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The Use of Cubic Smoothing Spline Models for Predicting Early Fruit Size in 'Keenan' Valencia (*Citrus sinensis* L. Osbeck) Oranges

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Abstract: Fruit size is an important factor for the sale of fruit in fresh markets. Fruit size prediction early in the growing season would help with planning harvest operations, administering marketing strategies and an advance determination of the proportion of fruit that will be suitable for certain size classes. Fruit diameter growth of 'Keenan' Valencia oranges was measured over five consecutive growing seasons (2014–2018) during Stage II (cell enlargement) and Stage III (maturation) periods between January and October. Fruits were randomly selected and tagged from around the tree canopy to record the fruit diameter at fortnightly intervals until harvest. The data were used to develop a fruit size prediction model using the cubic smoothing splines technique. Results indicated that from the fruit growth patterns, an accurate prediction of the final fruit size and distribution were possible during the early Stage II fruit development phase, 6–7 months ahead of the final harvest. It was concluded that fruit size must be 66 mm in diameter by 30 March to attain a fruit size > 77 mm at harvest. This model was tested in 2019 with an accuracy of 97% in predicting fruit size distribution harvest across three size classes.

Keywords: fruit modelling; fruit size prediction; fruit growth curves; size distribution; ASReml

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1. Introduction

Fruit size is an important factor for the profitable sale of citrus in both local and overseas markets. Therefore, it has become important for growers to have an estimate very early in the season about the fruit size of their crop. A model is needed which can provide growers an estimate of their final fruit size at harvest. Potential fruit size problems identified early in the season provide an opportunity for the growers to remove small undersized fruit by fruit thinning or they can use other management techniques to enhance fruit size which otherwise will not meet large fruit size requirements at harvest. The reduction in crop load by removing the smaller or undersized fruit during a specific phenological stage would be able to direct the partitioning of food reserves into the remaining fruit on tree resulting into possible gains in fruit size enhancement at harvest [1]. In addition to the fruit size enhancement, an early prediction of fruit size distribution at harvest is also needed by citrus growers and packing houses to assist with planning marketing programs. This will help the growers to know what proportion of their fruit will be destined for fresh consumption or the juicing factory.

The citrus industry is one of Australia's largest fresh produce exporters, with export volumes increasing 84% from 158,000 tonnes in 2014 to over 222,000 tonnes in 2022, planted over 29,000 ha. Thirty percent of Australian citrus is grown in the Riverina region of Australia with 'Keenan' Valencia orange [*Citrus sinensis* (L.) Osb.] the dominant variety. Total production in the 2022 season for Valencia orange in the Riverina was 140,000 tonnes over 4233 hectares. Riverina plantings are predominantly grown on 'Tri22' rootstock, the Australian selection of *Poncirus trifoliata*.

In the Australian citrus industry, the prediction of the final fruit size of Valencia has been traditionally based on forecasting data gathered in May and June for each growing season. Although these initial forecasts might be acceptable for preliminary market planning, they are too late in the fruit growth cycle to make the crop management decisions to enhance fruit size if fruits are to be sold for fresh consumption. A practice of fruit size enhancement strategies in an on-year crop is generally carried out before April as later removal has little or no effect on fruit size. Fruit growth rates are significantly decreased in Valencia oranges after April [2].

Three growth stages have been identified in citrus fruit: Stage I (cell division), Stage II (cell enlargement) and Stage III (maturation phase) [3]. In sweet orange, the transition from Stage I to Stage II has been reported to occur around mid to late December in the inland growing areas of south-east Australia [4]. Fruit size is mainly determined by the genetic make-up of the cultivar, but a range of cultural practices and climatic factors can affect the fruit size [5–7]. The accumulative fruit development during each growth stage until harvest determines the final fruit size [8]. During Stage I growth period it is very difficult to make appropriate predictions about the fruit size because the crop is going through different stages by adjusting its crop load due to the ongoing December fruit drop period [9].

In a heavy cropping year, this process is continuous from the phenological stage of petal fall to late December or early January in Australia. The climatic conditions can adversely affect the fruit drop and short sessions or periods of extreme (>40 °C) weather conditions can have an adverse effect on the fruit size at harvest [10,11]. The short-term variations in fruit size due to hot temperatures and/or due to significant rainfall events (>25 mm) can occur during the Stage II growth period under the Sunraysia conditions. Lack of water can negatively affect the fruit, resulting in fruit shrinkages, which have been reported in grapefruit in South Africa [12], and in 'Zhuju' tangerine in China [13]. In general, the growth rate stabilises once the fruit drop period is completed, and from that point onward the fruit growth stability improves through Stage II phase of fruit development. Therefore, it has been expected that once the Stage II phase of fruit development is fully underway, a more precise prediction of fruit size will be possible.

In the past, models were developed for early fruit size prediction in citrus crops such as 'Ellendale' mandarins [14], Valencia oranges [15], Clementine and Satsuma mandarins [16]. To the best of our knowledge, there is no fruit model available which can predict the final fruit size before April for Valencia orange. Since 'Keenan' is the dominant Valencia variety used in Australia for the commercial production of fresh fruit and juice, therefore, the objective of this investigation was to develop an early prediction model for 'Keenan' Valencia fruit size and fruit size distribution at harvest. This model could equally be used for fruit being harvested for fresh consumption or juice processing.

2. Materials and Methods

2.1. Experimental Site

The experimental site used during this study was situated at the New South Wales Department of Primary Industries (NSW DPI) Dareton Primary Industries Institute (latitude 34°01′ S and longitude 141°09′ E). The experimental site was situated in the Sunraysia growing district in south-east Australia. The soil type for this experiment was deep sandy loam from depth of 0–80 cm, and sandy clay from depth of 80–140 cm. The electric conductivity of the soil ranged between 0 and 0.4 dS/m, soil pH ranged between 8 and 9 (water), while the tree root zone was 80–100 cm deep. The average maximum temperature ranges 30–32 °C during December to February and 16–17 °C during June to August at Dareton. The average annual rainfall for the 5 experimental years was 285 mm. The annual rainfall of 314 mm, 188 mm, 400 mm, 330 mm, 330 mm, and 192 mm occurred in 2014, 2015, 2016, 2017, and 2018, respectively. Total accumulated heat units per year were approximately 1880 [17]. The trees were irrigated with an average of 15–16 ML/ha/season with low level, under-tree sprinklers.

Trees of 'Keenan' Valencia were planted on *Troyer citrange* rootstock in September 1968 at a spacing of 7.3 × 3.7 m (370 trees/hectare) in a north–south row orientation. Trees were 46 years old at the start of 2014. Trees were topped and hedged prior to the commencement of the experiment. Trees were lightly hand pruned to open the tree centres. The trunk circumference (cm) and tree height (m) were recorded for the experimental trees. The mean trunk circumference for the experimental trees was 80 cm, while the mean height for the experimental trees was 3.5–4.0 m. Nitrogen as Urea (46% N) was applied through the irrigation system at a rate of 240 kg/ha in a split (50:50) application in mid-spring and mid-summer each year. Double super phosphate (17.5% P) was banded at a rate of 250 kg/ha close to the tree drip line in 2014, 2016 and 2018. Potassium fertiliser was not applied as the soil held adequate levels of this element. Combined zinc and manganese foliar sprays were applied annually to the spring and autumn leaf flush.

2.2. Fruit Size Data

Fruit growth was measured and recorded for five consecutive growing seasons from 2014 to 2018. The climatic conditions varied across the experimental years and the trees carried different crop loads across different years (Table 1). In each growing season 100 fruit/tree for 10 trees (1000 fruit) were selected at random and tagged for the fruit size recording purposes from around the tree periphery. Fruit equatorial diameter (mm) was recorded with an electronic digital calliper (model CD-15 DC; Mitutoyo (UK) Ltd., Telford, UK) to within 0.01 mm accuracy. Fruit diameter (mm) was recorded at fortnightly intervals on 21 occasions between 1 January and 30 October for each growing season. Experimental data sets of fruit growth were recorded during Stage II and Stage III phenological phases which was used in developing the fruit growth model. The most active period for fruit growth expansion is January to March under the Sunraysia conditions and the climatic data for those months are given in Table 1.

Table 1. Climatic conditions during active fruit growth period (1 January–31 March), crop load (fruit number/tree), initial and final fruit size (mm) for five growing seasons in 'Keenan' Valencia oranges.

	Number of Days (January–March)		Accumulated Rainfall (mm) (January–March)	* Crop Load (Fruit/Tree)	* Initial Fruit Size (mm) 1 January	* Final Fruit Size (mm) at Harvest 30 October
	30–35 °C	>40 °C				
2014	17	16	97	975	38.5	72.5
2015	20	8	59	973	39.8	74.1
2016	23	13	70	715	42.0	78.9
2017	25	9	38	1320	34.6	72.0
2018	26	11	7	811	40.8	72.8
LSD	-	-	-	60	1.5	1.9

* Data were analysed with ANOVA and mean differences across years were compared with LSD (Least significant difference at 5%).

2.3. Fruit Harvest and Fruit Size Distribution

In each experimental year (2014–2018), and in validation year (2019), all fruit were harvested for each tree, and total fruit weight, number of fruits per tree and fruit size distribution was recorded for each tree by passing all fruit harvested across a commercial grader (Colour Vision Systems Pty. Ltd. Melbourne, Australia). Fruits were sorted into 5 size classes based on diameter (mm)/fruit per 20 kg carton: <65 mm (>138 fruit/carton), 66–69 mm (138–113 fruit/carton), 70–75 mm (113–88 fruit/carton), 76–77 mm (88 fruit/carton), and >77 mm (<80 fruit/carton).

2.4. Model Development

The following points were considered for development of the early fruit size prediction model:

1. The use of an appropriate statistical technique which will be able to explain the maximum differences in the fruit growth curve determined from recording the fruit size each year (Figure 1). The use of appropriate techniques will also consider any additional variations which might occur during the season.
2. The prediction of the final growth at an early date or a time interval from the established growth curve (Table 2), and to predict the final fruit size distribution for large fruit size classes which are commercially used by the Australian citrus industry for export purposes. (Table 3).
3. The determination of the required fruit size early in the growing season to meet the expected fruit size classes at harvest (Table 4).
4. Validation of the current model with a test on the crop harvested in 2019 (Table 5).

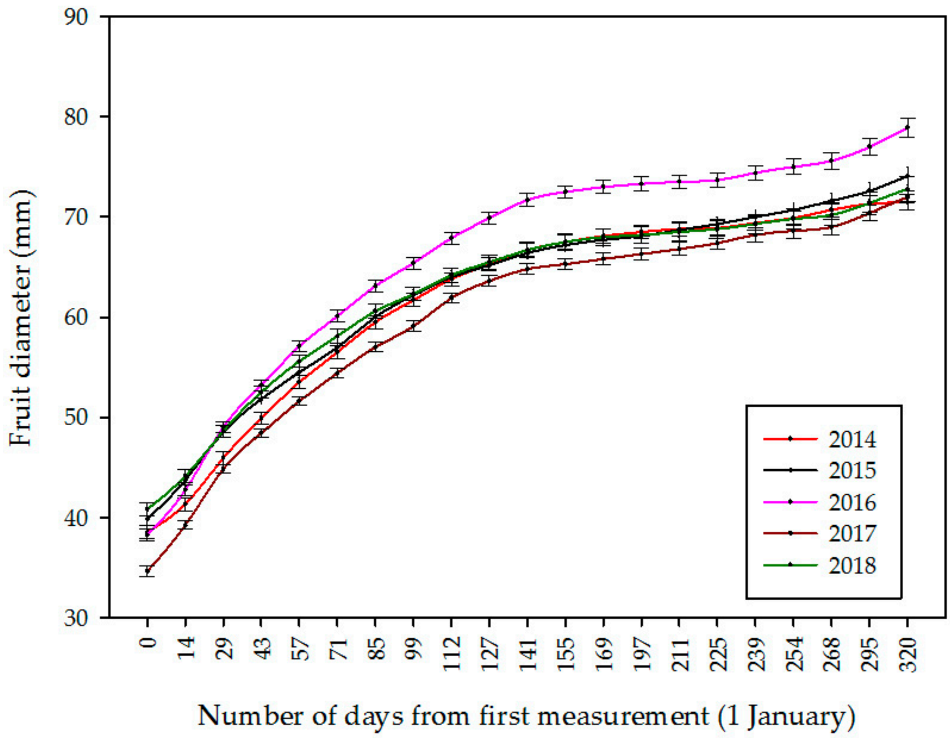

Figure 1. ASREM analysis was used to obtain smoothed splines from fruit diameter measurements at 21 events at fortnightly intervals from 1 January to 30 October for 5 growing seasons 2014, 2015, 2016, 2017 and 2018 in 'Keenan' Valencia oranges. Standard errors are given on each measurement date.

Table 2. Predicted growth increments and relationship to final fruit size at harvest for 'Keenan Valencia' oranges 2014–2018.

	2014		2015		2016		2017		2018	
x Early Dates	y Predicted Growth (mm)	z R^2 Values	y Predicted Growth (mm)	z R^2 Values	y Predicted Growth (mm)	z R^2 Values	y Predicted Growth (mm)	z R^2 Values	y Predicted Growth (mm)	z R^2 Values
15 January	28.9	0.56	29.5	0.67	31.9	0.41	29.0	0.56	26.1	0.40
15 February	20.5	0.71	18.9	0.79	22.6	0.64	20.5	0.75	18.1	0.60
15 March	14.6	0.80	15.5	0.81	15.7	0.79	14.6	0.85	12.5	0.70
30 March	12.2	0.82	13.8	0.82	13.0	0.81	12.0	0.87	9.4	0.75

x Four early dates, 15 January, 15 February, 15 March, and 30 March, were used to predict the final fruit size. y Predicted fruit growth from 15 January, 15 February, 15 March, and 30 March was determined with cubic smoothing spline models for the entire growing period. z Coefficient of determination (R^2 values) was determined by using regression analysis to compare the observed and predicted fruit size values. These results include all data points. The entire results given in the table indicated a statistical significance at $p < 0.001$.

Table 3. The final fruit size predicted at 15 January, 15 February, 15 March, and 30 March, and the observed final fruit size for five growing years in 'Keenan' Valencia oranges.

		Observed % Fruit	Predicted % Final Fruit Number at Early Dates			
Years	**Fruit Diameter (mm)**	**October 30**	**15 January**	**15 February**	**15 March**	**30 March**
2014	<65	4	4	6	6	6
	66–69	14	18	14	12	12
	70–75	36	54	50	44	38
	76–77	32	16	20	26	30
	>77	14	8	10	12	14
	[x] *p* Value	-	0.00	0.01	0.38	0.87
2015	<65	8	15	10	8	8
	66–69	12	8	8	12	10
	70–75	56	45	54	50	54
	76–77	16	20	18	22	20
	>77	8	8	10	8	8
	[x] *p* Value	-	0.07	0.54	0.67	0.87
2016	<65	0	0	0	0	0
	66–69	0	0	0	0	0
	70–75	34	30	32	32	32
	76–77	34	45	32	34	36
	>77	30	25	36	34	32
	[x] *p* Value	-	0.12	0.54	0.74	0.83
2017	<65	26	24	36	26	28
	66–69	22	35	18	28	24
	70–75	42	35	40	38	40
	76–77	10	6	6	8	8
	>77	0	0	0	0	0
	[x] *p* Value	-	0.03	0.09	0.53	0.82
2018	<65	16	16	20	16	20
	66–69	18	16	12	16	16
	70–75	38	46	46	42	34
	76–77	14	20	16	16	16
	>77	14	2	6	10	14
	[x] *p* Value	-	0.00	0.00	0.65	0.78

[x] Chi-squared analysis was used, and the predicted final fruit size was compared with observed fruit size distribution by *p* values. A non-significant result is indicated by *p* value > 0.05. However, a non-significant result shows a strong relationship between the observed and predicted values.

Table 4. The minimum fruit diameter (mm) required during January–March period to achieve fruit in large size classes at harvest in 'Keenan' Valencia oranges.

Measurement Dates	Size Classes		
	70–75 mm	**76–77 mm**	**>77 mm**
15 January	42	44	47
15 February	51	53	56
15 March	57	60	63
30 March	60	63	66

2.5. Statistical Analyses

The fruit growth data recorded during the 5 growing seasons was analysed by fitting cubic smoothing spline models for the development of a standard growth curve using ASReml 4.0 [18]. ASReml is a statistical software package that fits linear mixed model using Residual Maximum Likelihood (REML) [18]. The regression analysis in GenStat 21.0 was used for the comparison of the predicted fruit growth to the actual fruit growth [19]. The Chi-square goodness of fit test in GenStat was used for the comparison of the predicted fruit size distribution to the actual fruit size distribution for different size classes [19].

Table 5. The predicted and observed fruit size distribution (%) in 'Keenan' Valencia oranges during 2019 harvest for model validation.

Size Class	[x] Predicted in March 2019	[y] Observed in October 2019
70–75 mm	19	21
76–77 mm	55	52
>77 mm	12	15
[z] *p* value	0.62	

[x] Fruit were selected at random on 10 trees (100 fruit/tree), fruit diameter (mm) was recorded on 30 March 2019, and the prediction for the final size distribution was carried out using Table 4. [y] Ten experimental trees were harvested on 28 October 2019 and the observed fruit size distribution (%) was determined. [z] Chi-squared analysis was used, and the predicted fruit size distribution was compared with observed fruit size distribution by *p* values. A non-significance result is indicated by p value > 0.05. However, a non-significant result shows a strong relationship between the observed and predicted values.

3. Results and Discussion

3.1. Cubic Smoothing Spline Models

The data in which all the units (fruits in our case) are measured at the same TIME 'measurement date' are called repeated measurements. Analysis of variance (univariate approach) for each measurement date was not considered suitable because it was not possible to model plot-level covariate structure present in the data. The split-plot ANOVA technique was also not considered suitable for the fruit growth data. In split-plot ANOVA the TIME 'measurement date' used as a factor automatically assumes homogeneity of the covariate structure of the repeated measure data. In addition to that, it is not possible to randomly allocate TIME "sampling date". Smoothing splines are complicated functions which are constructed from the segments of cubic polynomials between the distinct values of the variate and constructed to be smooth at the junctions. Models that contain such functions are no longer linear but are described as additive models because the effects of separate explanatory variates are still combined additively [20]. The use of cubic smoothing splines is a modern statistical technique to analyse longitudinal data sets such as fruit growth. The use of cubic smoothing splines permits the inclusion of random coefficients, covariance modelling and estimation of non-smoothed deviations at the various levels of the designs. These deviations can occur in the fruit growth due to climatic factors such as changes in temperature regimes and rainfall events [21]. It has been previously reported that during the water stress conditions, fruit growth can be affected, causing the fruit to shrink [12]. In our experience, the fruit growth of Valencia orange either stop growing or shrinks during the winter months. However, the cubic smoothing functions can handle the fruit growth fluctuations with greater precision. The cubic smoothing splines have also been used to analyse the stem diameter growth of pine trees [22], because other models were not so effective to account for the fluctuations in the growth curves. The cubic smoothing spline technique uses the linear mixed models as a basis [20], and estimation was carried out using REML (residual maximum likelihood).

3.2. The Establishment of Fruit Growth Curves

The fruit size (growth) measurement was recorded, and those measurements were used to establish growth curves. Fruit size at each measurement date was predicted by fitting the cubic smoothing spline models to the fruit growth. During the five growing years, cubic smoothing spline model was used each year to predict and calculate the mean fruit growth for the entire growing season until harvest.

The analyses conducted via ASReml revealed that the predicted splines for 2014 to 2018 were not significantly different (Figure 1). However, there was a difference in the initial fruit size recorded on 1 January, but this difference was significant in the rate of fruit growth (slope) during the growing season (Table 1). Previously fruit growth was recorded for 'Nules' Clementine and 'Miho wase' Satsuma mandarins [16], and those findings were very similar to the fruit growth patterns recorded in our study.

The study for 'Nules' Clementine and 'Miho wase' Satsuma also revealed that the fruit growth (diameter) at the time of recording is generally the most critical element, which plays an important role in determining the final fruit size and not the negligible fluctuations in fruit size which occurs during the growing season. This outcome was also found in a previous study on 'Imperial' mandarins [23]. The tree which is free from any climatic stresses and receives normal scheduled irrigation, the fruit growth on those trees displays an accelerated growth during the active growth period from January through to the end of March under the Sunraysia conditions. Afterwards the expansion rate of fruit growth gradually decreases from April for navel oranges depending on the early-, mid-, and late-maturing varieties. On the other hand, in Valencia oranges a slight increase in growth occurs in September/October with the onset of spring [2]. The results reported in this study indicated that during 5 growing years no significant differences in fruit growth gradients were found for the same growth recording dates.

3.3. Prediction of Fruit Size and Percent Fruit Size Distribution

The mean predicted fruit growth obtained from the cubic smoothing spline analysis was added to the actual (observed) fruit growth which was obtained during the early phenological stages of the fruit growth for each growing season.

The final fruit size prediction was determined as given below:

Final fruit size ^{x} = Observed fruit diameter ^{y} + Predicted fruit growth ^{z};

^{x} = The final fruit size predicted for the harvest date (e.g., 30 October);
^{y} = The actual (observed) fruit diameter (mm) recorded at various early sampling dates;
^{z} = The mean growth which was predicted over the entire fruit recording period was determined by the cubic smoothing spline analysis.

In each growing season, the final size prediction was made at four early dates during January to March. This period was selected as it was after the completion of the natural fruit drop. This allowed time for any fruit load adjustment if required, such as fruit thinning.

Fruit size was measured on 21 occasions to establish a fruit growth curve for each growing season and splines were fitted to the data for 5 growing years (Figure 1). There were slight differences present across the years for the initial fruit size recorded at the start of the January. The initial fruit sizes for 2014, 2015, and 2016 were very similar; however, the initial fruit size for 2017 was significantly smaller than the initial fruit size observed for other years and initial fruit size for 2018 on 1 January (Table 1). After the determination of final fruit size using the smoothing spline models, fruit count was carried out followed by calculating the percentage of fruit in different size distribution classes (see Section 2.3). The actual fruit size distribution percentages were finally compared to the fruit size distribution obtained from the prediction model.

3.4. The Effect of Climatic Conditions and Crop Load on Fruit Growth

The effect of varying climatic conditions and different crop loads experienced during five growing seasons were analysed and discussed as follows:

3.4.1. Year 1—2014 Growing Season

During the 2014 growing year, fruit growth prediction was carried out on 15 January (day 1), 114 days after full bloom, 15 February (day 32), 15 March (day 60) and 30 March (day 75). The fruit size predicted on the above dates indicated a strong correlation with the observed values (Table 2). On 15 January, there was a significant relationship (R^2 = 0.56) when the predicted fruit growth was compared to the observed fruit growth; however, this relationship improved with the later date and was best predicted on 15 February with R^2 = 0.71 and 30 March with R^2 = 0.82, respectively (Table 2). A chi-square goodness-of-fit test was used to compare the observed and predicted percentage fruit size distribution (Table 3). The prediction in various size classes was possible as early as 15 March (p = 0.38) (Table 3); however, on 30 March (p = 0.87), there was a strong correlation between the actual and predicted fruit size. The predicted fruit size distribution in three larger classes

(70–75 mm, 76–77 mm and >77 mm) was 82% on 30 March compared to the observed value of 82% for the same three size classes. Previous research has suggested that the initial large sized fruit at the beginning of the active growth period produces larger fruit at harvest. There is evidence that the large fruit early in the season produced larger fruit at harvest in 'Navel' oranges [2] and in Satsuma mandarins [16].

A moderate to heavy crop load of 975 fruit per tree was observed in 2014 (Table 1). Although, there were more fruits found in the large size classes (Table 2). The initial fruit size was 38.5 mm on 1 January and the final fruit size was 72.5 mm on 30 October (Table 1). Hot weather conditions (16 days > 40 °C) occurred during the active growing season between January and March; however, 97 mm of rainfall from January to March was able to counter those effects. It is well established that rainfall during the active growth period contributes to the fruit growth increase [24], while good soil moisture availability during stages I and II phases of fruit development is also important for enhanced fruit growth rates [25]. The medium crop load and timely rainfall during Stage II resulted in large-sized fruit at harvest. These results also indicated that fruit size can be predicted with high accuracy when trees are carrying a crop load of around 900 fruit per tree.

3.4.2. Year 2—2015 Growing Season

During the 2015 growing season, fruit growth prediction was carried out on 15 January (day 1), 101 days after full bloom, 15 February (day 32), 15 March (day 60) and 30 March (day 75). The fruit size predicted on the above dates indicated a strong correlation with the observed values (Table 2). On 15 January, there was a significant relationship (R^2 = 0.67) when the predicted fruit growth was compared to the observed fruit growth; however, this relationship improved on the 15 March (R^2 = 0.81) and 30 March (R^2 = 0.82) (Table 2). A chi-square goodness of fit test was used to compare the observed and predicted percentage fruit size distribution (Table 3). The prediction of various size classes was possible as early as 15 February (p = 0.54); however, on 30 March (p = 0.87), there was a strong correlation between the actual and predicted fruit size (Table 3). Predicted per cent fruit size distribution in the larger classes (70–75 mm, 76–77 mm and >77mm) was 82% for the final predicted date (30 March) as compared to the observed value of 80% for the same size classes.

A moderate to heavy crop load of 973 fruits per tree was observed in 2015 (Table 1), but trees produced large sized fruit at harvest. The initial large fruit size of 39.8 mm at the beginning of Stage II resulted in a final fruit size of 74.1 mm (Table 1). In 2015, 59 mm of rain was received during the active growth period from January to March, and with only 8 days > 40 °C. Therefore, favourable climatic conditions would have also contributed to produce large fruit size at harvest.

3.4.3. Year 3—2016 Growing Season

During the 2016 growing season, fruit growth prediction was carried out on 15 January (day 1), 98 days after full bloom, 15 February (day 32), 15 March (day 61) and 30 March (day 76). The fruit size predicted on the above dates indicated a strong correlation with the observed values (Table 2). On 15 January, there was a significant relationship (R^2 = 0.41) when the predicted fruit growth was compared to the observed fruit growth; however, this relation improved on the 15 March (R^2 = 0.79) and 30 March (R^2 = 0.81), respectively. A chi-square goodness-of-fit test was used to compare the observed and predicted percentage fruit size distribution (Table 3). On 15 January (p = 0.12), the prediction of fruit size was possible in the 2016 growing season (Table 3). However, on 30 March (p = 0.83), this relationship was further enhanced between the actual and predicted final fruit size. In large fruit size classes (69–75 mm, 75–77 mm and >77 mm), the predicted percentage fruit size distribution was 100% as compared to the observed value of 98%. This accuracy was higher due to the absence of small fruit in size classes < 65 mm and 66–69 mm during 2016 growing season, which is also evidenced from the fruit growth curve (Figure 1).

A light crop load of 715 fruits per tree was observed in 2016 (Table 1). The lower fruit number per tree produced large-sized fruit at harvest and this was partly due to the large-sized fruit produced at the beginning of the active growth period around January. It has already been discovered that a larger initial fruit size results in a large-sized fruit at harvest [2]. Further evidence has also shown that the initial large-sized fruit produced larger fruit at harvest in Satsuma mandarins [16] and in navel oranges in Sunraysia growing district of Australia [26].

In addition to that the year had significant rainfall of 70 mm during January to March, coupled with 13 days of temperatures > 40 °C and the low crop load produced large sized fruit at harvest. The reduced crop loads by fruit thinning has been previously reported to increase fruit size in Valencia oranges [27] and in navel oranges [28].

3.4.4. Year 4—2017 Growing Season

During the 2017 growing season, fruit growth prediction was carried out on 15 January (day 1), 96 days after full bloom, 15 February (day 32), 15 March (day 60) and 30 March (day 75). The fruit size predicted on the above dates indicated a strong correlation with the observed values (Table 2). On 15 January there was a significant relationship ($R^2 = 0.56$) when the predicted fruit growth was compared to the observed fruit growth; however, this relationship was significantly enhanced on the 15 March ($R^2 = 0.85$) and 30 March ($R^2 = 0.87$), respectively. A chi-square goodness-of-fit test was used to compare the observed and predicted percentage fruit size distribution (Table 3). The prediction of fruit size into different size classes was possible as early as 15 February with ($p = 0.09$); however, it was enhanced on the 30 March ($p = 0.82$) (Table 3). The predicted percentage fruit size distribution in three larger classes (69–75, 70–75 mm and 76–77 mm) was 48% for the final predicted date compared to the observed value of 52%. This low percentage was due to the absence of fruit in class size > 77 mm. The growing season 2017 was a heavy cropping year and each tree had an average of 1320 fruit (Table 1). This contributed to small fruit size at harvest, which was evidenced by the small fruit size (34.6 mm) at the beginning of Stage II phase of fruit development.

The initial fruit size on 1 January was 34.6 mm and final fruit size was 72 mm. This season received lower rainfall of 38 mm from January to March, and mild temperatures. The weather was not very hot as compared to 2014 or 2016; however, the heavy crop load of 1320 fruit/tree and inadequate rainfall were the overriding factors producing small fruit size at harvest. Higher crop load plays an important role in the final fruit size [29]. In this study, 2017 was the worst year that caused the production of small sized fruit at harvest.

3.4.5. Year 5—2018 Growing Season

During the 2018 growing season, fruit growth prediction was carried out on 15 January (day 1), 105 days after full bloom, 15 February (day 32), 15 March (day 60) and 30 March (day 75). The fruit size predicted on the above dates indicated a strong correlation with the observed values (Table 2). On 15 January there was a significant relationship ($R^2 = 0.60$) when the predicted fruit growth was compared to the observed fruit growth; however, this relation improved with time and the best prediction was possible on 30 March ($R^2 = 0.75$). A chi-square goodness-of-fit test was used to compare the observed and predicted percentage fruit size distribution (Table 3). On 15 March ($p = 0.65$), the prediction of fruit size was possible in 2018 growing season; however, the relationship was further enhanced on 30 March ($p = 0.78$). In large fruit size classes, the predicted percentage fruit size distribution was 64% as compared to the observed value of 66%. This low percentage was due to the small percentage of fruit in large size classes for the 2018 growing season. A moderate crop load of 811 fruits per tree was observed in 2018 (Table 1). In terms of climatic conditions, this year was hot and dry, with 11 days of temperatures > 40 °C and only 7 mm of rain in 3 months. It has been previously reported that long periods with hot temperature conditions above 40 °C have resulted in reduced fruit growth in Valencia oranges [30]. In this season, hot weather and dry conditions were responsible for the smaller fruit size.

3.5. Early Size Requirements to Achieve the Required Fruit Size at Harvest

Based on the predicted growth model developed during this study, the required minimum fruit size for 'Keenan' Valencia oranges during January through to March for fruit to achieve the desired fruit size at harvest for different size classes are given in Table 4. This study concluded that the fruit should have reached 66 mm in diameter on 30 March to attain the required size of >77 mm at harvest (Table 4). Therefore, this study strongly recommends that fruit smaller than 44 mm or 47 mm in diameter in mid-January need to be thinned or nutrient/water management strategies implemented to help achieve a size class of 76–77 or >77 mm, respectively at harvest. However, the prediction should be based on the fruit size on 30 March because this is when fruit has normally reached 60–65% of its total growth, and the prediction accuracy is higher as indicated from the results of this study. The model developed during this study can be applied for the fruit size prediction for any dates or any given period from the commencement of active growth stage from early January to harvest.

3.6. The Validity of the Model (2019)

To test the validity of this model, 100 fruit per tree was randomly selected at a height of 1.5 m from around the tree canopy. The fruit diameter of the selected fruit was recorded on 30 March 2019 on 10 trees from the same experimental site that was originally used for 5 years of data collection to develop the model. The selection of this date was based on previous 5 years of data that predicted the final fruit size quite accurately in seasons with a range of crop loads and varying climatic conditions. The validation process considered the fruit size distribution prediction used in Table 4. Final harvest was carried out on ten trees on 28 October 2019, and fruit size distribution was carried out, and compared to the predicted fruit size distribution at harvest. The experimental trees used for this study carried 920 fruit per tree for the 2019 harvest. The results indicated a strong relationship when the predicted fruit size distribution was compared with the observed values (Table 5). Therefore, the model used in this study was validated effectively for the early fruit prediction in 'Kennan' Valencia oranges.

4. Conclusions

During the five growing seasons in this study, the predicted fruit growth increments stabilised after 15 January, although there was a year-to-year variation in the climatic conditions experienced during the study. The trees also carried different crop loads across different seasons. The model developed during this study is proven to be practical and could be utilised by citrus growers to predict final fruit size in Valencia oranges. It should be noted that the model is developed from fruit growth data recorded at Dareton (District of Sunraysia). The model needs to be modified for other growing regions which normally experience different climatic and soil conditions. Fruit from individual orchards may also differ in growth rates, due to differences in tree age, rootstock, nutrition and irrigation requirements, crop loads and tree health. Therefore, the model needs to be further tested and modified if used for other production regions or citrus cultivars. To test how widely this model can be applied to other growing regions and/or varieties, further data sets are needed to include into the cubic smoothing spline models to determine the required fruit size. Depending on the region in question a robust sampling protocol also need to be established which can accurately represent the fruit size distribution on the whole tree basis.

Previously an early fruit size prediction model for Valencia was developed using Mitscherlich-Spillman technique which resulted in the accurate prediction of the final fruit size but failed to predict the final fruit size distribution at harvest when predicted at earlier dates [15], However, in a second attempt, the model was improved to predict final fruit size and fruit size distribution only 4 months prior to harvest [14]. Even then, the model had limited commercial application for citrus growers as it could not predict 6–7 months prior to harvest.

The results of this study indicated that a precise prediction of early fruit size and fruit size distribution of harvest were possible during the active growth period (January–March) for 'Keenan' Valencia oranges. In addition to that this model was able to predict 6–7 months before harvest. Table 4 provides a template for the required fruit size in different classes at harvest. In case the size required at an early date in some growing seasons is not achievable due to crop load or climatic factors, then the required fruit size could be adjusted in the January or February periods via fruit thinning strategies [28] or enhanced nutrition strategies. In Australia, repeated foliar application of Potassium nitrate (KNO3 @ 2–3%) from December onwards is a recommended commercial strategy to enhance fruit size.

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