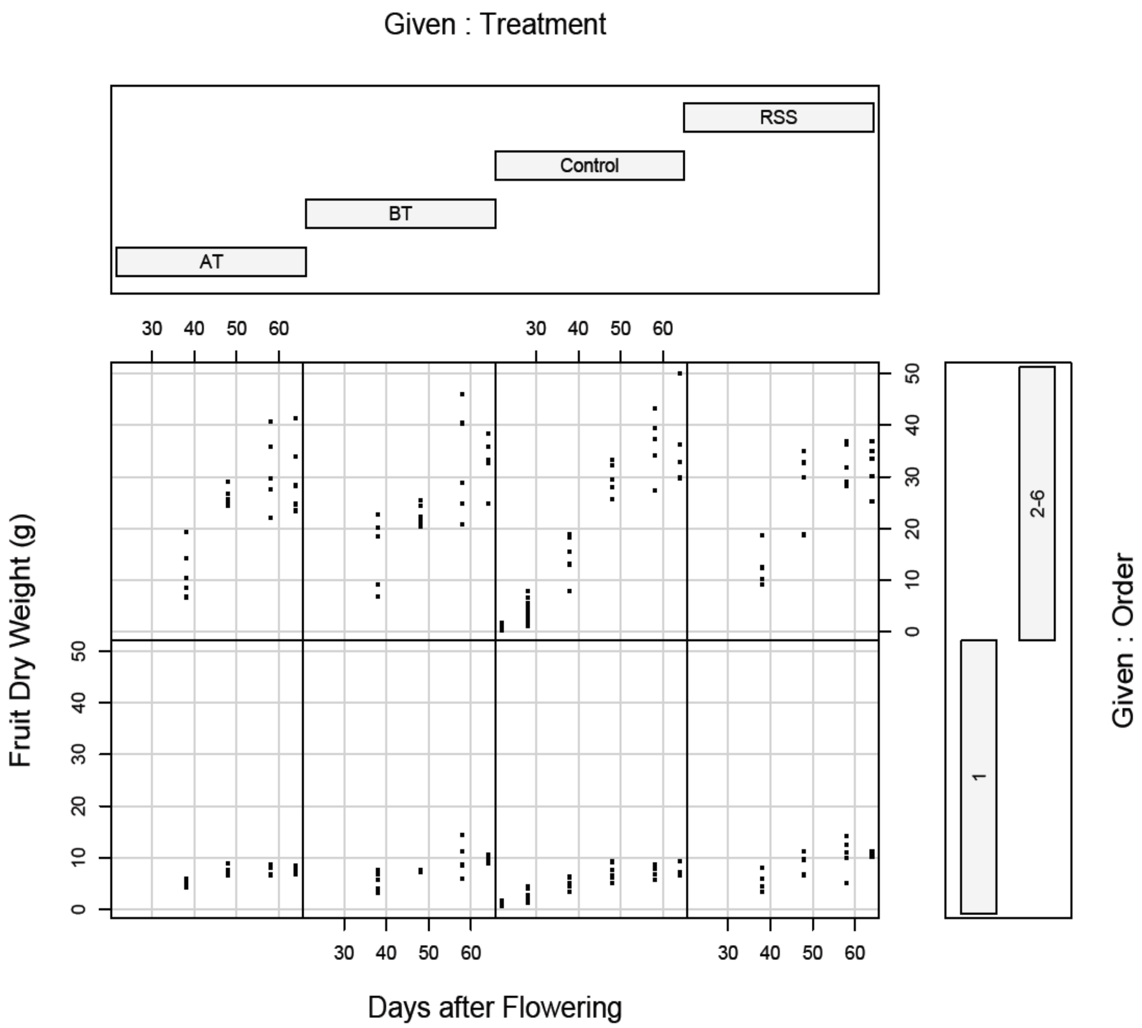


Figure 2: *Fruit dry weight (g) of the first fruit and 2-6 fruits at different days after flowering of the first truss on control, AT, BT and RSS treatments on commercial Gourmet tomato crop transplanted in 2013 in Bundaberg.*

WITHIN TREATMENT VARIATION IN FRUIT DRY WEIGHT OF THE FIRST TRUSS

The variability between plants in dry weight of the first fruit (Figure 3 A-D) and 2-6 fruits (Figure 4 A-D) of the first truss changed over time in the control and different treatments. The coefficient of variation (CV) of dry weight of the fruits was also highly variated at 38, 48, 58 and 64 days after flowering (destructive sampling time of the first truss of the main shoot of the research trial) in the control and other treatments (Table 3). The coefficient of variation of dry weight of first fruit was lower at ripening time of the fruits at 64 days after flowering of the first truss in all treatments except in BT at 48 days after flowering. The lowest and highest coefficient of variation of dry weight of first fruit and 2-6 fruits of the first truss was in BT at 48 and 38 days after flowering of the first truss respectively.

Table 3: *The coefficient of variation(CV) of dry weight(gm)of the first fruit and 2-6 fruits of the first truss at different destructive sampling days after flowering of the first truss in control and other treatments in commercial Gourmet tomato crops transplanted at 27th June in 2013 in Bundaberg.*

	The CV of the dry weight of the first fruit of the truss				The CV of the dry weight of the 2-6 fruits of the truss			
Treatments	38 DAF*	48 DAF*	58 DAF*	64 DAF*	38 DAF*	48 DAF*	58 DAF*	64 DAF*
Control	23.80	22.94	16.00	15.05	30.30	10.34	16.49	23.47
AT	12.12	12.05	11.95	7.61	42.33	7.34	23.27	24.24
BT	33.65	1.09	32.57	7.67	45.37	9.23	33.23	15.53
RSS	30.76	23.47	32.78	4.18	29.45	28.74	12.28	14.36

* Days after flowering (DAF) by destructive sampling of the first truss for the dry weight (gm) of the fruits

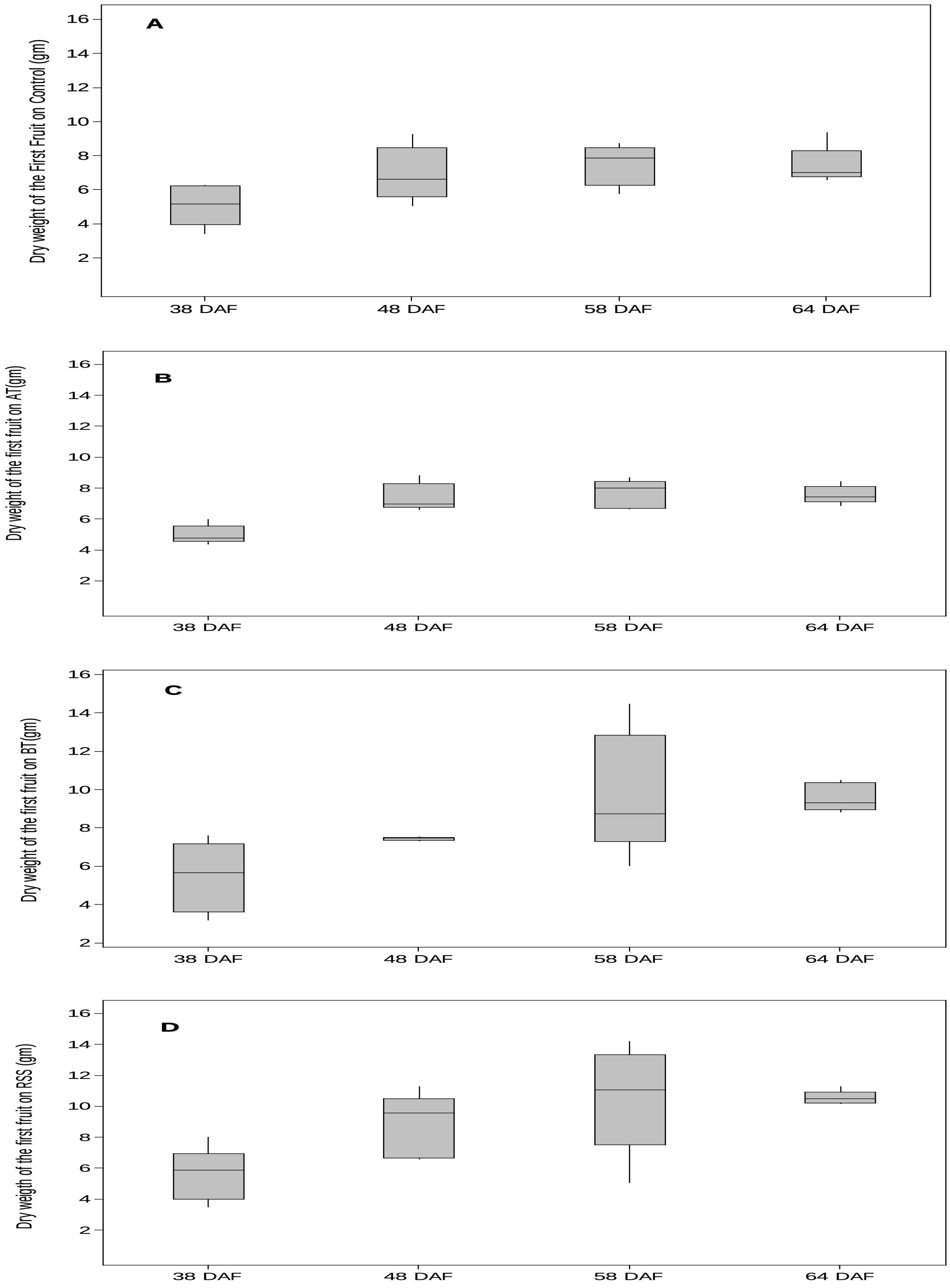


Figure 3: *Variation on dry weight of the first fruit of the first truss at 38 ,48, 58 and 64 days after flowering (DAF) by the destructive measurement of Gourmet tomato on Control (A), AT (B), BT (C) and RSS (D) treatments transplanted in 2013. Median values are indicated by the solid black line and box lower and upper boundaries are the 25thand 75thpercentiles.*

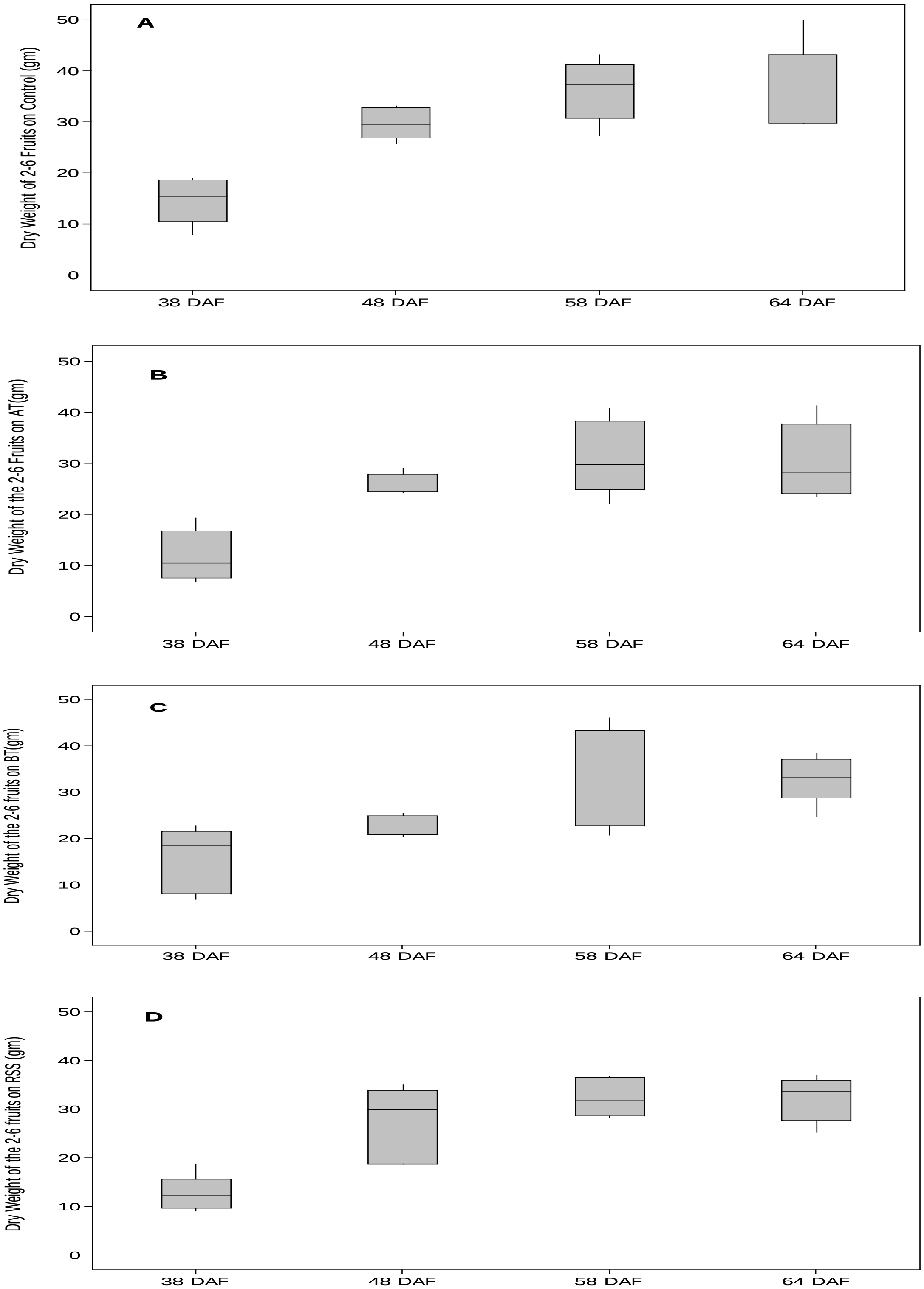


Figure 4: *Variation on dry weight of the 2-6 fruits of the first truss at 38, 48, 58 and 64 days after flowering (DAF) by the destructive measurement of Gourmet tomato on Control (A), AT (B). BT (C) and RSS (D) treatments transplanted in 2013. Median values are indicated by the solid black line and box lower and upper boundaries are the 25th and 75th percentiles.*

DRY WEIGHT AND DRY MATTER OF THE FRUIT

The dry weight and dry matter percentage of the fruits of the first truss was measured at different distructive days of sampling at 22, 28, 38, 48, 58 and 64 days after flowering (DAF; Table 4). It was significantly higher at 22, 28 and 38 days after flowering of the truss in the control treatment but no significant at 48, 58 and 64 days after flowering. It was also significantly different in the AT treatment at 38 and 48 days after flowering but not significantly different at 58 and 64 days after flowering. The dry weight of the first fruit and average of 2-6 fruits of the first truss in BT treatment was also significant only at 48 and 64 days after flowering but no significant differences at 38 and 58 days after flowering. The dry weight of the first fruit was always significantly higher than mean fruit weight of the remaining fruit on the first truss at 38, 48, 58 and 64 days after flowering in the RSS treatment. There was no significant different on the dry matter percentage of the tomato fruit for all treatments at 38, 48, 58 and 64 days after flowering (DAF). Two –way analysis of ANOVA table of dry weight of first fruit, 2-6 fruit and the truss is given in Appendix (Table 29-31).

Table 4: *The dry weight (g) and dry matter percentage of the first fruit and average of 2-6 fruits of the first truss of Gourmet tomato (Mean ± SE) at 22, 28,38,48,58 and 64 days after flowering on Control, AT, BT and RSS treatments transplanted in June 2013 in Bundaberg. The data presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the small same letters in each vertical column at each sampling days represent there was no difference and markings with the capital same letters in each row of the respective treatments at each sampling time represent there was no difference.*

Day	Treatment	Dry weight(g)			Dry matter (%)		
		1st fruit	Average of 2-6 fruits	Truss weight	1st fruit	Average of 2-6 fruits	Truss
22 DAF	Control	1.07 ± 0.21A	0.18 ± 0.06B	1.99 ± 0.38	5.6 ± 0.1	5.3 ± 0.4	5.5 ± 0.1
28 DAF	Control	2.30 ± 0.20A	0.74 ± 0.08B	6.04 ± 0.53	5.9 ± 0.1	6.0 ± 0.1	6.0 ± 0.1
38 DAF	Control	5.09 ± 0.53Aa	2.94 ± 0.39Ba	19.83 ± 2.02a	5.5 ± 0.0a	5.8 ± 0.0a	5.7 ± 0.0a
	AT	4.99 ± 0.27Aa	2.36 ± 0.44Ba	16.82 ± 2.25a	5.5 ± 0.0a	5.7 ± 0.0a	5.6 ± 0.0a
	BT	5.44 ± 0.81Aa	3.10 ± 0.62Aa	20.97 ± 3.88a	5.6 ± 0.1a	5.8 ± 0.1a	5.7 ± 0.1a
	RSS	5.54 ± 0.76Aa	2.51 ± 0.33Ba	18.13 ± 2.02a	5.5 ± 0.1a	5.6 ± 0.1a	5.6 ± 0.1a
48 DAF	Control	6.93 ± 0.71Aa	5.91 ± 0.27Aa	36.67 ± 1.78a	5.8 ± 0.3a	4.9 ± 0.1a	5.1 ± 0.0a
	AT	7.40 ± 0.39Aa	5.21 ± 0.17Ba	33.46 ± 0.68a	5.8 ± 0.2a	5.0 ± 0.1a	5.1 ± 0.1a
	BT	7.42 ± 0.03Aa	4.54 ± 0.18Ba	30.14 ± 0.94a	5.3 ± 0.1a	4.7 ± 0.0a	4.8 ± 0.0a
	RSS	8.76 ± 0.91Aa	5.40 ± 0.69Ba	35.79 ± 3.76a	5.4 ± 0.1a	5.0 ± 0.0a	5.1 ± 0.0a
58 DAF	Control	7.46 ± 0.53Aa	7.25 ± 0.53Aa	43.74 ± 2.64a	5.7 ± 0.0a	5.2 ± 0.3a	5.2 ± 0.2a
	AT	7.65 ± 0.40Aa	6.24 ± 0.64Aa	38.85 ± 3.08a	5.5 ± 0.2a	5.4 ± 0.2a	5.4 ± 0.2a
	BT	9.78 ± 1.42Aa	6.42 ± 0.95Aa	41.90 ± 5.16a	5.6 ± 0.3a	5.0 ± 0.3a	5.1 ± 0.2a
	RSS	10.53 ± 1.54Aa	6.48 ± 0.35Ba	42.94 ± 3.08a	5.1 ± 0.1a	5.0 ± 0.0a	5.0 ± 0.0a
64 DAF	Control	7.40 ± 0.49Ab	7.15 ± 0.75Aa	43.20 ± 3.62a	5.4 ± 0.1a	5.0 ± 0.0a	5.0 ± 0.0a
	AT	7.57 ± 0.25Ab	6.06 ± 0.65Aa	37.91± 3.28a	5.4 ± 0.0a	5.0 ± 0.0a	5.1 ± 0.0a
	BT	9.56 ± 0.32Aa	6.59 ± 0.45Ba	42.52 ± 2.21a	5.4 ± 0.1a	4.9 ± 0.0a	5.0 ± 0.0a
	RSS	10.54 ± 0.19Aa	6.42 ± 0.41Ba	42.68 ± 1.97a	5.2 ± 0.0a	4.9 ± 0.0a	5.0 ± 0.0a

DAF = Days after flowering of the first truss

QUANTUM YIELD OF THE LEAVES

The quantum yield of the leaf below the first truss on the main shoot displayed few significant differences between treatments and measurement dates (Figure 5). It tended to be higher at 52 and 57 days after flowering than at other time. The claim was approved by analysing two-way ANOVA (Table 4 A). It was found significant at all sampling dates and quantum yield of the treatments. There was no significant difference in the quantum yield at 43, 48, 52, 57 and 58 days after flowering of the first truss, but there was a trend towards lower values in the RSS and RSS-NT treatments than in the other treatments. The differences between sampling time in quantum yield of the leaf below first truss of the main shoot were statistically significant only at 63 and 64 days after flowering of the truss. The quantum yield was also significant between the measurement days and different treatments. The top pruning of the vegetative shoots in this commercial crop was done at 58 days after flowering of the first truss by the growers.

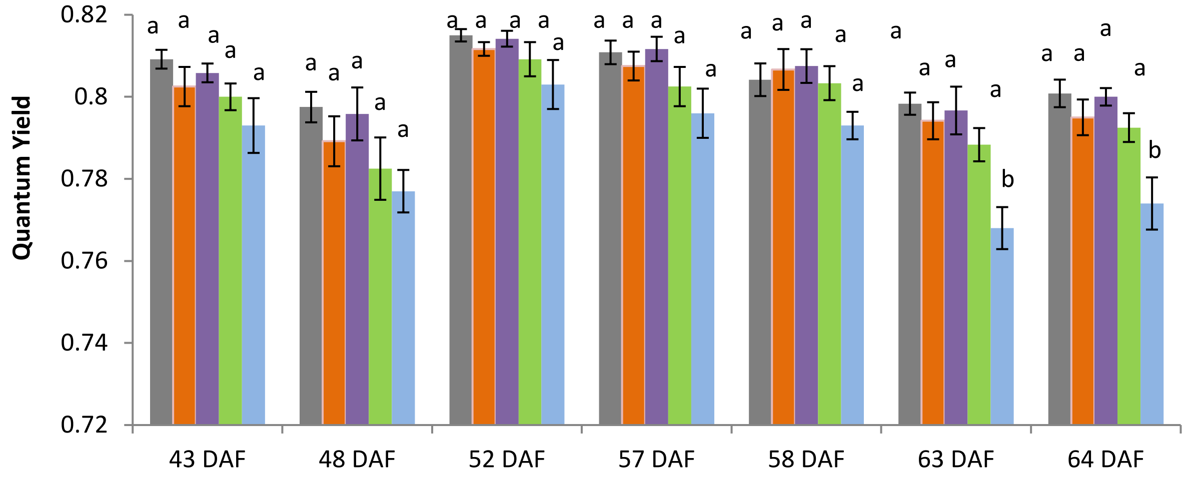


Figure 5: *Quantum yield on the leaves below first truss measured at 43, 48, 52, 57, 58,63 and 64 days after flowering on Gourmet tomato crops transplanted in 2013, Bundaberg. In the figure, the legend ▬ for quantum yield of the leaf on control, ▬ for quantum yield of the leaf on AT, ▬ for quantum yield of the leaf on BT, ▬ for quantum yield of the leaf on RSS and ▬ for quantum yield of the leaf on RSS-NT. The figure presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Columns with the same letter above then do not differ within sampling time.*

Table 4 A: Two-way analysis of ANOVA table of quantum yield on the leaves below first truss measured at 43, 48, 52, 57, 58, 63 and 64 days after flowering (DAF) on Control, AT, BT, RSS and RSS-NT on Gourmet tomato transplanted in Bundaberg, 2013.

Source	DF	SS	MS	F	P
Treatments	4	0.0016626	0.0004157	35.89	0.000
DAF	6	0.0022859	0.0003810	32.90	0.000
Error	24	0.0002779	0.0000116		
Total	34	0.0042264			

S = 0.003403   R-Sq = 93.42%   R-Sq(adj) = 90.68%

The quantum yield of the middle leaf on the lateral shoot below first truss of the main shoot did not vary significantly between treatments and sampling times (Figure 6). The treatments had no effect on photosynthesis on the middle leaf of the side shoot below first truss of the main shoot in field grown trellis tomato crops.

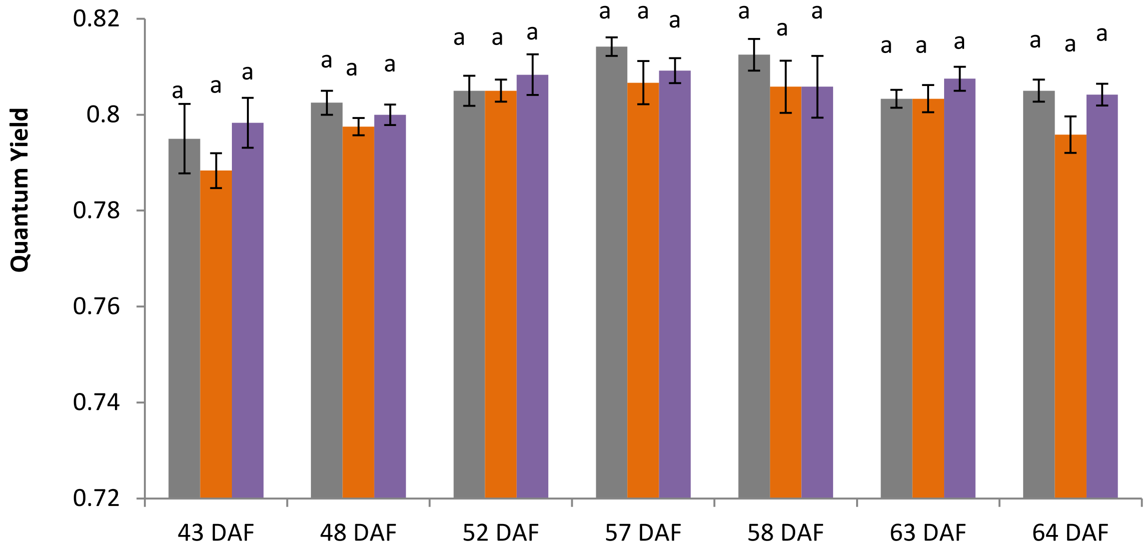


Figure 6: *Quantum yield on the middle leaves below first truss of the first side shoot measured at 43, 48, 52, 57, 58,63 and 64 days after flowering (DAF) on Gourmet tomato crops transplanted in 2013, Bundaberg. In the figure the ▬ for quantum yield of the leaf on control, ▀ for quantum yield of the leaf on AT, ▬ for quantum yield of the leaf on BT. Figure presented here are the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Columns with the same letter above them do not differ within sampling time.*

RATE OF FRUIT EXPANSION

The rate of fruit diameter increase of the first fruit varied between the treatments (Figure 7). The fruit diameter was significantly higher in RSS than other treatments. The rate of fruit expansion was lowest in the Control treatment. The first fruit of the first truss attained a maximum value on the18th day of the measurement (51 days after flowering).

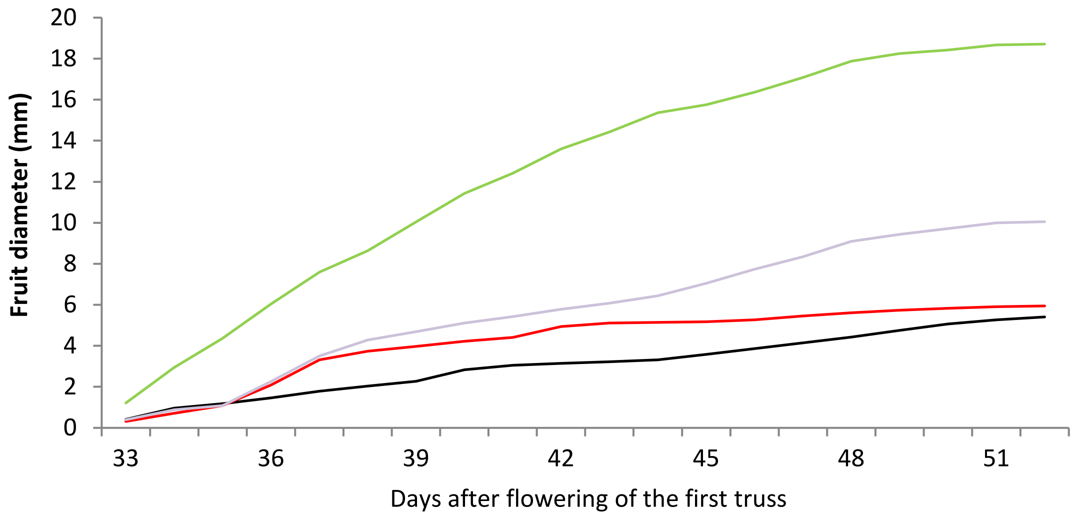


Figure 7: *The fruit diameter (mm) of the first fruit in 33- 52 days after flowering of the first truss of Gourmet tomato crops transplanted in 2013, Bundaberg. In the figure the legend —— for control, —— for pruning the shoot above truss of the first side shoot (AT) —— for pruning the shoot below the truss of the first side shoot (BT) and —— for removing the first side shoot below the first truss (RSS).*

The variation in the rate of fruit diameter expansion was linked to weather conditions and stage of fruit development (Figure 8-10). The pattern of fruit growth involved a period of shrinkage around mid day and expansion in the night. Shrinkage most likely corresponded to plant water status with high transpiration rate during the morning leading to low plant water potential and movement of water out of the fruit, and stomatal closure when water potential reached a critical level then allowed water uptake to exceed water loss so fruit expansion could recommence. The rate of shrinkage in fruit diameter was lower at 33-37 days after flowering (Figure 8) than in to 40- 52 day intervals after flowering (Figure 9-10).

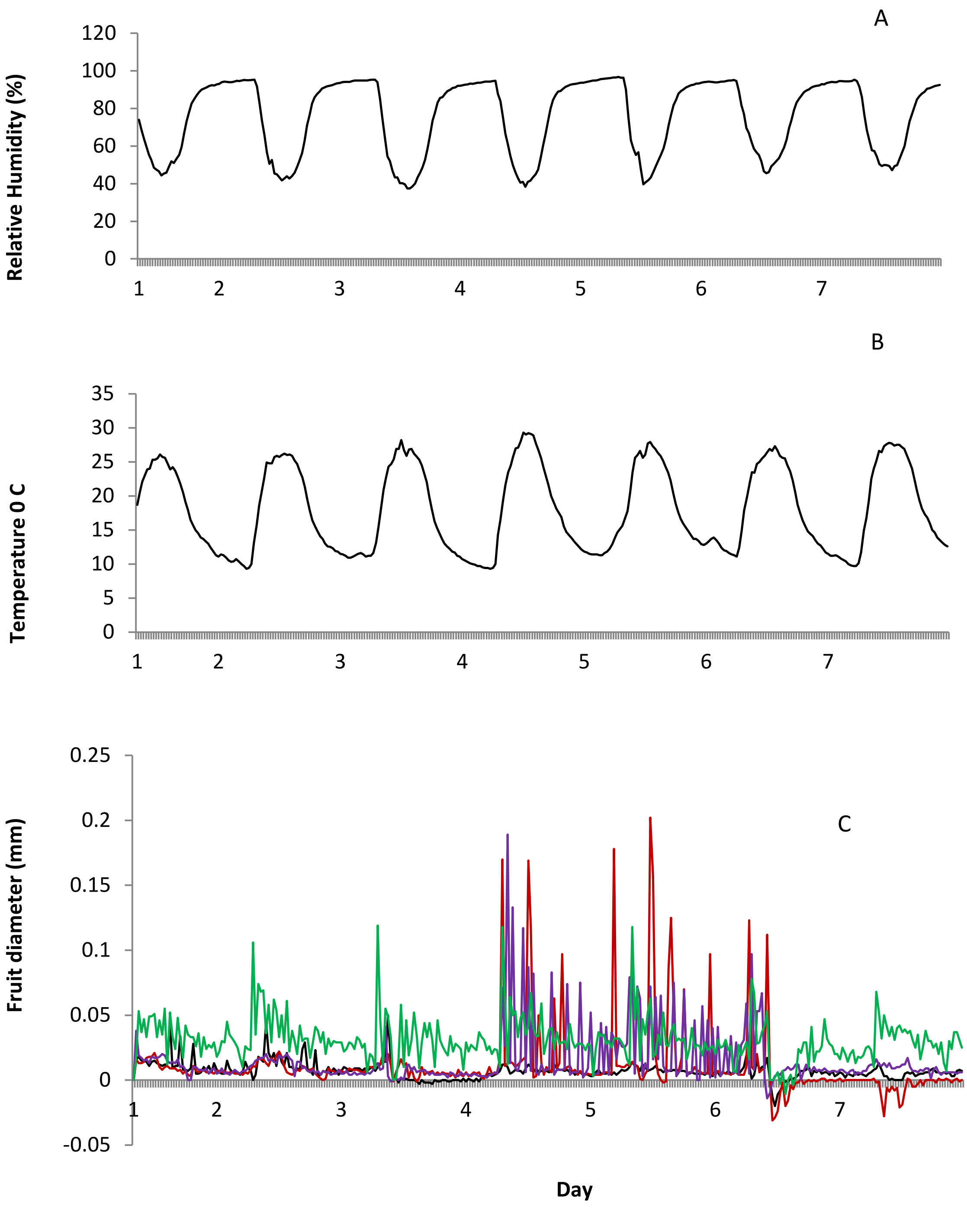


Figure 8: *Relative humidity (A), temperature (B) and the fruit diameter (C) in every thirty minutes in a week from 33-39 days after flowering (1 to 7 in x-axis respectively) of the first fruit of the first truss on control, AT, BT and RSS treatments on commercial tomato crop transplanted in 2013 in Bundaberg. In the figure the legend —— for control, —— for pruning the shoot above truss of the first side shoot (AT), —— for pruning the shoot below the truss of the first side shoot (BT) and —— for removing the first side shoot below the first truss (RSS).*

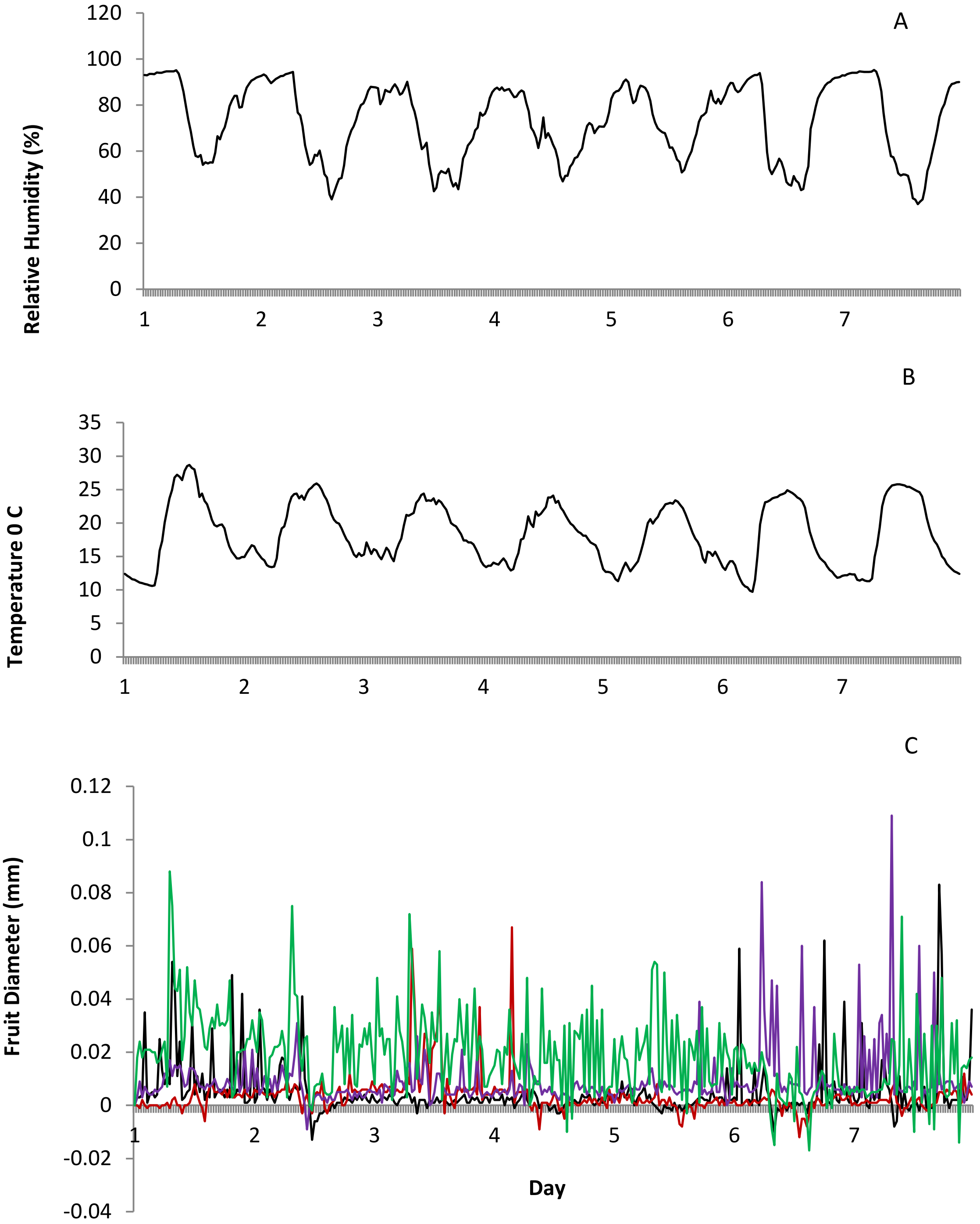


Figure 9: *Relative humidity (A), temperature (B) and the fruit diameter (C) in every thirty minutes in a week from 40-46 days after flowering (1 to 7 in x-axis respectively) of the first fruit of the first truss on control, AT, BT and RSS treatments on commercial tomato crop transplanted in 2013 in Bundaberg. In the figure the legend —— for control, —— for pruning the shoot above truss of the first side shoot (AT) —— for pruning the shoot below the truss of the first side shoot (BT) and —— for removing the first side shoot below the first truss (RSS).*

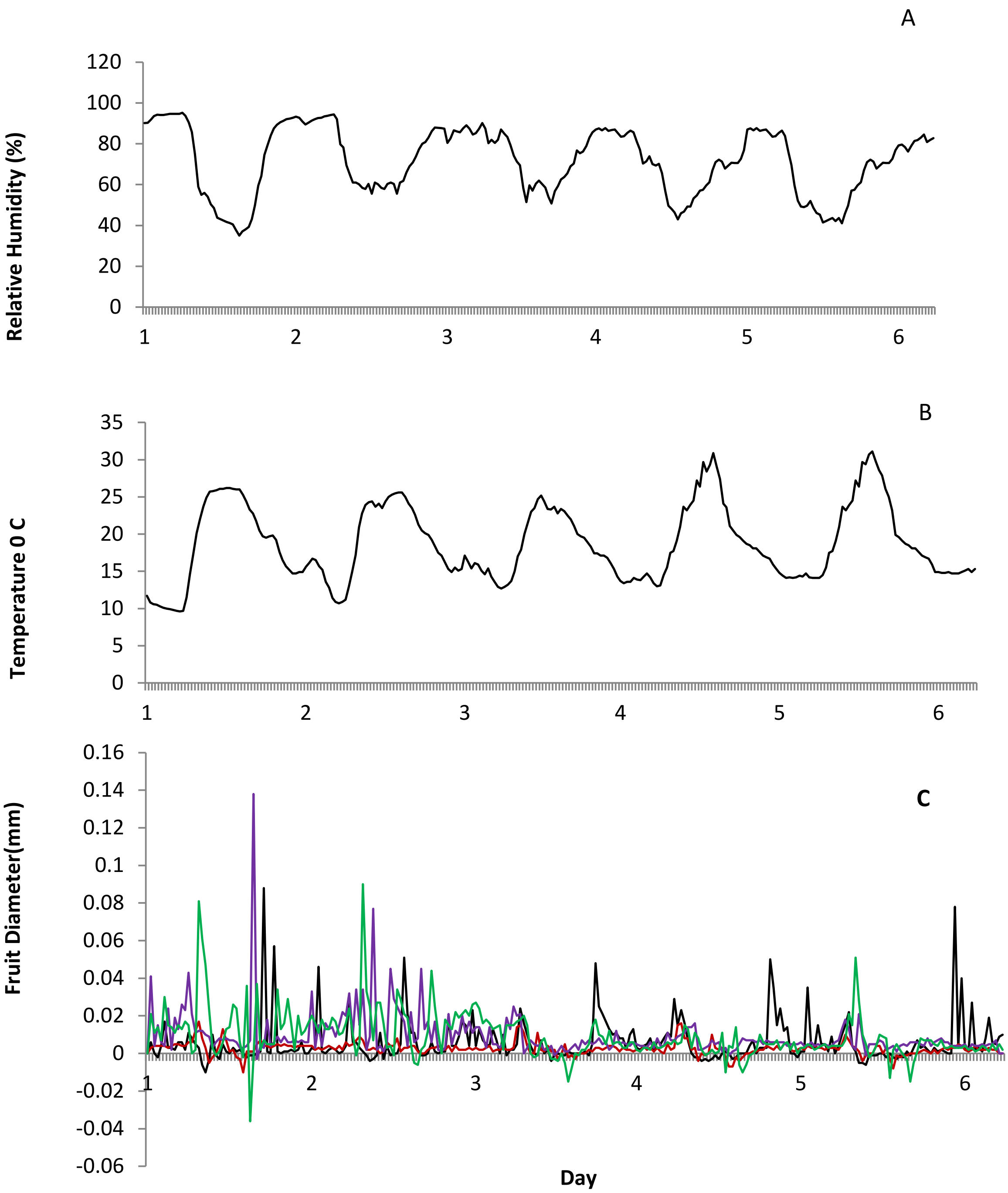


Figure 10: *Relative humidity (A), temperature (B) and the fruit diameter (C) in every thirty minutes in a week from 47-52 days after flowering (1 to 6 in x-axis respectively) of the first fruit of the first truss on control, AT, BT and RSS treatments on commercial tomato crop transplanted in 2013 in Bundaberg. In the figure the legend —— for control, —— for pruning the shoot above truss of the first side shoot (AT), —— for pruning the shoot below the truss of the first side shoot (BT) and —— for removing the first side shoot below the first truss (RSS).*

The variation of total fruit diameter expansion (Figure 11 A) at 48 hours period was rapid in AT, BT and RSS treatments only at nine days after pruning i.e.37 days after flowering time of the first truss. The variation of the rate of expansion of the fruit diameter at each 30 minutes interval was observed at 48 hours period at 37 days after flowering time of the first truss (Fig 11B).

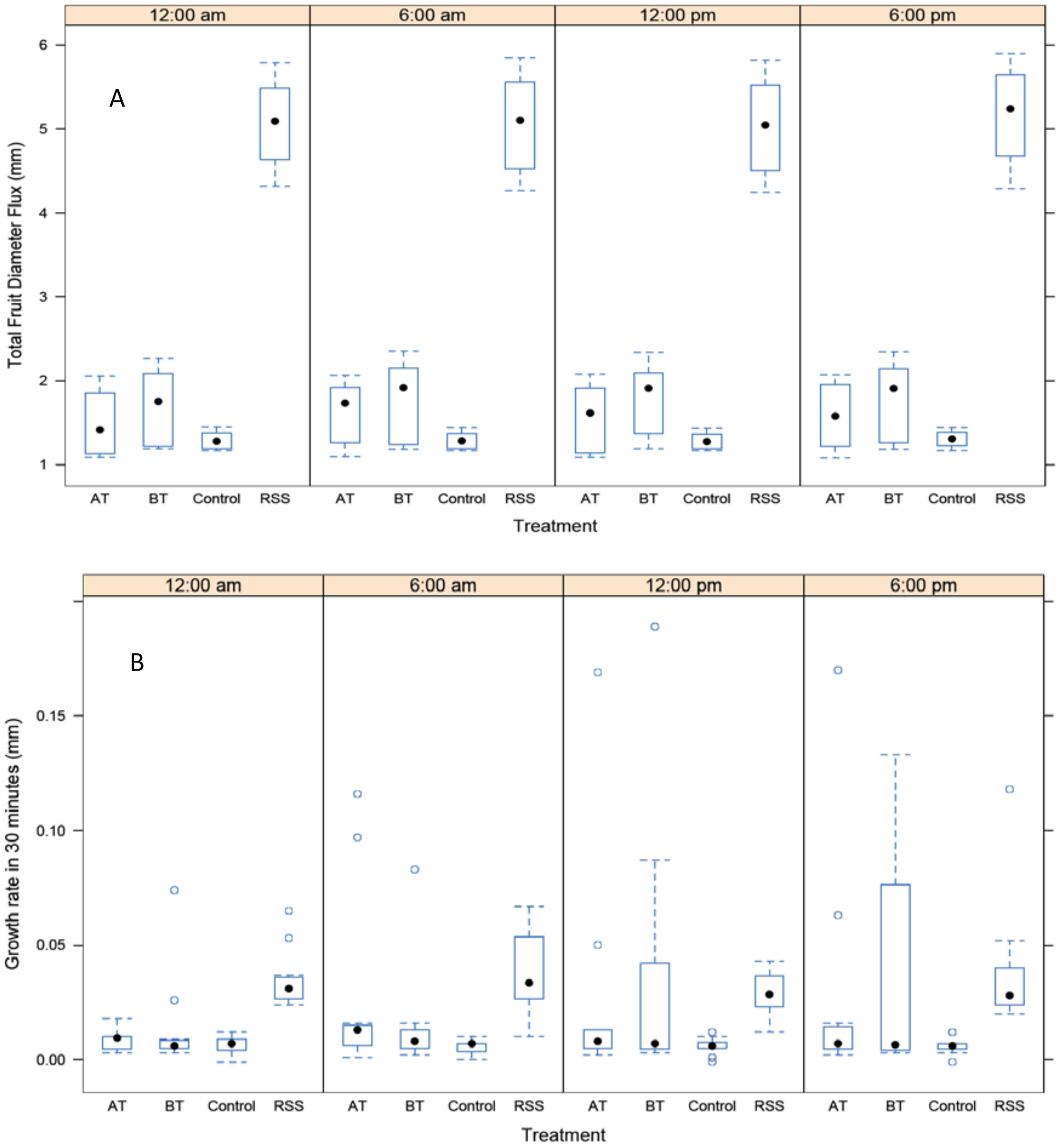


Figure 11: *The variation of total fruit diameter expansion (A) and growth rate of fruit diameter expansion at each thirty minutes interval (B) of different treatments at 28th August (nine days after pruning treatments imposed) i.e. at 37 days after flowering of the first truss on Gourmet tomato transplanted in 2013, in Bundaberg*

DISCUSSION

A considerable variability of fruit growth and photosynthesis between control and other treatments were recorded in the research trial described in this chapter. The treatments imposed in the trial influenced fruit growth rate and size, demonstrating that factors that influence assimilate partitioning have the potential to affect harvest timing and marketable yield and consistent results were observed by pruning treatments on fruit weight of the first truss and first harvesting time reported in an earlier research chapter. The different branching patterns of field grown tomato were observed to have a significant effect on assimilate partitioning to the fruits only at the maturity stages of the first fruit on the crops that pruned heavily and also on time to first harvest. The different pruning treatments had no significant impact on the photosynthesis rate of the plants but the removal of all fruit and top growing vegetative shoots from the plants induced a significant decrease in photosynthetic quantum yield.

The research result indicates that pruning treatments imposed in the trial influenced significantly the distribution of assimilates to the proximal fruit of the first truss and also promoted earlier maturity of the fruit. Although fruits and the growing shoots on all branches and main shoot are the major sink organs in field grown tomato plants, but leaves, stems, and roots also utilize assimilates and have a sink strength; hence leaves are not only source organ but also sink organ. The removal of the truss and vegetative growing point on the lowest lateral shoot (treatment BT) and removal of the entire lateral shoot (treatment RSS) reduced these sink organs in the vicinity of the first truss on the main shoot, theoretically resulting in less competition for assimilates compared to other treatments. These treatments induced the greatest dry matter partitioning to the first fruit on the main stem truss, but did not increase partitioning to the other fruit in the truss. The earlier harvesting time of the first truss due to heavy pruning of the field grown tomato crops was also consistent with the results presented in the earlier research chapter of this thesis. The early harvesting of tomato fruits due to the increased assimilate partitioning was also found by Sikes and Coffey (1989), De Koning (1989) and Richardson (2012). Although the result suggests that first fruit, i.e. proximal fruit of the truss, showed sink dominance for assimilate compared to distal fruits in the treatments in the initial stages of fruit growth but at the stage of fruit maturity and harvesting time it was only significant in BT and RSS indicating the effect of higher source-sink ratio of the plant due to pruning. The dominant effect of proximal fruit relative to distal fruit of a truss at the certain positions on the plant in greenhouse tomato was also observed by Bertin, 1995.

The dry matter distribution in the plant is mainly regulated by the sink themselves according to the generally accepted assumption in mechanistic models of dry matter distribution (Marcelis, 1994). Additional branches from the axils of the leaves on main shoot and on side shoots increases the number of shoots and fruit truss sink organs leading to greater competition for assimilate in field grown tomato crops. The sink strength of a field grown tomato plant is composed of sink strengths of all individual organs but fruit trusses are the main sink compare to others as in greenhouse tomato crops (De Koning & De Ruiter, 1991). The pruning treatments BT and RSS in this trial removed the significant amount of sink organs from the plants and balance the source-sink ratio on the tomato that regulates the carbon status of the plants (Osoria et al., 2014) accelerating first harvesting time of the crops. The pruning strategy to maintain optimum source-sink ratio in tomato was also explained in greenhouse tomato crops to be 0.5 (De Koning, 1994; Boote et al., 2012) where all the lateral shoots were pruned at 7-14 days intervals (Navarrete & Jeannequin, 2000) so that total vegetative sink strength was constant (Kano & Van Bavel; 1988) and leaf area index maintained at 2-3 $m^2.m^{-2}$ with the resulting light interception considered optimum for maximum production (De Koning, 1996a; Ho, 1996; and Ambrosszczyk et al., 2008).

The high variation on the distribution of assimilates to the first and other fruits at different stages of fruit growth in control and all treatments also explained that field grown tomato is highly source limited after development of fruiting trusses. The result was also consistent to the finding of the greenhouse tomato crops where the tomato plants at early stage under high irradiance is sink limited but during fully fruiting stage it is source limited (Li et al., 2015). The source–sink balance of a plant varies significantly during its life span because of the continuous organ initiation and development which affects both the sink and source strength of field grown tomato, and similar research result was also found by Wardlaw (1990) in greenhouse tomato. A high residual variability in fruit weight is not explained either by the fruit potential or by

its seed content, and may relate to internal regulations of the plant in response to the source-sink balance during crop development. Dynamic models able to simulate this pattern may help in developing approaches for the control of fruit weight variability (Bertin, 1995; Bertin et al., 1998). The variability of growth and development in field grown tomato crops was also explained by Philip (2013) due to frequent fluctuation of temperature in the cropping period. The result also showed that the temperature and relative humidity influenced the variation in dry matter partitioning of the fruits i.e. fruit shrinkage in midday and expansion at mid night due to water loss and carbon flux respectively. The similar research of fruit expansion was also explained by Bussières (2003) where the water import in the fruit is based on the values of various parameters of the stem, the fruit pedicel, the fruit calyx and the fruit and one important parameter is the fruit pedicel phloem conductivity. The phloem conductivity is an increasing function of the fruit size, probably due to the increasing size of elements of the sieve tubes in the pedicel phloem.
As the conductivity of a tube in which a liquid flow increases when the liquid viscosity decreases, and as the viscosity decreases when the temperature increases (Bussieres, 2003). Heuvelink (1995) also found that the dry matter partitioning to the individual fruit was double if fruit numbers in a truss was kept one instead of seven but total dry matter partitioning to the truss did not vary when either two or seven fruit were retained on the truss (Heuvelink, 1997). This indicates that the sink organs of tomato plant are source limited and potential growth of a single fruit depends on competition for assimilate within the sink organs. The increase of dry weight of single fruit at reduced number of fruits on each plant due to less competition for carbon among fruits was also found in greenhouse tomatoes (De Koning, 1994) and cucumber (Marcelis, 1993b). Therefore, further research is necessary in field grown tomato on plant architecture and canopy structure for optimum level of source-sink ratio to divert assimilate on fruit yield from its carbon pool as in greenhouse tomato where the distribution of dry matter to the fruits was around 64% and remaining dry matter distributed to the vegetative sink organs at a fixed ratio (7:3) to the leaves and stem (Heuvelink, 1997).

The research result in this pruning trial had indicated that the branching structure in field grown tomato affects dry matter distribution to the vegetative and generative sink organs in the plant, influencing fruit maturity and first harvesting time of the crops. While it is likely that branches of a plant work as semi-independent structures in terms of source/sink relations and are neither fully dependent nor universally interdependent (Watson & Casper, 1984), the assimilate produced in the leaves of each branch may not be only utilize locally. It appears likely that assimilate may be utilized locally at varying percentages at different growth stages and distributed to the different sinks organs within the plant when localised sink activity is low based on the data from literature reviews. Some researchers have concluded that a truss and the three leaves below it act as a sink-source unit and assimilate produced in the leaves are preferably supplied to the truss. It has also been asserted that the distribution of assimilates in a greenhouse tomato plant is localized (Ho & Hewitt, 1986) in a source-sink unit of a truss and three leaves below it (Tanaka & Fujita, 1974).

Assimilates produced in leaves on the branches or main shoot in field grown tomato plants translocate to different parts of the plant. The result showed that there was no significant differences on dry weight of the fruits of the first truss in control and other treatments at different stages of fruit growth that indicates the distribution of assimilates from one common pool in the field grown tomato plants. There are many research works that support the assumption that one common assimilate pool for dry matter distribution to different sinks in the plant exists and the assumption of no transport resistance in the phloem or limited influence of distance between sources and sink. The amount of carbon per unit area that is exported mainly depends on the carbon pool of the plant (Nishizawa et al., 2009). Heuvelink (1997) found that there was no effect on the distribution of dry matter to the vegetative and generative sink organs with the fruit loads whether in one shoot or in both shoots in greenhouse tomato plant. This finding is consistent with the dry matter partitioning in different branching patterns of field grown semi-determinate tomato in this experiment. Andriolo et al., (1998) also found that fruit position did not affect dry matter distribution to the sinks in tomato, supporting the one common pool of assimilate circulating freely in the plant. De Koning, (1994); Heuvelink & Marcelis (1989); Jones et al., (1991) also found that the sink organs of the tomato plant receive assimilate from one common assimilate pool; in their mechanistic models of simulation of dry matter partitioning. Schapendonk and Brouwer (1984) found that increasing the distance between sources and sink organs had no impact on fruit growth in cucumber. Wardlaw (1990); and Farrar (1992) also explained that the phloem in the plant itself does not limit the translocatory flux. The result of this experiment and research work described by other researcher supports the conclusion of one common assimilates pool for dry matter partitioning even in semi-determinate tomato plants.

Although the result of this experiment and other research work clearly explained the distribution of assimilate from one common assimilate in tomato, but there was also evidence of translocation of assimilate from the leaves to closest proximal fruit of the truss only at fruit maturity stage at treatments BT and RSS in this experiment. The assimilate produced in the nearby leaves of the first truss of the main shoot and dry weight of the first fruit i.e. proximal fruit of the first truss in the experiment was significant only after top shoot pruning that indicates the utilization of assimilates locally. The result was also consistent to greenhouse grown pepper plants where the leaf photosynthesis capacity of the nearby leaf in fruit shoot is mainly driven by the sink demand of the most proximal fruit (Gonzalez-Real et al., 2009), and also explained in apple tree (Hansen, 1967; 1969) and other tree plants (Urban et al., 2003). The utilization of assimilates locally in greenhouse tomato was also explained by Khan and Sager (1966) that the first truss is a major sink for assimilates from all leaves above or below the truss and later when it matures, the leaves closest to the truss become its most important supplier. The translocation pattern of assimilates is not always static (Watson & Casper, 1984) but changes over the different stages of growth and development of the plant (Marquis, 1996). Preston (1998) found that the integration pattern of assimilate translocation declined and sectorial pattern increased during fruiting when assimilate demand at each axillary branch or node was high. The removal of all fruits from the plants in commercial field grown tomato crops is not practiced, therefore, further detailed research is required to investigate the translocation and distribution of assimilate in field grown tomato at different stages of the vegetative or generative growth and development period through one assimilate pool to all the sink organs and or preferentially localize distribution from source leaves to the close sink organs.

The fruit loads varied in the control and pruning treatments applied in the commercial field grown tomato due to removal of fruit trusses from the side shoot but did not have any significant impact on leaf photosynthetic quantum yield except in the most severe pruning regime. The effect was significant with removal of all the generative sink organs. Even the fruitless plants had similar assimilate production before top pruning due to partitioning of assimilate to vegetative sinks i.e. new growing shoots from the axils of the leaves of the branches and main shoot. The result was in contrast to that observed with greenhouse tomato where higher fruit load increases the photosynthesis capacity of the plants (Tanka & Fuzita, 1974; Marcelis & Heuvelink, 1990) and even complete fruit removal decreased leaf photosynthesis rate by 50% (Tanka & Fujita, 1974). The result also showed that the fruits had no significant impact in photosynthesis rate in nearby leaves of the fruit trusses of the main shoot and the first side shoot below first truss in control and treatments. This may be due to the growth and development of vegetative sink organs from the axil of the leaves of the main and side shoots. The photosynthesis rate of the nearby leaves of the fruit truss in this experiment was contradictory to the research published for pepper plants (Gonzalez-Real et al., 2009), in apple tree (Hansen, 1967; 1969) and other tree species (Urben et al., 2003).

Fruit loads did not appear tohave any effect on photosynthesis rate, even following complete removal of fruit trusses before top shoot pruning at 58 days after flowering of the first truss, indicating no feedback mechanism was operating. This may be due to the growth and development of vegetative sink organs from the axil of the leaves of the main and side shoots. The result contradicts the findings in greenhouse tomato crops where low sink demand or low numbers of fruits per truss reduces photosynthesis rate of the leaves due to partititioning of assimilates to the leaves (Tanka & Fujita, 1974; Marcelis, 1991; and Qian et al., 2012). Top vegetative shoot pruning in field grown trellis tomato crops is normally practiced a few days before harvesting time to increase fruit size by diverting assimilate from vegetative sink organs to generative sink organs. Pruning to divert assimilate from vegetative to generative sink organs in green house tomato crops was also explained by Xiao et al., (2004) with removal of young leaves which compete as sinks with developing fruit. The removal of all lateral shoots from tomato plants grown in greenhouse and the production of about three leaves and a truss every week (De Koning, 1994) makes it easier to predict the harvesting time and yield of the crops given the constant partitioning ratio of assimilate to the generative and vegetative sink organs whereas it is difficult to maintain an optimum source-sink ration due to the complex branching patterns in field grown tomato crops. Further detailed study on branching patterns in field grown tomato is necessary to maintain an optimum source-sink ratio that helps for predicting time of first harvest and yield of the crops.

The variation in the rate of fruit diameter expansion was linked to weather conditions and stage of fruit development (Figure 8-10). The pattern of fruit growth involved a period of shrinkage around mid day and expansion in the night. Shrinkage most likely corresponded to plant water status with high transpiration rate during the morning leading to low plant water potential and movement of water out of the fruit, and stomatal closure when water potential reached a critical level then allowed water uptake to exceed water loss so fruit expansion could recommence. The rate of shrinkage in fruit diameter was lower at 33-37 days after flowering (Figure 8) than in to 40- 52 day intervals after flowering.

CONCLUSION

The different branching patterns of field grown tomato had significant impact on assimilate partitioning to the first fruit of the first truss only at maturity stages of the fruit, and resulted in significantly earlier time to first harvest of the crops due to less competition for the assimilate. The fruit maturation rate and first harvesting time on commercial field grown tomato was influenced by certain levels of pruning strategy of the crops that might be an input parameter on the prediction of harvesting time and yield of the crops. The fruit load on different branching patterns of commercial field grown trellis tomato had no significant effect on the photosynthesis rate of the plants but, significant impact was observed only by manipulating fruitless plants after top shoot pruning of the plants that removed the growing vegetative sink organs of the plants**.** The branching patterns in field grown tomato makes difficult to maintain an optimum source-sink ratio and increases the difficulty for predicting time to first harvest and yield of the crops in field environments; therefore further in-depth research is required in source- sink relation and carbon partitioning for optimum production.

CHAPTER 7

MODELLING HARVESTING TIME AND YIELD OF FIELD GROWN TOMATO

ABSTRACT

Three heat unit models were selected for comparison with the industry standard calendar day method of prediction of harvest time. The base parameters for the models were generated using the 217 commercial data set of Roma and Gourmet tomato crops from the 2008-2011 seasons obtained from SP Exports. An improved calendar date model was also generated using the trends in time from transplanting to harvest that existed in the 217 crop data set. Model accuracy was then assessed against actual crop performance for 27 Roma and 26 Gourmet tomato crops grown in the Bundaberg region in the 2012/14 seasons. The coefficient of determination (r^2 = 75.98 and 74.44 for all seasons in Roma and Gourmet tomato crops respectively) for growing degree days and harvest time of the crops was stronger for the standard heat unit model than for heat unit models incorporating a ceiling temperature or light intensity. The coefficient of determination (r^2 = 87.20 and 90.60 for each season in Roma and Gourmet tomato crops respectively) for time to first harvest between observed harvest day of the test crops and predicted harvest time based on the standard heat unit method was strong. Predictions from the best day degree model of first harvesting time were an improvement on both the improved calendar day and standard calendar day methods for field grown trellis tomato crops in the sub-tropical region in Queensland, Australia.

INTRODUCTION

The development and use of models for predicting the time to first harvest and yield of field grown tomato is important to improve the efficiency in production schedule and volume of production for regular supply of fresh tomatoes to fulfil the demand of various supermarkets for the tomato growers. Forecasting models are tools for growers to assist in the management of production schedules where multiple crops are grown over an extended production season.

Different approaches have been used to develop predictive models for harvest time and yield in different crops. The use of weather parameters for prediction of harvest time and yield is a traditional method, and the extent of weather influence on harvest time and crop yield depends not only on the magnitude of weather variables but also on the weather pattern over the crop season. The number of input variables in such models can be very high if multiple weather parameters are included. The forecasting of harvest time and yield using crop parameters is another approach of crop modelling. The statistical models, farmers appraisal, and remote sensing techniques are others approaches used for crop forecasting (Jaina et al., 1985; Agarwal & Jaina, 1996; Garbulsky et al., 2011; Agarwal, 2012). Increasingly, integrated approaches incorporating elements from different modelling approaches are being used in different countries to produce greater accuracy in harvesting time and yield predictions.

Simple heat unit models (Austin and Ries, 1965; 1968; Perry *et al.*, 1997) to more complicated models (Wolf et al., 1986; McAvoy et al, 1989a; Cockshull et al., 1992; Hisaeda and Nishina (2007); Higashida, 2009; Wada et al., 2013) based on solar radiation are two weather based approaches used for predicting of harvest time and yield in tomato crops. Perry *et al.*, (1997) examined heat unit models to predict harvest time in field grown tomatoes in southeast USA. Heat unit summation methods were found to provide an improved accuracy of harvest time prediction when compared with the industry practice of prediction based on a standard number of days after planting. Many studied in greenhouse tomato crops have also concluded that yield prediction can be done based on solar radiation. Higashide (2009) described that yield can be predicted using a model based on solar radiation from 10 to 4 days before anthesis. Hisaeda and

Nishina (2007) also explained that the yield in greenhouse tomato crops can be predicted based on cumulative solar radiation 8 weeks to 1 week before harvesting. Wada et al., (2013) found that yield can be predicted from the simulation model of integrated solar radiation and averaged air temperature at 19 to 27 ºC in single –truss system in greenhouse grown tomato crops.

Heat unit accumulation models were also used for predicting first harvest and yield of other fruits and vegetables crops. Perry and Wehner (1996) described that heat unit models can predict more accurately than calendar day methods for predicting cucumber harvesting in North Carolina. Tan et al., (2000) also used that heat unit models best predict the duration of chronological time from emergence to harvesting of broccoli. Umber et al., (2011) studied the heat unit requirement for harvesting of two new banana hybrids for exports, while Marra et al., (2002) concluded that thermal time models can predict harvesting time of peach fruit during the first 25 to 52 days of fruit development period in different cultivars. Heat unit models reduced the prediction error from 69 % to 22 % depending on cultivar when compared to a calendar day method in high bush blueberry fruits (Carlson & Hancock, 1991). Hueso et al., (2007) noted that heat unit models are superior to calendar day method for predicting harvest maturity of the ‘Algerie’ loquat, but only in water- stressed trees.

The growers of field grown tomato crops in Queensland currently use a standard day counting or calendar date method to predict harvest time, and have no formal system for predicting likely crop yield. Target yields are set based on the yield needed for profitability rather than any system incorporating site or seasonal factors that may impact upon yield potential. The data presented in Chapter 4, utilising crop records from a four year period, showed that the predicted time for harvesting of the crops was poorly matched with actual harvesting time and actual crop yield varied widely from the target or estimated crop yields. There is scope for improved models to assist growers to improve efficiency in managing production schedule and volume of production for regular supply of fresh tomatoes to fulfil the demand from the market for consistency in supply.

In this Chapter, two approaches were used for prediction of harvesting time of field grown tomato in this region. The approaches were the use of heat models and analysis of production trend data from historic crop records. There is no published research work or recorded research for heat unit models to predict first harvest time of field grown semi-determinate trellis tomato in sub-tropical and tropical regions.

The objective of this research was to develop a superior model to the industry standard calendar day model for predicting first harvest time so that the local industry could evaluate the model for widespread adoption to increase production efficiency. The models were intended as an interim measure, with incremental improvements to be incorporated in future years as effects of other factors such as soil type and pruning strategies are more fully understood.

MATERIALS AND METHODS

The commercial crop data set described in Chapter 4 was used to evaluate the heat unit requirements of crops from transplanting to first harvest. Daily maximum and minimum temperature data and light intensity from 2012 to 2014 were collected from Bundaberg Aero Club weather station (Latitude - 24.89 º and longitude152.32 º East) close to the field tomato growing areas (Appendix, Table 28) and justification on using this weather data is given in Chapter 2. Ten base temperatures of 0, 2, 4, 6, 8, 10, 12, 14, 16, and 18 ºC, covering the range of base temperatures studied by previous researchers, and five ceiling temperature of 26, 28, 30, 32 and 34 ºC, which are close to or above the reported optimal temperature for tomatoes, were selected for heat unit calculations. The heat unit accumulations of each of the 217 Roma and Gourmet tomato crops were calculated by summation of heat units from transplanting to first harvest time. The crops were grouped based on the transplanting seasons to identify and assess the impact of season on heat unit requirements.

The three most common of heat unit methods (Perry et al., 1986, 1997) were selected to compare for assessment.

- Method 1: Standard Day degree Method (GDD)

  $GDD = \sum ((T_x + T_n) / 2 - Base)$

  Where T_x and T_n are the daily maximum and minimum temperatures respectively.

- Method 2: Reduced Ceiling Method of Growing Degree Day

  $GDD = \sum (((T_c - (T_x - T_c)) - Base)$ If $T_x > T_c$ (ceiling temperature), otherwise Method 1.

- Method 3: Standard Day degree Method (GDD) multiplied by daily light intensity

  $GDD = \sum \{(T_x + T_n) / 2 - Base\} * \text{Daily light intensity}$

Where T_x and T_n are the daily maximum and minimum temperatures respectively.

The heat unit summation approach used by Arnold (1959) was used to find out the suitable heat unit method in this region. A heat unit summation becomes equivalent to the total number of developmental units occurring between stages of development. Heat unit summations from a series of transplanting in one season or in a number of seasons can be calculated on a number of selected base temperatures and the base giving the least variation can be found. By using a great number of base temperatures this method will give a fairly accurate indication of the actual base temperature. According to Arnold (1959), the coefficient of variation is the best statistic to use a measure of variability

IMPROVED CALENDAR DATE METHOD

The analysis of the commercial crop data set in Chapter 4 revealed significant variations between the mean actual harvest time of crops transplanted at different times of the year and the predicted harvest time based on the standard calendar date method adopted by industry i.e. counting the day from transplanting to first harvesting time of the crops for certain accumulated heat unit for ripening of the tomato fruits that is practiced by field tomato growers in this region. An improved calendar date model was developed using the commercial crop data set. A regression equation that best fit the commercial crop data set was developed using averaged crop data of Roma and Gourmet tomato grown in SP Exports from 2008-2011.

COMMERCIAL FIELD CROPS FOR TESTING THE MODELS

To assess the thermal time and improved calendar date models, a new commercial crop data set was obtained. Records for 27 Roma and 26 Gourmet commercial field tomato crops from the 2012/14 seasons were obtained from a tomato grower. Daily maximum and minimum temperature data and light intensity from 2012 to 2014 were collected from Bundaberg Aero Club weather station (Latitude - 24.89 º and longitude152.32 º East) close to the field tomato growing areas (Appendix; Table 28). The crops covered the full range of major production windows for the region, and the crop records included location, transplanting date and harvest time data. For each crop, a predicted harvest time was generated using the models developed in the project. For thermal time models, long term and daily temperature averages were used and a summation of degree day units was done from transplanting date to the date where the critical day degree threshold was reached. For the improved calendar date model, the transplanting date was used in the regression equation to generate a predicted harvest time. Similarly, for the industry standard calendar date method the predicted harvest time was read from the table listing transplanting dates and predicted harvest dates. For each model, differences between predicted and actual harvest date for each crop were calculated and analysed to assess model accuracy.

STATISTICAL ANALYSIS

The coefficient of variation (CV) of growing degree days from transplanting to first harvesting time of Roma and Gourmet tomato crops was calculated using Minitab version 16 to identify the superior method of prediction of time to first harvest of the tomato crops. The one way analysis of variances on observed and predicted first harvesting time in different methods of prediction was performed in Minitab 16. The coefficient of determination and other parameters to identify the best model for prediction was also performed by regression analysis of different heat units and calendar day methods of prediction in Minitab. The comparisons of the different measured variables were performed by one way analysis of variance in Tukey's method at 95 percent confidence interval and all the statistically significant findings are reported at $p \leq 0.05$. Transformation of the data was performed by Johnson transformation in Minitab 16 and square root transformation in excel where normality assumption and homogeneity of variance of the data were violated in the study.

RESULTS

HEAT UNITS REQUIREMENTS FOR FIRST HARVESTING TIME OF FRUITS

Different base and ceiling temperatures were found to provide the best prediction for first harvest time for each of the three thermal time models in both Roma and Gourmet tomato crops (Table 1). The variation in predicted versus actual first harvest time was higher in heat unit Method-3 than other methods, suggesting it would be the least reliable predictive model. Heat unit Method -2 displayed less variation than the other heat unit models for the combined crop data across all seasons and the winter season crops for both Roma and Gourmet tomatoes. The heat unit method -1 had the lowest coefficient of variation (CV) for the summer, autumn and spring seasons for both Roma and Gourmet tomatoes. The finding of base and ceiling temperatures of 18 and 26 ºC as optimum in heat unit Method-2 in winter planted crops, the model that had the lowest CV for both Roma and Gourmet tomato crops, is interesting given those temperatures would rarely be experienced in the winter months. This suggests the result was an anomaly. The coefficient of variation was found to be lower in the heat unit methods than the calendar date method for both Roma and Gourmet tomato crops except in autumn and spring season respectively.

Comparatively, heat unit method-1 was better for each season than Method-2 and 3 based on the lowest CV, according to the approach used by Arnold (1959) for assessment of the heat unit requirements for first harvesting time of the tomato crops. The variation in different parameters of the regression analysis were found for these three heat unit models based on the heat unit accumulation from transplanting to first harvesting time of the crops at specific base and ceiling temperature in all seasons and each season in both Roma and Gourmet tomato (Table 2 and regression equation in Appendix Table 16-27). The heat unit accumulation at base temperature of 6 º Celsius was found to have the highest coefficient of determination (r^2) of 75.98 and 74.44 in heat unit method-1 for both Roma and Gourmet tomato crops respectively for all seasons. The predictive capacity of first harvesting time of both Roma and Gourmet tomato crops of these three heat unit methods were observed to be more than 70 % except in method-3 in each season of Roma tomato. The regression analysis showed that the p value is significant indicating the parameter estimates (coefficient) is not equal with 0 in all heat unit methods.

The coefficient of variation (CV) of heat unit requirement for first harvesting time varied with base temperature for both Roma and Gourmet tomato crops in heat unit method-1(Table 3). The CV of heat unit requirements for the crops transplanted in all seasons was lowest at 6 ºC base temperature. Less variability in the crops transplanted in autumn and winter in Roma and summer and autumn seasons in Gourmet tomato was found at a base temperature 6 ºC. Crops transplanted in spring had less variability in heat unit requirements for first harvesting at 0 ºC and 2 ºC base temperature for both Roma and Gourmet tomato respectively.

Varying the base and ceiling temperature in Method-2 resulted in changes in heat unit requirements for each crop in the data set, with different base and ceiling temperature combinations producing the lowest CV for Roma (Table 4) and Gourmet (Table 5) tomato crops transplanted in each season. The crops transplanted in summer season displayed lowest variation in heat unit requirements for first harvesting time across a broad range of ceiling temperature of 26, 28, 30, 32 and 34 º C and base temperatures of 0, 0, 18, 18, and 18 º C respectively, whereas base temperatures of 18, 14, 12, 12 and 12 º C in autumn; 18, 16, 14, 14 and 14 º C in winter and 0, 4/6/8, 14, 6 and 2/4 º C in spring season were found respectively for Roma tomato. The variation was lowest at ceiling temperature of 26, 28, 30, 32 and 34 º C and at base temperatures of 0, 0, 6/8/10/14, 16, and 14 º C in summer; 18, 16, 14, 14 and 14 º C in autumn; 18, 14, 12, 14 and 14 º C in winter; and 0, 0, 12, 8 and 6/8 º C in spring respectively in Gourmet tomato crops.

The optimum base temperatures at ceiling temperature of 26, 28, 30, 32 and 34 º C were 0, 16, 14, 12, and 12 º C respectively for Roma tomato (Appendix; Table 12) and 0, 18, 14, 14 and 14/12 º C respectively for Gourmet tomato (Appendix; Table 12). The variation of optimum base and ceiling temperature was observed for Roma and Gourmet tomato in the combined season’s data set (Appendix; Table 13) and in each individual season (Appendix; Table 14 & Table 15) in heat unit Method-3.

Table 1: *The lowest coefficient of variation (CV) of growing degree days (GDD) at specific base and ceiling temperature of three heat unit methods, number of transplanted crops, mean first harvesting day, and CV of industry predicted harvesting method for all and each season in Roma and Gourmet tomato crops transplanted in 2008-2011 in Bundaberg*

Crop	Season	Crop numbers transplanted	First harvesting day	Heat Unit Method -1*			Heat Unit Method- 2*				Heat Unit Method- 3*				Method4@
				Base	CV (%)	GDD	Base	Ceiling	CV (%)	GDD	Base	Ceiling	CV (%)	GDD	CV (%)
Roma	All	99	78	6	10.36	1213	12	32	**10.22**	**1135**	0	28	11.28	40204	18.19
Roma	Summer	30	67	14	**6.28**	**749**	18	34	8.25	773	0	32	9.39	45834	9.07
Roma	Autumn	29	91	6	**11.15**	**1223**	12	34	11.37	1157	0	34	11.38	38740	**9.25**
Roma	Winter	17	96	6	5.40	1223	18	26	**4.56**	**479**	4	26	10.59	33501	11.93
Roma	Spring	23	65	0	**6.46**	**1508**	14	30	7.53	884	0	28	8.66	42446	6.92
Gourmet	All	118	77	6	9.20	1225	14	30	**8.69**	**956**	0	28	10.16	40454	20.10
Gourmet	Summer	44	67	6	**6.98**	**1287**	14	34	7.05	1040	0	28	8.76	39389	6.99
Gourmet	Autumn	29	93	6	**5.86**	1266	14	34	6.25	1013	2	28	7.23	36355	12.35
Gourmet	Winter	20	95	10	6.17	803	18	26	**5.12**	**510**	8	26	10.40	26639	11.34
Gourmet	Spring	25	66	2	**8.91**	**1362**	6	34	9.52	1433	0	26	11.80	37763	**4.83**

* Heat unit method 1, 2 and 3: Based on as described in materials and method section of the chapter
@ Method 4: Industry used calendar day method for prediction of first harvesting day of Roma and Gourmet tomato

Table 2: *Regression parameters of three heat unit methods(HUM) of predicting first harvesting time of Roma and Gourmet tomato fruits based on heat unit accumulation at lowest CV at specific base and ceiling temperature for all seasons and each season of the crops.*

Parameters	All seasons of Roma tomato			Each season of Roma tomato			All seasons of Gourmet tomato			Each season of Gourmet tomato		
	HUM-1	HUM-2	HUM-3	HUM-1	HUM-2	HUM-3	HUM-1	HUM-2	HUM-3	HUM-1	HUM-2	HUM-3
r^2 (%)	75.98	73.30	71.63	72.89	71.57	67.16	74.44	74.26	71.35	72.82	72.24	72.34
S	8.80	9.27	9.56	9.35	9.57	10.29	8.79	8.82	9.31	9.06	9.16	9.14
F^*	74.33	64.52	59.00	63.16	59.15	48.04	82.28	81.48	70.35	75.68	73.52	73.88
P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

* *$F_{(4, 98)}$ for Roma Tomato crops and $F_{(4,117)}$ for Gourmet Tomato crops. Regression equation is given in Appendix (Table16-27)*

Table 3: *The co-efficient of variation (CV) of growing degree days at different base temperatures for all and each season in Roma and Gourmet tomato in heat unit method-1*

Crop	Season	Crop number	CV (%) in different base temperature (º C) in Heat Unit Method- 1									
			0	2	4	6	8	10	12	14	16	18
Roma	All	99	11.38	10.82	10.40	**10.36**	11.10	13.25	17.64	25.72	41.03	75.74
Roma	Summer	30	8.97	8.66	8.31	7.91	7.46	6.98	6.52	**6.28**	6.77	9.02
Roma	Autumn	29	11.72	11.41	11.18	**11.15**	11.61	13.11	16.76	24.91	45.03	127.66
Roma	Winter	17	7.84	7.40	6.88	**5.40**	5.67	6.27	6.64	11.81	28.47	201.05
Roma	Spring	23	**6.46**	8.61	8.86	9.28	9.96	11.04	12.79	15.65	20.57	29.96
Gourmet	All	118	10.48	9.81	9.30	**9.21**	9.99	12.00	17.00	25.00	40.00	73.00
Gourmet	Summer	44	7.09	7.05	7.00	**6.98**	7.01	7.13	7.40	7.98	9.12	11.39
Gourmet	Autumn	29	7.70	6.99	6.29	**5.86**	6.27	8.42	13.30	23.07	45.83	142.68
Gourmet	Winter	20	7.96	7.58	7.15	6.67	6.24	**6.17**	7.48	12.48	29.21	235.87
Gourmet	Spring	25	8.94	**8.91**	8.93	9.04	9.30	9.85	10.89	12.85	16.60	24.31

Table 4: *The co-efficient of variation (CV) of growing degree days at different ceiling and base temperatures for each season in Roma tomato in heat unit method-2*

Crop	Season	Crop number	Ceiling temperature(°C)	CV (%) at different base temperature (º C) in Heat Unit Method- 2									
				0	2	4	6	8	10	12	14	16	18
Roma	Summer	30	26	**16.29**	16.62	17.03	17.53	18.19	19.06	20.28	22.11	25.14	31.01
Roma	Autumn	29	26	17.00	16.95	16.89	16.82	16.73	16.63	16.51	16.36	16.20	**16.15**
Roma	Winter	17	26	10.05	9.86	9.64	9.37	9.03	8.60	8.02	7.22	6.08	**4.56**
Roma	Spring	23	26	**13.00**	13.28	13.64	14.09	14.67	15.46	16.57	18.22	20.88	25.76
Roma	Summer	30	28	**14.66**	14.80	14.96	15.16	15.40	15.71	16.11	16.65	17.42	18.61
Roma	Autumn	29	28	14.66	14.44	14.19	13.91	13.58	13.23	12.86	**12.57**	12.64	13.99
Roma	Winter	17	28	8.67	8.38	8.05	7.66	7.19	6.64	6.01	5.42	**5.37**	7.35
Roma	Spring	23	28	10.11	10.09	**10.08**	**10.08**	**10.08**	10.09	10.13	10.23	10.44	10.89
Roma	Summer	30	30	12.28	12.22	12.15	12.07	11.98	11.87	11.73	11.56	11.35	**11.06**
Roma	Autumn	29	30	13.62	13.35	13.05	12.71	12.36	12.01	**11.75**	11.77	12.59	15.44
Roma	Winter	17	30	8.37	8.07	7.73	7.32	6.85	6.31	5.76	**5.39**	5.84	8.52
Roma	Spring	23	30	8.46	8.33	8.20	8.06	7.91	7.75	7.62	**7.53**	7.60	8.03
Roma	Summer	30	32	10.83	10.68	10.51	10.31	10.08	9.82	9.51	9.14	8.72	**8.26**
Roma	Autumn	29	32	13.33	13.04	12.72	12.37	12.00	11.66	**11.42**	11.53	12.54	15.74
Roma	Winter	17	32	8.39	8.10	7.76	7.37	6.93	6.43	5.94	**5.67**	6.25	9.01
Roma	Spring	23	32	8.39	8.33	8.28	**8.26**	8.27	8.36	8.57	8.99	9.78	11.21
Roma	Summer	30	34	10.71	10.55	10.37	10.17	9.94	9.68	9.37	9.02	8.64	**8.25**
Roma	Autumn	29	34	13.28	12.99	12.67	12.31	11.95	11.60	**11.37**	11.49	12.54	15.80
Roma	Winter	17	34	8.39	8.09	7.76	7.37	6.92	6.42	5.94	**5.67**	6.27	9.05
Roma	Spring	23	34	8.54	**8.51**	**8.51**	8.54	8.63	8.81	9.13	9.71	10.68	12.36

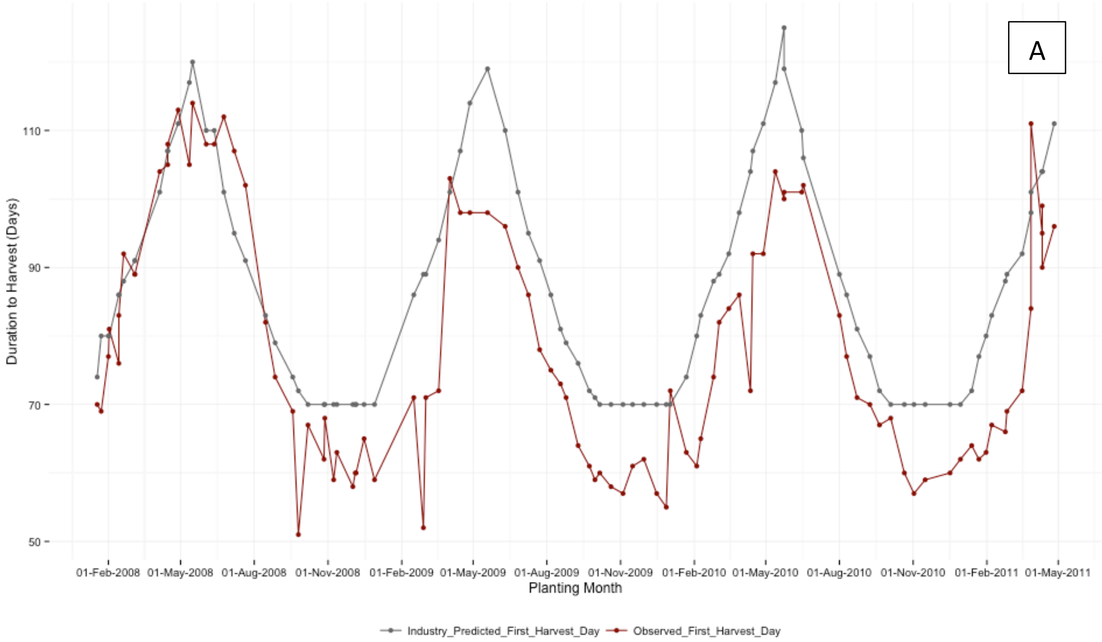
***Table 5**: The co-efficient of variation (CV) of growing degree days at different ceiling and base temperatures for each season in Gourmet tomato in heat unit method-2*

Crop	Season	Crop number	Ceiling temperature(°C)	CV (%) at different base temperature (° C) in Heat Unit Method-2									
				0	2	4	6	8	10	12	14	16	18
Gourmet	Summer	44	26	**11.02**	11.27	11.57	11.96	12.46	13.13	14.09	15.53	17.94	22.67
Gourmet	Autumn	29	26	14.84	14.71	14.54	14.34	14.09	13.78	13.36	12.79	11.98	**10.81**
Gourmet	Winter	20	26	9.81	9.63	9.41	9.15	8.82	8.41	7.86	7.13	6.14	**5.12**
Gourmet	Spring	25	26	**13.59**	13.83	14.12	14.49	14.95	15.58	16.44	17.70	19.71	23.33
Gourmet	Summer	44	28	**10.13**	10.26	10.40	10.58	10.80	11.07	11.43	11.92	12.62	13.70
Gourmet	Autumn	29	28	11.74	11.35	10.89	10.35	9.70	8.92	8.00	7.05	**6.62**	8.62
Gourmet	Winter	20	28	8.60	8.33	8.03	7.67	7.25	6.77	6.24	**5.80**	5.93	7.96
Gourmet	Spring	25	28	**11.52**	11.55	11.59	11.64	11.70	11.79	11.91	12.10	12.40	12.92
Gourmet	Summer	44	30	8.64	8.63	8.63	**8.62**	**8.62**	**8.62**	**8.62**	**8.62**	8.64	8.68
Gourmet	Autumn	29	30	10.52	10.05	9.51	8.89	8.18	7.40	6.67	**6.40**	7.64	11.93
Gourmet	Winter	20	30	8.38	8.11	7.80	7.45	7.04	6.60	**6.17**	5.96	6.53	9.15
Gourmet	Spring	25	30	10.04	9.98	9.91	9.83	9.76	9.69	**9.64**	9.65	9.76	10.12
Gourmet	Summer	44	32	7.59	7.53	7.46	7.39	7.32	7.24	7.17	7.12	**7.11**	7.22
Gourmet	Autumn	29	32	10.28	9.79	9.24	8.60	7.87	7.09	6.40	**6.28**	7.80	12.42
Gourmet	Winter	20	32	8.37	8.10	7.80	7.45	7.06	6.64	6.25	**6.11**	6.78	9.51
Gourmet	Spring	25	32	9.68	9.62	9.57	9.54	9.54	9.55	9.65	9.90	10.40	11.39
Gourmet	Summer	44	34	7.49	7.43	7.36	7.29	7.22	7.15	7.09	**7.05**	7.08	7.24
Gourmet	Autumn	29	34	10.25	9.76	9.20	8.56	7.83	7.05	6.36	**6.25**	7.81	12.46
Gourmet	Winter	20	34	8.36	8.10	7.79	7.44	7.05	6.63	6.25	**6.11**	6.80	9.55
Gourmet	Spring	25	34	9.64	9.59	9.55	**9.52**	9.54	9.58	9.72	10.01	10.60	11.71

IMPROVED CALENDAR DAY AND CALENDAR DAY METHODS FOR PREDICTION

The trend of predicted first harvesting time for Roma (Figure 1 A) and Gourmet (Figure 1 B) tomato crops transplanted in different months in a year that was practiced by the industry and observed harvesting time of the crops is given in Figure 1 (A & B). The mean first harvesting day of Roma and Gourmet tomato crops in each season was statistically significant (Table 6) indicating seasonal variation in harvesting days of the crops from transplanting to first harvesting time. The observed first harvesting time and prediction of first harvesting time by improved and industry calendar method was significantly higher in autumn and winter seasons, but it was significantly lower in summer and spring seasons in both Roma and Gourmet tomato crops.

The variation of the statistical regression parameters were observed between actual and predicted first harvesting time of improved calendar day and industry used calendar day methods in Roma and Gourmet tomato crops (Table 7). The scatter plot of regression showed that the coefficient of determination (r^2) of prediction is higher in improved calendar day method than industry used calendar day method in both Roma and Gourmet tomato crops (Figure 2; A & B and Table 7).



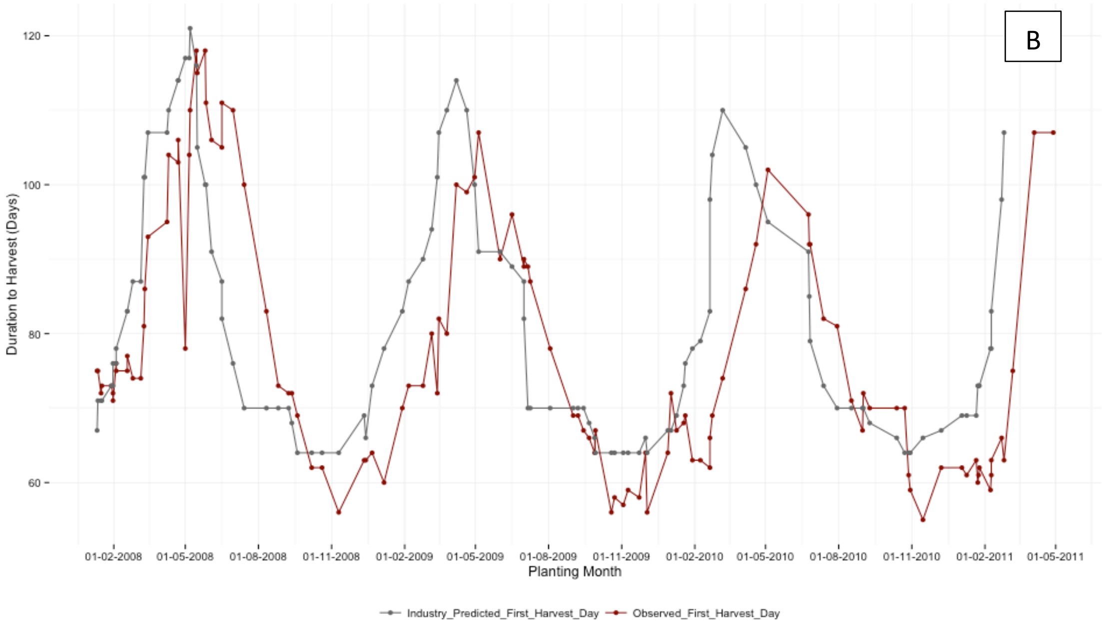
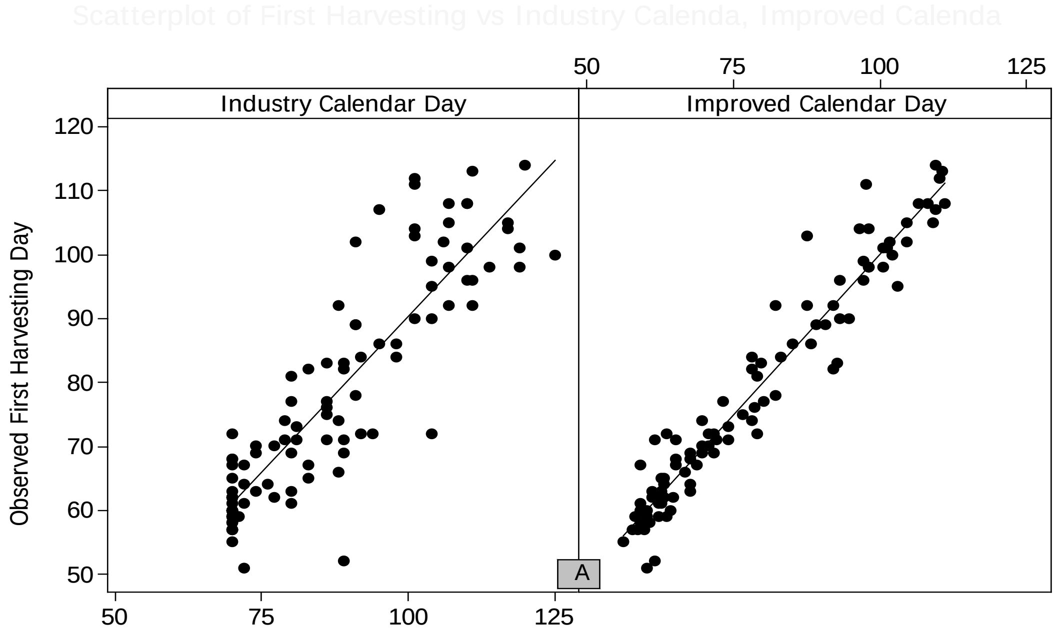


Figure 1, *Observed first harvest day from transplanting and industry predicted first harvest day of Roma (A) and Gourmet (B) tomato crops transplanted in Bundaberg in different months of the years 2008-2011. The legend - for observed first harvest day and the legend - for industry predicted first harvest day of the crops transplanted different months of the years in 2008-2011.*



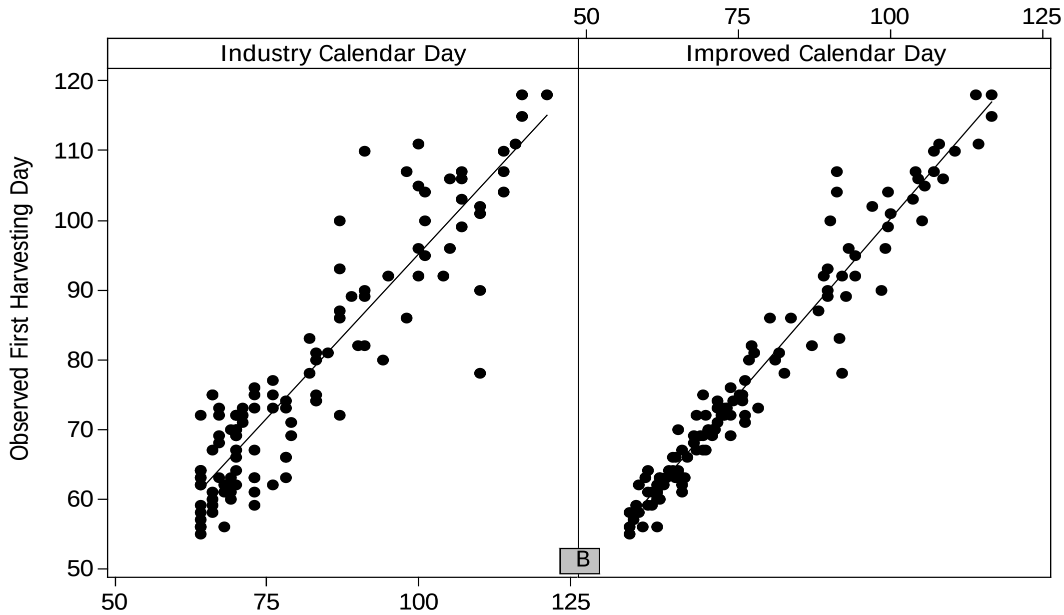


Figure 2: *Scatter plot of regression of observed first harvest day vs prediction of first harvest day of industry and improved calendar day method of Roma (A) and Gourmet (B) tomato of the crops transplanted in SP Exports in years 2008-2011.*

Table 6: *Mean observed first harvest day, improved and industry used calendar day methods for prediction of first harvesting time and coefficient of variation (CV) in all and each season of Roma and Gourmet tomato crops. The crop data represents the mean values ± SE, which were analysed at the significant levels of P ≤ 0.05 at Tukey,s. Values with the same letters on each column of Roma and Gourmet tomato represent there was no difference*

Crop	Season	Observed first harvest day	CV (%)	Improved calendar day	CV (%)	Industry used calendar day	CV (%)
Roma	All	77.7 ± 2.41	21.44	77.9 ± 2.37	21.06	87.0 ± 2.40	19.14
Roma	Summer	66.5 ± 1.57^{b}	12.95	65.5 ± 1.36^{b}	11.34	76.5 ± 1.27^{b}	9.07
Roma	Autumn	91.3 ± 2.81^{a}	16.65	89.5 ± 2.63^{a}	15.85	102.1 ± 1.75^{a}	9.25
Roma	Winter	95.5 ± 2.87^{a}	12.37	97.4 ± 2.59^{a}	10.96	102.6 ± 2.97^{a}	11.93
Roma	Spring	64.8 ± 1.47^{b}	10.89	66.5 ± 1.68^{b}	12.13	73.3 ± 0.92^{b}	6.02
Gourmet	All	77.7 ± 1.54	21.59	77.6 ± 1.50	20.96	81.3 ± 1.50^{b}	20.10
Gourmet	Summer	66.5 ± 0.91^{b}	9.12	66.1 ± 0.898^{b}	9.01	69.5 ± 0.73^{b}	6.97
Gourmet	Autumn	93.1 ± 2.65^{a}	15.35	90.4 ± 2.55^{a}	15.16	99.2 ± 2.27^{a}	12.35
Gourmet	Winter	95.3 ± 2.57^{a}	12.07	97.4 ± 2.35^{a}	10.82	96.4 ± 2.44^{a}	11.34
Gourmet	Spring	65.5 ± 1.12^{b}	8.58	66.9 ± 1.16^{b}	8.69	69.4 ± 0.67^{b}	4.83

Table 7: *Regression equations and other parameters of industry calendar and improved calendar day method of prediction of the first harvesting day of Roma and Gourmet tomato transplanted in SP Exports in the year 2008-2011*

Parameters	Industry Calendar day-Roma	Improved Calendar Day-Roma	Industry Calendar day-Gourmet	Improved Calendar Day-Gourmet
Regression Equation	$X^1 = -7.10 + 0.974\ Y^1$	$X^1 = -0.02 + 1.00\ Y^2$	$X^1 = -0.40 + 1.01\ Y^3$	$X^1 = 1.21 + 0.940\ Y^4$
SE of Coefficient	4.663 & 0.05230	2.061 & 0.02575	3.163 & 0.03813	1.653 & 0.02086
T	-1.52 & 18.63	- 0.01 & 38.92	0.38 & 24.66	- 0.24 & 48.27
S	8.26393	4.33731	6.74210	3.66876
r^2 (%)	78.1	94.0	84.1	95.3
F^+	346.93	1514.55	608.24	2329.88
P	< 0.01	< 0.01	< 0.01	< 0.01

X^1 Actual first harvesting day of tomato fruits

Y^1 Predicted date of first harvesting of Roma tomato fruits by industry used calendar day method

Y^2 Predicted date of first harvesting of Roma tomato fruits by improved calendar day method

Y^3 Predicted date of first harvesting of Gourmet tomato fruits by industry used calendar day method

Y^4 Predicted date of first harvesting of Gourmet tomato fruits by improved calendar day method and $^+$ F (1, 98) in Roma and F (1,117) in Gourmet tomato.

OBSERVED AND PREDICTED HARVEST TIME OF THE TEST CROPS

The variation between actual and predicted first harvesting time calculated for each of the 27 Roma and 26 Gourmet test crops differed between the models in each season (Table 8). The first harvesting time of Roma and Gourmet tomato crops was significantly higher in the crops transplanted in winter season in all predicting methods. The coefficient of variation (CV) of first harvesting time of the test crops was lower for each season than all season in all predicting methods. The first harvesting time of the fruits in both Roma and Gourmet tomato was significantly higher in the crops transplanted in winter season in all predicting methods of first harvesting except in industry used calendar day method in Gourmet tomato (Table 8). The mean predicted first harvesting time in each season was observed lower in all predicting methods than industry used calendar day method.

The variation of coefficient of determination (r^2) of regression analysis between observed harvest day and predicted harvest day of the test crops based on different prediction methods of first harvesting were observed for both Roma and Gourmet tomato crops (Table 9). The coefficient of determination (r^2) of prediction of first harvesting time was higher with 87.2 and 90.6 % in daily heat unit accumulation at base temperature of each season in heat unit method-1 than in other prediction methods for both Roma and Gourmet tomato crops respectively. The standard heat unit method of prediction of first harvest time (heat unit method-1) based on heat unit accumulation at daily or long mean had higher predictability of first harvesting than improved and calendar day methods except in daily heat unit accumulation in all seasons in Gourmet tomato.

Table 8: *Observed and predicted first harvesting time and coefficient of variation (CV %) in different predicting methods for the test crops for all and each season of Roma and Gourmet Tomato transplanted in 2012-2014 in Bundaberg. The data are the mean values ± SE, which were analysed at the significant levels of $P \leq 0.05$ at Tukey,s. Values with the same letters on each column of Roma and Gourmet tomato represent there was no difference*

Crop	Season	Crop	Observed 1st Harvest Day	CV	DHUA-All Seasons*	CV	DHUA-Each Season+	CV	HUALM#	CV	Improved Calendar Day	CV	Industry used Calendar day	CV
Roma	All	27	78.0 ± 3.13	20.46	82.3 ± 3.63	22.95	83.4 ± 3.45	21.51	81.5 ± 3.32	21.14	79.7 ± 3.16	20.64	89.6 ± 3.22	18.64
Roma	Summer	8	63.9 ± 1.17^{c}	5.19	63.6 ± 1.55^{b}	6.87	69.3 ± 1.70^{b}	6.94	66.4 ± 1.05^{b}	4.48	65.1 ± 1.41^{b}	6.11	75.5 ± 1.76^{b}	6.60
Roma	Autumn	8	84.0 ± 2.61^{b}	8.79	93.0 ± 4.59^{a}	13.95	93.4 ± 4.43^{a}	13.42	91.7 ± 4.12^{a}	12.70	90.5 ± 4.20^{a}	13.11	102.5 ± 3.37^{a}	9.30
Roma	Winter	6	101.2 ± 1.82^{a}	4.39	103.2 ± 3.59^{a}	8.53	103.8 ± 3.76^{a}	8.88	101.2 ± 3.25^{a}	7.87	96.3 ± 3.99^{a}	10.14	104.0 ± 5.70^{a}	13.42
Roma	Spring	5	63.2 ± 2.50^{c}	8.84	69.8 ± 4.84^{b}	15.51	65.4 ± 2.73^{b}	9.34	65.7 ± 2.70^{b}	9.20	65.6 ± 2.91^{b}	9.91	74.4 ± 2.77^{b}	8.32
Gourmet	All	26	75.6 ± 2.70	18.23	79.5 ± 3.40	21.84	80.1 ± 3.49	22.19	81.6 ± 3.83	23.93	77.3 ± 2.81	18.54	83.0 ± 3.10	19.05
Gourmet	Summer	8	67.4 ± 1.25^{b}	5.26	63.1 ± 0.64^{c}	3.59	66.5 ± 0.85^{b}	3.59	67.1 ± 0.34^{b}	1.45	66.0 ± 1.65^{b}	7.06	69.5 ± 1.59^{b}	6.48
Gourmet	Autumn	6	83.5 ± 3.98^{a}	11.68	90.7 ± 5.09^{ab}	13.75	92.7 ± 4.19^{a}	11.08	96.5 ± 4.83^{a}	12.26	89.5 ± 4.17^{a}	11.41	101.5 ± 4.20^{a}	10.14
Gourmet	Winter	5	95.8 ± 2.27^{a}	5.29	101.0 ± 5.22^{a}	11.57	103.8 ± 6.12^{a}	13.18	107.6 ± 6.16^{a}	12.81	94.6 ± 2.38^{a}	5.62	96.6 ± 3.30^{a}	7.63
Gourmet	Spring	7	63.9 ± 1.98^{b}	8.21	73.1 ± 4.08^{bc}	14.76	68.0 ± 2.79^{b}	10.84	66.7 ± 1.58^{b}	6.27	67.3 ± 2.36^{b}	9.27	72.7 ± 2.06^{b}	7.48

* *Prediction of first harvesting time of the test crops based on daily heat unit accumulation at base temperature of all seasons in heat unit method -1*

\+ *Prediction of first harvesting time of the test crops based on daily heat unit accumulation at base temperature of each season in heat unit method -1*

\# *Prediction of first harvesting time of the test crops based on heat unit accumulation-long mean at base temperature of each season in heat unit method -1*

***Table** 9: Regression equations and coefficient of determination (r^2) of observed and prediction of first harvesting days of the test crops of Roma and Gourmet tomatoes by different methods of prediction*

Prediction Method	Regression Equation - Roma Tomato	(r^2 %)	Regression Equation- Gourmet Tomato	(r^2 %)
DHUA-all seasons*	$X = 12.16 + 0.8004\ Y^1$	86.3	$X = 22.72 + 0.6657\ Y^1$	70.3
DHUA-each season+	$X = 7.36 + 0.8473\ Y^2$	87.2	$X = 16.48 + 0.7381\ Y^2$	90.6
HUALM-each season#	$X = 6.343 + 0.8791\ Y^3$	86.7	$X = 21.02 + 0.6694\ Y^3$	89.8
Improved Calendar Day	$X = 6.629 + 0.8959\ Y^4$	82.0	$X = 8.363 + 0.8704\ Y^4$	81.8
Industry Calendar Day	$X = 2.291 + 0.8447\ Y^5$	75.3	$X = 13.93 + 0.7435\ Y^5$	72.6

* *Prediction of first harvesting time of the test crops based on daily heat unit accumulation at base temperature of all seasons in heat unit method -1*

\+ *Prediction of first harvesting time of the test crops based on daily heat unit accumulation at base temperature of each season in heat unit method -1*

\# *Prediction of first harvesting time of the test crops based on heat unit accumulation-long mean at base temperature of each season in heat unit method -1*

X = Observed first harvest day of the test crops of Roma and Gourmet tomatoes.

Y^1 = *Prediction of first harvesting day of the tomato based on daily heat unit accumulation at base temperature of all seasons in heat unit method -1*

Y^2 = *Prediction of first harvesting day of the tomato based on daily heat unit accumulation at base temperature of each season in heat unit method -1*

Y^3 = *Prediction of first harvesting day of the tomato based on heat unit accumulation-long mean temperature at base temperature of each season in heat unit method -1*

Y^4 = *Prediction of first harvesting day of the tomato based on improved calendar day method*

Y^5 = *Prediction of first harvesting day of the tomato based on industry used calendar day method*

DISCUSSION

Considerable variability between the three heat unit models and improved as well as standard calendar day methods for predicting first harvest time of field grown trellis tomato crops was recorded in the analysis described in this chapter. As in the analysis of three heat unit models described by earlier researchers (Tydesley, 1978; Perry et al., 1997) the heat unit models predicted first harvest time of field grown tomato crops more accurately than the standard calendar day method in most of the seasons. Prediction accuracy, based on lowest coefficient of variation (CV) as recommended by Arnold (1959), was superior in heat unit models except for the crops transplanted in the autumn and spring season in Roma and Gourmet tomato respectively. The result for first harvesting time was also consistent with that described in greenhouse tomato crops (Hisaeda and Nishina, 2007; Higashida, 2009; Wada et al., 2013); in cucumber (Perry and Webner, 1996); broccoli (Tan et al., 2000); hybried banana (Umber et al., 2011); blueberry fruits (Carlson & Hancock, 1991); Algerie loquat (Hueso et al., 2007).

The optimum base and/or ceiling temperature for the most accurate heat unit accumulation of the field grown tomato crops differed with season, which was consistent with previous thermal time model studies (Perry & Wehner, 1996; Perry et al., 1997; Wada et al., 2013) and highlights the importance of local data sets in generating usable thermal time models for field tomato crop prediction. The regression analysis also showed that the coefficient of determination (r^2) of growing degree days from transplanting to first harvesting time of the crops and actual first harvesting time based on heat unit method -1 had the best predictive capacity for harvesting time for all seasons in Roma and Gourmet tomato. The strength of the relationship between thermal time model prediction and actual first harvest time of tomato was approximately 74 and 76 percent in Roma and Gourmet tomato respectively and the remaining percentage may be influenced by other factors such as soil type, moisture stress, drainage, cultural practices, depth of transplanting, and slope of the land (Lana & Haber, 1952; Titly, 1985; Benton-Jones, 2008).

The result showed that the coefficient of variation (CV) of the heat unit requirements of the crops from transplanting to first harvesting time was lowest at base temperature of 6 ºC or below for the completed data set and in each season except in summer and winter in Roma and Gourmet tomato crops respectively. The crops transplanted in the spring season had also lowest variation in heat requirements for harvesting at 0 and 2 º C base temperature, presumably due to more warm or hot days of their cropping systems at early days of the summer season; but Bundaberg temperature would never get to 0 and 2 in spring season and it really does seem unlikely in this region. The result was also not consistent at base temperature of 6, 8 and 10º Celsius where an increase from areas with a warm early spring to the cooler ones was noted as explained by Calaelo and Portas (1987). The base temperature of the heat unit model in this sub-tropical and tropical region was not consistent with result of Monteith (1981) who described the base temperature as approximately 10 º C or higher than temperate climate crops, with a base of 10 º Celsius (Edey, 1977) and 10.5 º Celsius (Benton-Jones, 2008) also described for greenhouse tomato.

The high variation of the actual and predicted first harvesting days of Roma and Gourmet tomato crops indicated that the low accuracy of the industry used method of prediction may have been due to other factors also involved in the ripening process of the fruits in field grown tomato. The analysis of historical crop records of first harvesting time of the tomato fruits showed that a similar seasonal trend of first harvesting time of the fruits occurred in each year, indicating that temperature might be one of the major factors for the ripening of the tomato fruits and that frequent fluctuations in temperature in the field may induce variability in the industry used method of prediction. Consistent with previous research in greenhouse (Peet et al, 1997; Adams et al, 2001; Uzun, 2006; 2007) and in field grown tomato (Perry et al, 1997), the time from transplanting to first harvesting time in crops displayed a strong seasonal trend which was consistent with early crop development rate and ripening being strongly influenced by temperature, soil and also other factors that are related with crop growing location in tomato (Hussain et al., 1999; Sharp et al., 2000; Lobell et al., 2007; Patane & Cosentino, 2010) and also in other crops (Morgan & Connolly, 2013). The day count method for prediction of first harvesting time based on historical crop records predicted more accurately than the industry day count method as the method incorporates to some extent the range of factors involved in growth and development of field grown tomato plants. Similar research of improvement of predictability of tomato fruit ripening and yield based on historical crop records was also presented by McKeown et al., 2010 and Lee et al., 2011.

The analysis of the result of this chapter showed that heat unit method -1 (standard day degree heat unit method) is superior to other heat unit methods for prediction of first harvesting time. Heat unit method 3 was poor under field conditions due to fluctuation in light intensity. The high coefficient of variation (CV) of the predicted first harvesting time compare to actual first harvest time of the test crops based on heat unit accumulation transplanted in all seasons and each season indicated that other factors were also involved in ripening process of the field grown tomato fruits and the result was consistent to the findings of earlier researchers in greenhouse tomato (Hussain et al., 1999; Sharp et al., 2000; Lobell et al., 2007; Hildebrandt et al., 2007; Daei et al., 2009; Miramari, 2009; Patane & Cosentino, 2010) and also in other crops (Morgan & Connolly, 2013).The relationship between actual and predicted first harvesting time of the test crops was strongest, i.e. the coefficient of determination (r^2) of 87.2 and 90.6 percent, based on the daily heat unit accumulation at season specific base temperature than other methods of prediction in Roma and Gourmet tomato crops respectively. This was also consistent with the explanation of different base temperature for each season and or location by earlier researchers to calculate the growing degree days on prediction of harvesting time of the crops (Monteith, 1981; Calado & Portas, 1987; Perry et al., 1997), but contradicting with recommendations for only a single base temperature for all seasons (Edey, 1977; Benton-Jones, 2008).

The prediction of first harvest time of the test crops was strongest based on daily or long term mean heat accumulation than improved or industry used calendar method for both Roma and Gourmet tomato crops except in the daily heat unit accumulation at the single base temperature of 6^{o} Celsius for all seasons in Gourmet tomato that indicates the thermal time models are more accurate for prediction but, other factors are also involved in the variation on fruit ripening and yield. The improved calendar day method of prediction of first harvest time of the test crops was superior to the industry used calendar day method, but with lower coefficient of determination of 82 percent in both

Roma and Gourmet tomato crops that also indicate the different factors involved location to location for the variation.

It was concluded that heat unit methods and the improved calendar day method of prediction of harvesting were more precise and superior to the industry used calendar day method in field grown trellis tomato in this region. Further research is necessary to identify the different factors and levels of impact for accurate prediction in each location to incorporate the model parameters of first harvesting of field grown tomato crops.

CONCLUSION

. The base thermal time model was found to be a more precise method for prediction of first harvesting time of field grown trellis tomato than the other predictive models. The improved calendar date model, while slightly less accurate than the thermal time models, may provide growers with a more familiar model to adopt given their current reliance on a calendar date model. Base thermal time and seasonal pattern models were developed that provided improved predictability over the calendar date model used by industry

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

This research project was conducted to examine the data and parameters needed for the development of a model with improved predictability of time of first harvest and yield of field grown tomato under sub-tropical condition in Queensland, Australia. The growers of field grown tomato crops in Queensland currently use a standard day counting or calendar date method to predict harvest time, and have no formal system for predicting likely crop yield. Target yields are set based on the yield needed for profitability rather than any system incorporating site or seasonal factors that may impact upon yield potential. Using crop records from a four year period, it was shown that the predicted time for harvesting of the crops was poorly matched with actual harvesting time and actual crop yield varied widely from the target or estimated crop yields. There is scope for improved models to assist growers to improve efficiency in managing production schedule and volume of production for regular supply of fresh tomatoes to fulfil the demand from the market for consistency in supply.

The growth and development of tomato plant under commercial field production conditions are influenced by environmental and crop management factors that may not be adequately considered in greenhouse models, and need to be incorporated in models if the accuracy of greenhouse models is to be replicated in the field. In both systems dry matter production will be determined by carbon balance, but different factors may limit the rates of the reactions controlling the carbon balance; gross photosynthesis minus losses from growth and maintenance respiration. Light intensity, carbon dioxide concentration and temperature account for much of the variability in carbon balance under greenhouse conditions (Dayan et al., 1993), whereas supply of water and nutrients may limit assimilate production under field conditions. Carbon dioxide concentration will also remain relatively stable under field conditions, while the range of light intensity and temperature to which crops may be exposed is broader than that experienced in greenhouse production. The tomato crop models and their input parameters that are used in predicting harvesting date and yield in greenhouse tomato crops are not sufficient as such but additional parameters have to be incorporated in field grown tomato crop models for predicting the harvesting time and yield.

Considerable variability of phenological traits were observed between plants within a crop and between the crops in the monitoring of the commercial crops transplanted in different locations and times. As expected, crops grown under high temperature displayed faster growth rates and phenological development, and this relationship in field grown tomato crops was also consistent with the considerable volume of literature describing the effects of temperature on growth and development of greenhouse tomato crops that have impact on harvesting and yield of the crops (Peet et al., 1997; Sato et al., 2000; Adams et al., 2001; Uzun, 2007). Many research publications have described that temperature and light play the main role in regulating the rate of growth and development of greenhouse tomato crops, influencing maturation rate and therefore harvesting time and yield, and these factors are clearly important in field tomato crops also. In tropical and subtropical conditions, with only small changes in day length throughout the year, variations in temperature would appear to have the greatest influence on crop development.

The significant differences in number of nodes, leaves and shoots development at flowering time of the first truss indicated that there is a strong relationship between these phenological traits and temperature as well as light intensities which could also impact upon fruit development. Similar types of research were also described for greenhouse tomato by Kinnet, 1977; Uzun, 2006 and also in field grown processing tomato crops (Scholberg et al., 2000). The nodes/leaves formed before initiation of the first inflorescence decreased with increasing light intensity (Kinet, 1977) and the node number below first truss declined linearly with decreasing temperature in the range of 7.4 to 24.2 ^{o} C, but the effect was modified by light intensity (Uzun, 2006). High light intensity enhanced prolific leafy vegetative growth of the plant that impact by prolonging the time taken for fruit development (Scholberg et al., 2000). Differences in node number at which the first truss was initiated showed that the variation in flowering time was due to differences in the time of initiation rather than simply plant growth rate, and therefore an interaction effect of factors including temperature and light intensity, may have contributed to the development of inflorescences. Although, the tomato plants in their native habitat are day neutral i.e. photoperiod-insensitive (Pneuli et al., 1998), the result suggested that the temperature alone did not control flowering time, but interactions between different environmental and site related other factors regulating the flowering time of the field grown tomato crops.

The result of crop monitoring data also showed significant differences in first harvesting time and yield of the tomato, but the differences of harvesting time did not follow the same pattern as for flowering time of the plants indicating that temperature is mainly responsible for the fruit ripening process after flowering. Similar types of research on ripening of tomato fruit was also described in greenhouse tomato crops by Sawhney & Polowick, 1985; Zhang et al., 2005; Boote et al., 2012; Wada et al., 2013. High temperature above an optimum range reduces crop yield by reducing the duration for growth and also reducing the harvest index of the crops. The field grown tomato is exposed to large fluctuations in temperature, light intensity and other environmental factors within a short periods of time, therefore the prediction of effects of the interactions between these environmental factors on crop growth and yield is complex. The impact of high temperature on yield reduction of tomatoes crops has been noted in glasshouse studies (Uzun, 2007) and sub-optimal temperatures also have been shown to result in increased vegetative growth of the plants that reduces the final yield of the crop.

The monitoring of commercial field grown tomato crops also suggested that there is no or very weak relationship between crop phenological traits and first harvesting time as well as in the yield of the crops. The flowering time only explained approximately 50 percent of the variation in harvesting time of the tomato crops. This result clearly indicated that there are other environmental and edaphic as well as site related crop management factors that have impact on the variation of first harvesting time and yield of the crops. Similar research findings was also explained in processing tomato crops grown in Mediteranian region (Patane and Cosentino, 2010) and greenhouse grown tomato crops (Kleiber et al., 2014).

Plant development patterns in semi-determinate types of tomatoes grown in field vary from the indeterminate types generally grown in greenhouse production. The crop data received from the crop monitoring of field grown tomato indicated that the variation in crop growth and development pattern of the field tomato crops transplanted in different seasons was mainly affected by temperature. However, the data generated in the project indicated that there are other factors such as soil type and crop establishment factors that may affect harvesting time and yield of the crops. Transplanting in wet soil is likely to induce compaction of the soil, reducing root system growth and uptake of plant nutrients from the soil (Tracy et al., 2013). This mechanism may explain the delayed flowering in the commercial Gourmet crop transplanted in April. The literature also suggests that soil salinity often affects the timing of development of the crops, with Pasternak et al., (1979) reporting that onions flowered earlier under salt stress conditions whereas salinity delayed flowering of tomato crops. Heavy metals in the soil reduce the growth of tomato and other crops that delays the flowering and harvesting time of the crops (Hildebrandt et al., 2007). As soil conditions in field crop production may vary greatly from site to site, the potential for soil factors such as heavy metals, compaction and salinity to affect flowering time and subsequently harvesting cannot be discounted. Similar type of research on results of soil compaction, salinity and drought on reducing the growth and development of the crops and yield have been described by Sharp et al., 2000; Hussain et al., 1999; Bindon et al., 2008; Posades et al., 2008; Daei et al., 2009; Miramari, 2009; and El-Sadek, 2013. The environmental and soil factors influenced harvesting and yield of the crops in each location should be included in the parameters of the model for harvesting and yield.

The analysis of commercial field crop monitoring data demonstrated the significant differences between the crops on harvesting time and yield. Environmental and crop management factors such as temperature, light, soil type, and crop establishment practices may contribute to the variation within a crop and between the crops transplanted at different locations and times, but assessments from only three crops were not sufficient to identify the factors affecting harvesting and yield as well as to provide reliable trends of harvesting and yield. Therefore, the analysis of the crops transplanted at different locations and soil types by the SP Exports in Bundaberg region in 2008 to 2011 were performed to identify the variation between the crops and factors affecting harvesting time and yield as well as to provide reliable trends of harvesting and yield. The time from transplanting to first harvesting time in crops displayed a strong seasonal trend which was consistent with early crop development rate being strongly influenced by temperature and also other factors that are related with crop growing location. The seasonal trends of first harvesting and yield were consistent with the trends of detailed monitoring of the commercial crops as well as with previous research described in the greenhouse tomato crops (Peet et al., 1997; Adams et al., 2001; Uzun, 2006; 2007) and in field grown tomato (Perry et al., 1997).

The analysis of the 217 commercial crop records indicated that along with temperature, soil type influenced harvesting time, duration of harvesting and yield of field grown tomato crops. The crops transplanted in late autumn and in winter developed under comparatively lower temperature days and required more days to harvest whereas crops transplanted in late spring and early summer were grown in comparatively higher temperature condition and were harvested earlier. The seasonal trend of harvesting time of the crops was clear, but significant crop to crop variability, and year to year variability, was also evident in the data. This variability was unlikely to be explained by temperature alone, highlighting the importance of identifying other factors impacting on crop development if accurate crop models are to be developed.

Soil type was found to be a factor affecting timing of first harvest in field grown tomato crops. Crops transplanted in clay soil required a longer duration from transplanting to first harvesting than crops grown in loamy and sandy soils. Differences in soil water holding capacity and moisture release characteristics is a possible explanation of the influence on rate of crop development, with rate of soil drying previously shown to influence shoot growth in tomato (Hussain et al., 1999; Sharp et al., 2000) and in other crops (Morgan & Connolly, 2013). Predicting the timing of the first harvest in field grown tomatoes is a key element of harvest scheduling for production companies managing large numbers of crops over multiple locations.

The analysis of the crop records also showed that crop yield was much more variable between crops than either time to first harvest or duration of harvest, most likely reflecting the greater range of site related factors that may affect yield. This was consistent with the research finding in processing tomato (Patane and Cosentino, 2010) and greenhouse grown tomato crops (Lobell et al., 2009; Kleiber et al., 2014).The high variation in yield of each crops transplanted in different weeks and seasons in a year was consistent with the crop yield of previous researchers that also explained the high yield variation in tomato by Sadras et al., 2002 and Lobell et al., 2007.

In addition to the climatic and edaphic (soil) factors, there are also other factors that were shown to have a small impact on harvesting time and yield on field grown tomato crops. The transplanted seedlings age was one of the factors affecting harvesting time of the field grown tomato crops. The younger transplanted seedlings (21 days old) flowered earlier and at lower nodes as compare to 27 and 31 days old transplanted seedlings and a similar trend was found in harvesting time of the crops. Although transplant seedlings age had a statistically significant impact on flowering and harvesting time of the tomato plants, the scale of the response at only 1 or 2 days difference is not likely to contribute to a meaningful impact from a commercial crop management perspective for the growers. The results do have some management significance by demonstrating that a wide window of transplant seedling ages can be used, so growers can use either younger or older than commercial standard seedlings for transplanting to escape bad weather or for managing labour availability and other managerial aspects for the plantings.

The research trial conducted in pruning treatments indicated that pruning is a crop managerial factor that has also an impact on harvesting time and yield of field grown tomato crops. Pruning within short interval of time at the first truss or second truss flowering date did not significantly affect the harvesting time and yield of the crops but the amount of pruning (light or heavy pruning) had a significant impact on harvesting time and yield of the crops. Pruning level (i.e. early or late at first truss or second truss flowering time and light or heavy) did not have a significant effect on the fruit numbers and weight of the first and the second truss on the plant, but harvesting time of these trusses was earlier on heavily pruned compared to lightly pruned plants. Heavy pruning in greatly reduces the number of trusses and number of fruits on later formed trusses, therefore adversely impacting plant yield. The knowledge gained from the pruning experiments can be applied by the growers of field grown tomato in applying appropriate levels of pruning for targeted harvesting times and crop yields.

The pruning research trial conducted in commercial tomato crops indicated that branching patterns of field grown tomato crops had considerable variability of dry matter distribution to the vegetative and generative sink organs in the plant, influencing fruit maturation rate and first harvesting time of the crops. The branching patterns of field grown tomato crops had a significant effect on assimilate partitioning to the fruits only at the maturity stages of the first fruit of the first truss that were pruned heavily and also resulted in significant differences on the first harvesting time of the crops. The result was also consistent with the explanation of earlier researchers that only a small amount of assimilate being utilized locally at certain growth stages of the plant but most of the assimilate produced in the plant being distributed to the different sinks organs within the plant from one assimilate pool, suggesting a whole plant assimilate distribution model rather than the theory that branches of a plant works as semi-independent structures in terms of source/sink relations (De Koning, 1994; Heuvilink, 1995; Andriolo et al., 1998).

The result also demonstrated that pruning treatments had no significant impact on the photosynthesis rate of the plants but the removal of all fruits and pruning of top growing vegetative shoots from the plants induced a significant decrease in photosynthetic quantum yield. The result indicated that the fruit loads of different branching patterns on commercial field grown tomato do not have any significant impact on dry matter production of the plant. An effect of branching pattern on dry matter production was only observed by manipulating the treatments with removal of all the generative sink organs in a shoot pruning regime that is not practiced by the commercial tomato growers. Even fruitless plants had a similar assimilate production rate before top pruning, presumably due to partitioning of assimilate to vegetative sinks such as new growing shoots instead of to fruits. While assimilate distribution patterns are a key component of the physiological basis of plant development, the scope for incorporation of assimilate partitioning modules in field tomato crop models appears limited due to range of factor that influence partitioning under commercial production conditions. Plant to plant variability is such that accuracy in prediction of fruit and truss maturity patterns at a plant level will be masked at a crop level. The result contradicted the finding in greenhouse tomato crops that low sink demand or low numbers of fruits per truss reduces photosynthesis rate of the leaves due to deposition of assimilates on the leaves (Tanka & Fujita, 1974; Marcelis, 1991; and Qian et al., 2012). The branching patterns in field grown tomato makes difficult to maintain an optimum source-sink ratio and increases the difficulty for predicting first harvesting time and yield of the crops in field environments.

Three common heat unit methods described by earlier researchers (Tydesley, 1978; Perry et al., 1997) were used for comparison based on the analysis of accumulated heat unit (growing degree days) from transplanting to first harvesting time of the 217 crops grown by SP Exports. Prediction accuracy, based on lowest coefficient of variation (CV) as recommended by Arnold (1959), was superior in most of the seasons in these three heat unit models. Thermal time models that provided an adequate prediction of harvest time of field grown tomato crops were therefore able to be generated. Use of different base temperatures for different production windows through the season suggests that variations in physiological responses existed to the wide range of temperatures experienced through the season in field conditions. The result was also consistent with the explanation of the earlier researchers in field grown tomato (Perry et al., 1997), as well as in greenhouse tomato crops (Hisaeda and Nishina, 2007; Higashida, 2009; Wada et al., 2013) and also highlights the importance of local data sets in generating usable thermal time models for field tomato crop prediction. The standard growing degree day (heat unit method-1) had the strong coefficient of determination (r^2) of prediction of first harvesting time of field grown tomato. The strength of the relationship between the actual first harvesting time and predicted first harvesting time of the crops by standard growing degree day method was approximately 75 percent which indicates that other environmental and site related factors have also influenced on first harvesting time of field grown tomato crops.

The analysis of the different methods of prediction of first harvesting time and actual first harvesting time of the test crops showed that heat unit method -1 (standard growing degree day) based on daily heat unit accumulation from transplanting to first harvesting time at base temperature in each season was superior to other methods of prediction of first harvesting time. The relationship between actual and predicted first harvesting time of the test crops was stronger, i.e. the coefficient of determination (r^2) of approximately

90 percent based on the daily heat unit accumulation at season specific base temperature, than other methods of prediction in field grown tomato crops. The result was also consistent with the explanation of different base temperature for each season and or location by earlier researchers to calculate the growing degree days on prediction of harvesting time of the crops (Monteith, 1981; Calaelo & Portas, 1987; Perry et al., 1997). The improved calendar day method of prediction of first harvest time of the test crops was also superior to the industry used calendar day method, and the coefficient of determination of 82 percent indicating other factors have also influenced on first harvesting time of field grown tomato crops. It was concluded that standard growing degree day (heat unit method-1) and improved calendar day method of prediction of first harvesting were more precise and superior than the industry used calendar day method in field grown trellis tomato in this region.

Production of tomato crop in the field is inherently more variable than production under controlled environment conditions in greenhouse crops. The high level of plant to plant and crop to crop variability in key plant development parameters under field conditions was amply demonstrated within this study. Identification of the component processes that have the largest influence on crop production attributes is more difficult under field conditions because of the broad range of variables present. For example, flowering time, and the node at which the first flowering truss was initiated, is one key development phase that has been used to explain variation in important production stages such as harvest time in other crops. In field tomatoes in this study, 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. Seasonal patterns in harvest time demonstrated the importance of temperature in determining crop growth and fruit maturation rate, so base models incorporating thermal time calculations or seasonal average performance data can approximate time of harvesting independently of component processes such as flowering time. Base thermal time and seasonal pattern models were developed that provided improved predictability over the current calendar date model used by industry. No adequate prediction of yield was achieved, and much more work is needed in identification of the key factors causing the very large crop to crop differences in yield in commercial production in the study location.

No adequate prediction of yield was achieved, and much more work is needed in identification of the key factors causing the very large crop to crop differences in yield in commercial production in the study location the effect of soil type on early crop development is an area that warrants further investigation. The greater understanding of the very complex assimilate distribution patterns in the branched, semi-determinant type tomatoes grown in the field may assist in prediction of total crop yield and the distribution of that yield over the multiple picking dates involved in field production. While the project was not able to refine a crop model beyond the temperature based models presented, the identification of areas for further investigation and documentation of responses to important management practices does provide a solid grounding for ongoing research to support the field tomato industry in the Queensland production region.

CONCLUSIONS

Crop production in the field is inherently more variable than production under controlled environment conditions. The high level of plant to plant and crop to crop variability in key plant development parameters under field conditions was amply demonstrated within this study. Identification of the component processes that have the largest influence on crop production attributes is more difficult under field conditions because of the broad range of variables present. In field tomatoes in this study, 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. Seasonal patterns in harvest time demonstrated the importance of temperature in determining crop growth and fruit maturation rate, so base models incorporating thermal time calculations or seasonal average performance data can approximate time of harvesting independently of component processes such as flowering time. Base thermal time and seasonal pattern models were developed that provided improved predictability over the current calendar date model used by industry. No adequate prediction of yield was achieved, and much more work is needed in identification of the key factors causing the very large crop to crop differences in yield in commercial production in the study location.

Identification of factors other than temperature that are impacting on crop development is important if more accurate crop models are to be developed. Soil type was found to be a factor affecting timing of first harvest in field grown tomato crops. Predicting the timing of the first harvest in field grown tomatoes is a key element of harvest scheduling for production companies managing large numbers of crops over multiple locations, and therefore the effect of soil type on early crop development is an area that warrants further investigation.

Statistically significant but not commercially important differences in harvest dates were found with transplant age and pruning treatments. Further refinement of field crop models may be possible with more research in these areas. In particular, greater understanding of the very complex assimilate distribution patterns in the branched, semi-determinant type tomatoes grown in the field may assist in prediction of total crop yield and the distribution of that yield over the multiple picking dates involved in field production. While the project was not able to refine a crop model beyond the temperature based models presented, the identification of areas for further investigation and documentation of responses to important management practices does provide a solid grounding for ongoing research to support the field tomato industry in the Queensland production region.

CHAPTER 9

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APPENDICES

Table1: *Regression equations(RE) of commercial and adjusted first harvesting time and node number at the first truss in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of commercial first harvesting	RE of adjusted first harvesting
1	Gourmet-February	x = 68.9 + 0.09 y	X = 70.7 - 0.39 y
2	Gourmet-March	x = 66.8 + 0.423 y	X = 59.8 + 1.23 y
3	Gourmet-April	x = 110.0 + 0.04 y	X= 97.1 + 1.33 y
4	Roma-February	x = 40.3 + 3.38 y	X = 37.4 + 3.38 y
5	Roma-March	x = 63.3 + 1.29 y	X = 62.2 + 0.911 y
6	Roma-April	x = 97.3 + 0.35 y	X = 92.1 + 0.64 y

x = Commercial first harvesting; X = Adjusted first harvesting; and y = Node number at the first truss

Table 2*: Regression equation (RE)of commercial and adjusted first harvesting time and leaf number at the time of first flower in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of commercial first harvesting	RE of adjusted first harvesting
1	Gourmet- February	x = 28.0 + 3.57 y	X = 32.0 + 3.07 y
2	Gourmet- March	x = 58.7 + 1.01 y	X = 51.3 + 1.55 y
3	Gourmet-April	x = 108.0 + 0.119 y	X= 110.0 - 0.226 y
4	Roma-February	x = 31.5 + 3.17 y	X = 27.4 + 3.27 y
5	Roma-March	x = 63.4 + 0.793 y	X = 57.7 + 0.997 y
6	Roma-April	x = 87.5 + 1.44 y	X = 82.7 + 1.64 y

x = Commercial first harvesting; X = Adjusted first harvesting; and y = Leaf number at the time of first flower

Table 3: *Regression equation (RE)of commercial and adjusted first harvesting time and shoot number at the time of first flower in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of commercial first harvesting	RE of adjusted first harvesting
1	Gourmet- February	x = 63.4 + 5.00 y	X = 112.0 - 1.70 y
2	Gourmet- March	x = 66.5 + 2.62 y	X = 61.7 + 4.87 y
3	Gourmet-April	x = 116.0 - 1.78 y	X= 95.7 + 1.75 y
4	Roma-February	x = 70.9 - 0.18 y	X = 66.4 + 1.32 y
5	Roma-March	x = 70.7 + 0.777 y	X = 64.0 + 3.31 y
6	Roma-April	x = 98.6 + 1.84 y	X = 68.7 - 0.65 y

x = Commercial first harvest; X = Adjusted first harvesting and y = Shoot number at the time of first flower

Table 4: *Regression equation (RE)of commercial and adjusted first harvesting time and flowering days of the first truss after transplanting in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of commercial first harvesting	RE of adjusted first harvesting
1	Gourmet- February	x = 44.8 + 1.01 y	X = 42.5 + 1.03 y
2	Gourmet- March	x = 60.2 + 0.529 y	X = 55.9 + 0.679 y
3	Gourmet-April	x = 69.4 + 1.32 y	X= 53.0 + 1.74 y
4	Roma-February	x = 36.0 + 1.54 y	X = 28.8 + 1.74 y
5	Roma-March	x = 65.9 + 0.333 y	X = 55.3 + 0.741 y
6	Roma-April	x = 81.2 + 0.957 y	X = 72.9 + 1.23 y

x = Commercial first harvest; X = Adjusted first harvesting; and y = Flowering days of the first truss

Table 5: *Regression equation (RE) of harvesting fruits and weight in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits and weight
1	Gourmet- February	x = 0.324 + 0.100 y
2	Gourmet- March	x = 1.14 + 0.0837 y
3	Gourmet-April	x = 1.14 + 0.0640 y
4	Roma-February	x = - 0.700 + 0.0979 y
5	Roma-March	x = 0.312 + 0.0770 y
6	Roma-April	x = 1.00 + 0.0665 y

x = Harvested fruits weight; and y = Harvested fruits

Table 6: *Regression equation (RE) of harvested fruits and node number at the first truss in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits and node
1	Gourmet- February	x = 39.7 + 0.58 y
2	Gourmet- March	x = 78.0 - 0.59 y
3	Gourmet-April	x = 25.5 + 5.35y
4	Roma-February	x = 124.0 - 6.75 y
5	Roma-March	x = 131.0 - 1.53 y
6	Roma-April	x = 124.0 - 3.78 y

x = Harvested fruits; and y = Node number at the first truss

***Table 7**: Regression equation (RE) of harvested fruits and fruit truss numbers in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits & fruit truss number
1	Gourmet- February	x = 8.9 + 2.85 y
2	Gourmet- March	x = 63.4 + 0.75 y
3	Gourmet-April	x = 46.0 + 1.44 y
4	Roma-February	x = 21.7 + 3.03 y
5	Roma-April	x = 61.7 + 3.16 y
6	Roma-April	x = 75.3 + 1.71 y

x = Harvested fruits; and y = fruit truss numbers

***Table 8:** Regression equation (RE) of harvested fruits and shoots with fruit truss in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits & shoot with fruit truss
1	Gourmet- February	x = 51.3 - 1.72 y
2	Gourmet- March	x = 59.9 + 2.56 y
3	Gourmet-April	x = 56.4 + 1.53 y
4	Roma-February	x = 24.3 + 7.96 y
5	Roma-March	x = 49.9 + 11.7 y
6	Roma-April	x = 87.3 + 1.57 y

x = Harvested fruits; and y = Shoots with fruit truss

***Table 9**: Regression equation (RE) of total fruits and fruit harvesting duration in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits and duration
1	Gourmet- February	x = 8.9 + 0.555 y
2	Gourmet- March	x = 8.9 + 0.555 y
3	Gourmet-April	x = 122 - 1.06 y
4	Roma-February	x = 18.1 + 0.716 y
5	Roma-March	x = 126 - 0.05 y
6	Roma-April	x = - 4.1 + 1.46 y

x = Harvested fruits; and y = Fruit picking duration

***Table10:** Regression equation (RE) of total fruits and fruit picking frequency in Gourmet and Roma tomato transplanted in different months in 2011, Bundaberg.*

SN	Crop	RE of harvested fruits and harvesting frequency
1	Gourmet- February	x = - 7.6 + 4.27 y
2	Gourmet- March	x = - 7.6 + 4.27 y
3	Gourmet-April	x = 26.1 + 2.81 y
4	Roma-February	x = 4.7 + 4.62 y
5	Roma-March	x = - 13.8 + 8.01 y
6	Roma-April	x = 14.2 + 5.56 y

x = Harvested fruits; and y = Fruit picking frequency

Table11: *Coefficient of variation (CV) of first harvest day, duration, total and marketable yield of Roma and Gourmet tomato transplanted at different weeks in 2008-2011.*

	Coefficient of Variation (CV) of Roma Tomato				Coefficient of Variation (CV) of Gourmet Tomato			
Weeks	First Harvest Day	Harvest Duration	Total Yield	Marketable Yield	First Harvest Day	Harvest Duration	Total Yield	Marketable Yield
1-4	7.36	14.75	17.23	18.78	7.59	17.45	39.77	42.17
5-8	11.05	8.30	14.98	14.73	8.08	14.97	22.06	22.13
9-12	8.14	14.21	10.24	9.44	8.90	14.26	21.48	20.62
13-16	6.50	17.08	6.59	6.43	4.22	10.07	22.48	22.08
17-20	6.49	14.43	13.80	13.41	7.85	8.68	34.17	33.81
21-24	9.92	9.01	6.27	6.11	8.91	8.36	31.24	30.73
25-28	10.62	9.03	18.72	18.36	10.65	11.39	20.12	19.96
29-32	3.45	9.42	15.43	15.42	6.89	10.58	7.43	7.46
33-36	3.82	8.92	13.19	13.30	6.31	6.53	5.61	5.60
37-40	4.36	9.34	11.09	11.46	6.07	8.86	9.75	9.68
41-44	3.36	6.81	20.11	20.23	2.20	10.06	14.48	14.29
45-48	2.25	5.60	19.00	18.88	2.09	13.58	18.60	18.58
49-53	3.83	14.96	21.06	20.69	3.87	20.41	17.68	17.53

Table 11 A: *The mean ± Standard error of mean (SE) of the first harvesting, harvest duration, total and marketable yield of Roma and Gourmet tomato in clay, loamy and sandy soils transplanted by SP Exports in 2008- 2011 in Bundaberg. The data presented here are the mean values ± SE, which were analysed at the significant levels of P<0.05 at Tukey,s. Values with the same letters in each column for Roma and Gourmet tomato represent there was no difference.*

	Roma Tomato				Gourmet Tomato			
Soil	First Harvest Day	Harvest Duration	Total Yield	Marketable Yield	First Harvest Day	Harvest Duration	Total Yield	Marketable Yield
Clay	83.44 ± 2.49^{a}	56.75 ± 4.22^{a}	72.35 ± 2.36^{a}	64.71 ± 2.14^{a}	85.65 ± 2.47^{a}	47.76 ± 6.34^{a}	66.62 ± 3.69^{a}	59.76 ± 3.34^{a}
Loamy	67.08 ± 2.18^{b}	44.35 ± 2.46^{a}	65.27 ± 3.90^{a}	58.25 ± 3.49^{a}	69.53 ± 1.31^{b}	51.02 ± 1.74	70.30 ± 3.26^{a}	62.90 ± 2.94^{a}
Sandy	75.80 ± 3.154^{ab}	64.19 ± 2.34^{b}	66.26 ± 3.86^{a}	59.24 ± 3.49^{a}	74.00 ± 4.72^{ab}	56.60 ± 1.99^{a}	71.92 ± 8.3^{a}	64.33 ± 7.40^{a}

Table 12: *The co-efficient of variation (CV) at different ceiling and base temperatures for all seasons in Roma and Gourmet tomato (Heat unit method-2)*

Crops	Season	Number of Crops	Ceiling Temperature(°C)	CV (%) at different Base Temperature (° C) in Heat Unit Method -2									
				0	2	4	6	8	10	12	14	16	18
Roma	All	99	26	**23.27**	23.39	23.53	23.72	23.96	24.30	24.80	25.56	26.89	29.58
Roma	All	99	28	18.29	17.98	17.63	17.21	16.73	16.16	15.49	14.76	**14.12**	14.23
Roma	All	99	30	15.24	14.73	14.15	13.49	12.75	11.94	11.14	**10.58**	10.89	13.46
Roma	All	99	32	14.10	13.54	12.92	12.23	11.49	10.77	**10.22**	10.23	11.58	15.48
Roma	All	99	34	13.95	13.39	12.77	12.09	11.38	10.71	**10.26**	10.43	12.00	16.12
Gourmet	All	118	26	**23.15**	23.25	23.36	23.51	23.71	23.99	24.39	25.04	26.19	28.57
Gourmet	All	118	28	17.75	17.38	16.94	16.44	15.83	15.11	14.25	13.25	12.27	**12.05**
Gourmet	All	118	30	14.67	14.09	13.43	12.66	11.79	10.82	9.82	**9.04**	9.25	12.02
Gourmet	All	118	32	13.52	12.89	12.17	11.37	10.50	9.60	8.85	**8.69**	10.06	14.15
Gourmet	All	118	34	13.36	12.72	12.01	11.21	10.35	9.50	**8.83**	**8.83**	10.40	14.68

***Table 13**: The co-efficient of variation (CV) at different ceiling and base temperatures for all seasons in Roma and Gourmet tomato (Heat unit method-3)*

Crops	Season	Number of Crops	Ceiling Temperature(ºC)	CV (%) at different Base Temperature (º C) in Heat Unit Method -3									
				0	2	4	6	8	10	12	14	16	18
Roma	All	99	26	**12.29**	12.48	12.72	13.05	13.48	14.09	14.99	16.41	18.85	23.64
Roma	All	99	28	**11.28**	11.38	11.53	11.72	11.99	12.37	12.95	13.83	15.28	17.82
Roma	All	99	30	**12.02**	12.30	12.67	13.14	13.76	14.60	15.77	17.42	19.87	23.70
Roma	All	99	32	**12.87**	13.29	13.81	14.48	15.34	16.46	17.97	20.06	23.04	27.52
Roma	All	99	34	**13.09**	13.53	14.09	14.80	15.70	16.89	18.47	20.64	23.72	28.33
Gourmet	All	118	26	**11.82**	12.01	12.24	12.55	12.97	13.55	14.41	15.76	18.06	22.58
Gourmet	All	118	28	**10.16**	10.23	10.32	10.47	10.69	11.02	11.54	12.38	13.80	16.35
Gourmet	All	118	30	**10.59**	10.83	11.15	11.58	12.17	12.97	14.11	15.75	18.18	21.98
Gourmet	All	118	32	**11.34**	11.72	12.20	12.82	13.64	14.73	16.20	18.24	21.17	25.55
Gourmet	All	118	34	**11.45**	11.85	12.36	13.02	13.88	15.01	16.54	18.65	21.65	26.13

***Table 14**: The co-efficient of variation (CV) at different ceiling and base temperatures for each season in Roma tomato (Heat unit method -3)*

Crops	Season	Number of Crops	Ceiling Temperature(°C)	CV (%) at different Base Temperature (° C) in Heat Unit Method -3									
				0	2	4	6	8	10	12	14	16	18
Roma	Summer	30	26	**11.56**	11.80	12.10	12.50	13.03	13.78	14.89	16.66	19.79	26.38
Roma	Autumn	29	26	**12.18**	12.21	12.25	12.30	12.37	12.48	12.63	12.87	13.31	14.24
Roma	Winter	17	26	10.61	10.60	**10.59**	10.59	10.59	10.61	10.67	10.79	11.09	11.88
Roma	Spring	23	26	**9.10**	9.26	9.47	9.77	10.21	10.86	11.86	13.48	16.29	21.73
Roma	Summer	30	28	**10.52**	10.60	10.71	10.83	11.00	11.22	11.52	11.96	12.63	13.73
Roma	Autumn	29	28	**11.56**	11.63	11.72	11.86	12.08	12.42	12.97	13.88	15.49	18.55
Roma	Winter	17	28	**11.45**	11.56	11.71	11.91	12.19	12.58	13.16	14.06	15.57	18.33
Roma	Spring	23	28	**8.66**	8.67	8.68	8.71	8.75	8.81	8.93	9.13	9.48	10.17
Roma	Summer	30	30	9.58	9.57	9.56	9.54	9.53	9.51	9.49	9.47	**9.46**	**9.46**
Roma	Autumn	29	30	**11.53**	11.67	11.87	12.16	12.58	13.20	14.15	15.64	18.07	22.34
Roma	Winter	17	30	**11.69**	11.84	12.03	12.28	12.63	13.11	13.82	14.90	16.65	19.80
Roma	Spring	23	30	**9.63**	9.72	9.83	9.97	10.14	10.36	10.67	11.09	11.70	12.64
Roma	Summer	30	32	**9.39**	9.40	9.41	9.43	9.47	9.53	9.63	9.79	10.05	10.49
Roma	Autumn	29	32	**11.42**	11.57	11.79	12.10	12.57	13.25	14.29	15.90	18.53	23.05
Roma	Winter	17	32	**11.89**	12.06	12.27	12.56	12.93	13.46	14.21	15.35	17.19	20.44
Roma	Spring	23	32	**10.77**	10.97	11.22	11.52	11.90	12.38	13.00	13.83	14.98	16.66
Roma	Summer	30	34	**9.40**	9.41	9.43	9.46	9.52	9.60	9.72	9.92	10.23	10.74
Roma	Autumn	29	34	**11.38**	11.53	11.75	12.07	12.54	13.24	14.29	15.92	18.58	23.15
Roma	Winter	17	34	**11.90**	12.07	12.29	12.57	12.95	13.48	14.24	15.39	17.24	20.50
Roma	Spring	23	34	**11.14**	11.38	11.67	12.03	12.47	13.02	13.73	14.68	15.99	17.87

***Table 15**: The co-efficient of variation (CV) at different ceiling and base temperatures for each season in Gourmet tomato (Heat unit method -3)*

Crops	Season	Number of Crops	Ceiling Temperature(°C)	CV (%) at different Base Temperature (° C) in Heat Unit Method -3									
				0	2	4	6	8	10	12	14	16	18
Gourmet	Summer	44	26	**8.94**	9.04	9.17	9.37	9.65	10.08	10.78	12.00	14.31	19.48
Gourmet	Autumn	29	26	8.60	8.55	8.49	8.42	8.33	8.24	8.13	8.02	**7.97**	8.19
Gourmet	Winter	20	26	10.43	10.42	10.41	10.41	**10.40**	10.42	10.46	10.58	10.86	11.62
Gourmet	Spring	25	26	**11.80**	11.91	12.05	12.25	12.52	12.93	13.55	14.56	16.35	19.93
Gourmet	Summer	44	28	**8.76**	8.79	8.83	8.89	8.97	9.08	9.26	9.53	9.98	10.80
Gourmet	Autumn	29	28	7.25	**7.23**	7.25	7.32	7.50	7.85	8.51	9.68	11.77	15.65
Gourmet	Winter	20	28	**11.18**	11.28	11.42	11.59	11.84	12.20	12.73	13.56	14.96	17.57
Gourmet	Spring	25	28	**12.02**	12.08	12.16	12.26	12.39	12.55	12.76	13.06	13.50	14.21
Gourmet	Summer	44	30	**9.01**	9.04	9.07	9.11	9.15	9.21	9.28	9.37	9.50	9.68
Gourmet	Autumn	29	30	**7.36**	7.49	7.70	8.04	8.56	9.36	10.58	12.48	15.50	20.57
Gourmet	Winter	20	30	**11.46**	11.60	11.78	12.01	12.34	12.79	13.44	14.46	16.12	19.11
Gourmet	Spring	25	30	**12.28**	12.37	12.48	12.61	12.78	12.99	13.26	13.64	14.17	14.98
Gourmet	Summer	44	32	**9.43**	9.51	9.60	9.71	9.85	10.02	10.25	10.55	10.97	11.57
Gourmet	Autumn	29	32	**7.33**	7.48	7.72	8.10	8.68	9.55	10.86	12.87	16.02	21.27
Gourmet	Winter	20	32	**11.62**	11.78	11.97	12.23	12.58	13.07	13.78	14.85	16.59	19.70
Gourmet	Spring	25	32	**12.78**	12.93	13.11	13.33	13.61	13.97	14.43	15.07	15.95	17.27
Gourmet	Summer	44	34	**9.41**	9.49	9.58	9.70	9.84	10.03	10.27	10.58	11.02	11.66
Gourmet	Autumn	29	34	**7.31**	7.46	7.70	8.08	8.66	9.54	10.86	12.88	16.05	21.32
Gourmet	Winter	20	34	**11.63**	11.78	11.98	12.25	12.60	13.09	13.80	14.88	16.63	19.75
Gourmet	Spring	25	34	**12.85**	13.01	13.21	13.45	13.75	14.13	14.64	15.31	16.27	17.68

***Table 15A**: Analysis of deviance for possible best models with lowest AIC in full model for the harvesting days of Roma tomatoes.*

```
fm9R: HarvestDay ~ Seedling_Age + (1 | Block)
fm8R: HarvestDay ~ Seedling_Age + Truss_Number + (1 | Block)
fm7R: HarvestDay ~ Seedling_Age + Truss_Number + Pruning_Regime + (1 |
fm7R:     Block)
     Df   AIC   BIC   logLik deviance    Chisq Chi Df Pr(>Chisq)
fm9R  4 25338 25362 -12664.9    25330
fm8R  9 18814 18868  -9398.2    18796 6533.350      5  < 2.2e-16 ***
fm7R 12 18776 18848  -9375.9    18752   44.596      3  1.128e-09 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 15B: Correlation matrix of factors in the full linear-mixed effects model for Roma tomatoes transplanted in Bundaberg, 2012.

	Intercept	SDIn-A	Truss-2	Truss-3	Truss-4	Truss-5	Truss-6	Pr -REL	Pr-RLH
Seedling Age	-0.617	0.000							
Truss -2	-0.141	0.003							
Truss -3	-0.143	-0.141	0.491						
Truss -4	-0.142	-0.141	0.487	0.483					
Truss -5	-0.142	-0.141	0.485	0.481	0.477				
Truss -6	-0.140	-0.141	0.482	0.478	0.474	0.472			
Pruning Regime(1:1)	-0.110	-0.141	-0.001	-0.004	-0.002	-0.005	-0.007		
Pruning Regime(1:2)	-0.116	-0.141	0.002	0.003	0.007	0.007	0.008	0.502	
Pruning Regime(2:2	-0.110	-0.141	-0.002	-0.001	-0.001	-0.004	-0.005	0.511	0.499

***Table 16**: Regression equation of prediction of first harvest day of tomato fruits of Roma tomato based on heat unit method-1in all seasons*

SN	Season	Regression Equation
1	Summer	x = -15.75545 + 0.0637966 y
2	Autumn	x = 13.3020 + 0.0637966 y
3	Winter	x = 19.2889 + 0.0637966 y
4	Spring	x = - 6.34378 + 0.0637966 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 17**: Regression equation of prediction of first harvest day of tomato fruits of Roma tomato based on heat unit method-2 in all seasons*

SN	Season	Regression Equation
1	Summer	x = 4.51926 + 0.543514 y
2	Autumn	x = 27.0223 + 0.543514 y
3	Winter	x = 32.6282 + 0.543514 y
4	Spring	x = 7.80813 + 0.543514 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 18**: Regression equation of prediction of first harvest day of tomato fruits of Roma tomato based on heat unit method-3 in all seasons*

SN	Season	Regression Equation
1	Summer	x = 10.5197 + 0.0014015 y
2	Autumn	x = 38.2268 + 0.0014015 y
3	Winter	x = 37.2236 + 0.0014015 y
4	Spring	x = 5.33835 + 0.0014015 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 19**: Regression equation of prediction of first harvest day of tomato fruits of Gourmet tomato based on heat unit method-1in all seasons*

SN	Season	Regression Equation
1	Summer	x = -1.25798+ 0.526328 y
2	Autumn	x = 26.4863 + 0.526328 y
3	Winter	x = 32.8783 + 0.526328 y
4	Spring	x = 6.41097 + 0.526328 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

Table 20*: Regression equation of prediction of first harvest day of Gourmet tomato fruits based on heat unit method-2 in all seasons*

SN	Season	Regression Equation
1	Summer	x = 8.80649 + 0.0597225 y
2	Autumn	x = 32.9578 + 0.0597225 y
3	Winter	x = 38.0271 + 0.0597225 y
4	Spring	x = 11.8262 + 0.0597225 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

Table 21*: Regression equation of prediction of first harvest day of Gourmet tomato fruits based on heat unit method-3 in all seasons*

SN	Season	Regression Equation
1	Summer	x = 32.5049 + 0.000861899 y
2	Autumn	x = 58.9954 + 0.0014015 y
3	Winter	x = 59,5067 + 0.0014015 y
4	Spring	x = 27.7398 + 0.0014015 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

Table 22*: Regression equation of prediction of first harvest day of Roma tomato based on heat unit method-1in each season*

SN	Season	Regression Equation
1	Summer	x = 21.4541 + 0.0601325 y
2	Autumn	x = 17.7836 + 0.0601325 y
3	Winter	x = 23.6677 + 0.0601325 y
4	Spring	x = - 25.864 + 0.0601325 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

Table 23*: Regression equation of prediction of first harvest day of Roma tomato based on heat unit method-2 in each season*

SN	Season	Regression Equation
1	Summer	x = 26.8455 + 0.0512473 y
2	Autumn	x = 30.2982 + 0.0512473 y
3	Winter	x = 71.2554 + 0.0512473 y
4	Spring	x = 19.5364 + 0.0512473 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 24**: Regression equation of prediction of first harvest day of Roma tomato based on heat unit method-3 in each season*

SN	Season	Regression Equation
1	Summer	x = 14.8832 + 0.00112543 y
2	Autumn	x = 47.746 + 0.00112543 y
3	Winter	x = 57.8268 + 0.00112543 y
4	Spring	x = 17.0561 + 0.00112543 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 25**: Regression equation of prediction of first harvest day of Gourmet tomato based on heat unit method-1in each season*

SN	Season	Regression Equation
1	Summer	x = 8.60362 + 0.449674 y
2	Autumn	x = 36.188 + 0.449674 y
3	Winter	x = 59.2107 + 0.449674 y
4	Spring	x = 3.13031 + 0.449674 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 26**: Regression equation of prediction of first harvest day of Gourmet tomato based on heat unit method-2 in each season*

SN	Season	Regression Equation
1	Summer	x = 19.6793 + 0.044992 y
2	Autumn	x = 47.5444 + 0.044992 y
3	Winter	x = 72.3403 + 0.044992 y
4	Spring	x = -0.130134 + 0.044992 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

***Table 27**: Regression equation of prediction of first harvest day of Gourmet tomato based on heat unit method-3 in each season*

SN	Season	Regression Equation
1	Summer	x = 22.4308 + 0.00111765 y
2	Autumn	x = 52.4714 + 0.00111765 y
3	Winter	x = 65.5269 + 0.00111765 y
4	Spring	x = 22.1538 + 0.00111765 y

x = Prediction of first harvest day of fruits; and y = Heat unit accumulation based on heat unit method

Table 28: *The monthly weather data from the Bundaberg Aero Club[@] close to the tomato crop production blocks in 2012- 2014*

2012		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	29.6	30.4	29.1	27.6	24.5	21.4	21.7	23.8	25.7	27.1	29.1	31.7
	Min*	20.8	21.3	20.0	17.0	13.2	12.1	10.9	9.3	13.0	14.9	17.6	20.0
Rainfall	mm	263.8	74.0	241.4	37.2	27.6	183.0	89.4	11.4	18.0	27.0	38.2	47.6
TCSR+	MJ/h	658.0	635.4	552.5	500.2	422.4	322.5	388.5	536.6	619.1	758.1	858.6	947.5
2013		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	31.9	29.7	28.6	27.4	24.2	22.3	23.3	25.6	28.5	29.3	30.0	30.4
	Min*	21.7	20.6	20.0	17.3	13.7	11.8	13.1	9.7	15.1	16.8	18.6	19.0
Rainfall	mm	494.8	237.4	179.6	40.6	60.6	29.8	15.6	0.8	3.0	37.4	48.2	75.4
TCSR+	MJ/h	765.5	598.1	538.3	511.6	445.8	367.0	395.8	583.7	608.8	739.1	698.6	850.1
2014		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°c)	Max*	31.7	30.5	30.2	28.3	25.6	23.8	22.9	23.7	25.9	28.2	30.0	30.4
	Min*	21.4	20.8	20.0	17.9	14.4	12.5	8.2	11.5	12.6	15.3	19.6	21.0
Rainfall	mm	32.8	68.8	192.4	83.6	7.0	18.6	3.4	62.4	17.8	13.0	70.2	150.2
TCSR+	MJ/h	750.3	603.5	609.0	525.4	446.7	381.9	457.6	470.2	602.7	741.2	761.0	711.9

[*]Maximum and minimum Temperature was based on mean of maximum and minimum temperature of the month.

[+] Total cumulative solar radiation (TCSR) was based on the cumulative solar radiation of the days on each month.

[a] Mega joules per hour

[@]Justification is given in Chapter 2 on the use of data

Table 29: Two –way ANOVA table of dry weight (gm) of first fruit of Control, AT, BT and RSS treatments at 38, 48, 58 and 64 days after flowering (DAF) of the first truss of Gourmet tomato transplanted in Bundaberg, 2013.

Source	DF	SS	MS	F	P
Treatments	3	11.9891	3.9964	8.57	0.005
DAF	3	33.5102	11.1701	23.94	0.000
Error	9	4.1984	0.4665		
Total	15	49.6978			

S = 0.6830 R-Sq = 91.55% R-Sq(adj) = 85.92%

Table 30: Two-way analysis of ANOVA table of dry weight (gm) of 2-6 fruits of Control, AT, BT and RSS treatments at 38, 48, 58 and 64 days after flowering (DAF) of the first truss of Gourmet tomato transplanted in Bundaberg, 2013.

Source	DF	SS	MS	F	P
Treatments	3	41.25	13.749	5.21	0.023
DAF	3	987.07	329.024	124.70	0.000
Error	9	23.75	2.639		
Total	15	1052.06			

S = 1.624   R-Sq = 97.74%   R-Sq(adj) = 96.24%

Table 31: Two-way analysis of ANOVA table of dry weight (gm) of first truss of Control, AT, BT and RSS treatments at 38, 48, 58 and 64 days after flowering of the first truss of Gourmet tomato transplanted in Bundaberg, 2013.

Source	DF	SS	MS	F	P
Treatments	3	36.97	12.323	3.63	0.058
DAF	3	1384.29	461.431	135.76	0.000
Error	9	30.59	3.399		
Total	15	1451.85			

S = 1.844   R-Sq = 97.89%   R-Sq(adj) = 96.49%