Predicting broccoli development
II. Comparison and validation of thermal time models

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Abstract

Models predicting broccoli ontogeny and maturity should ideally be precise and readily adopted by farmers and researchers. The objective of this study was to compare the predictive accuracy of thermal time models for three broccoli (\textit{Brassica oleracea} L. var.\textit{italica} Plenck) cultivars (‘Fiesta’, ‘Greenbelt’ and ‘Marathon’) from emergence to harvest maturity (Model 1), from emergence to floral initiation (Model 2), and from floral initiation to harvest maturity (Model 3). Comparisons were also made between Model 1 and Model 4 (Models 2 and 3 combined). Model 1 is useful when the timing of floral initiation is not known. When Model 1 was tested using independent data from 1983 to 1984 sowings of three cultivars (‘Premium Crop’, ‘Selection 160’ and ‘Selection 165A’), it predicted harvest maturity well. Prediction of floral initiation using Model 2 is useful for timing cultural practices, frost and heat avoidance. Where timing of floral initiation was recorded, predictions of harvest maturity were most precise using Model 3, since the variation which occurred from emergence to floral initiation was removed. The good predictions for Model 4 suggests that it would best predict the chronological duration from emergence to harvest maturity.

\textit{Keywords:} Broccoli; Modelling; Temperature; Thermal time; \textit{Brassica oleracea}

1. Introduction

Some thermal time models for broccoli use the same base temperature from sowing to harvest (Titley, 1987; Marshall and Thompson, 1987) while others use...
slightly different base temperatures according to phenological interval (Diputado and Nichols, 1989). Specific models have also been developed to predict floral initiation (Wurr et al., 1995; Tan et al., 1998, 2000) and harvest maturity from floral initiation (Wurr et al., 1991; Tan et al., 2000). Our working hypothesis is that when the base ($T_{\text{base}}$) and optimum ($T_{\text{opt}}$) temperatures are similar in each phenological interval (Tan et al., 2000), it may be possible to combine models predicting floral initiation and harvest maturity or use a single thermal time model to predict harvest maturity from emergence. The objective of this study was to compare the predictive accuracy of thermal time models of three broccoli cultivars (‘Fiesta’, ‘Greenbelt’ and ‘Marathon’) from emergence to harvest maturity (EHM) (hereafter called Model 1), from emergence to floral initiation (EFI) (hereafter called Model 2), and from floral initiation to harvest maturity (FIHM) (hereafter called Model 3) using root mean square deviation (RMSD) and regression. Comparisons were made between a combined EFI and FIHM model (hereafter called Model 4) and a single EHM model (Model 1). Details of Model 2 and Model 3 are described in the first paper of this series (Tan et al., 2000).

2. Materials and methods

2.1. Model

An optimisation program, DEVEL (Holzworth and Hammer, 1992), was used to determine the temperature and photoperiod responses of each cultivar from the experimental data for duration of EHM. A simplex optimisation method is used by DEVEL. Details of the functions of DEVEL are presented in the first paper of this series (Tan et al., 2000).

Accumulated thermal time (°C day) for durations of EFI, FIHM and EHM (days, $i = 1$ to $n$) were calculated using the estimated $T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C (derived in this study and in Tan et al., 2000) based on the equation:

$$\text{Thermal time} = \sum_{i=1}^{n} \left[ \frac{(T_{\text{Dmax}} + T_{\text{Dmin}})}{2} \right] - T_{\text{base}}$$  \hspace{1cm} (1)

where $T_{\text{Dmax}}$ is the daily maximum temperature and $T_{\text{Dmin}}$ the daily minimum temperature. All $T_{\text{Dmin}} < T_{\text{base}}$ were considered to be equal to 0°C, and all $T_{\text{Dmax}} > T_{\text{opt}}$ were considered to be equal to 20°C (Barger system) (Arnold, 1974; Titley, 1987; Wurr et al., 1991). The EFI, FIHM and EHM thermal time models in this study have three parameters; viz. (i) thermal time calculated from (ii) $T_{\text{base}}$ and (iii) $T_{\text{opt}}$ for the durations of EFI, FIHM and EHM, respectively (Tan et al., 2000). The EFI and FIHM models were combined in Model 4 using the sum of chronological duration (days) for EFI and FIHM predicted by the EFI and FIHM models, respectively.
2.2. Field experiment

A field experiment was conducted at The University of Queensland (UQ, Gatton) (latitude 27°33’ S, longitude 152°20’ E, altitude 89 m), located in the Lockyer Valley, approximately 80 km west of Brisbane, Queensland. Details are presented in the first paper of this series (Tan et al., 2000). Briefly, three broccoli (Brassica oleracea L. var. italic Plenck) cultivars, ‘Fiesta’ (Bejo Zaden BV, Holland), ‘Greenbelt’ and ‘Marathon’ (Sakata, Japan), were sown on eight dates (11 March, 20 March, 1 April, 10 April, 21 April, 1 May, 12 May, 22 May 1997), (sowings No. 1–8) under natural and extended (16 h) photoperiods. The natural photoperiods ranged from 12.6 to 11.3 h. A split split-plot experimental design with three replicates was used. Photoperiod treatment was the main plot, sowing date the sub-plot, and cultivar the sub-sub-plot, each randomised within the next higher level.

2.3. Commercial farm crops for testing the models

Crop ontogeny data to test the models were obtained from a commercial farm (latitude 27°39’ S, longitude 151°21’ E, altitude 364 m), located near Brookstead on the Darling Downs, approximately 200 km west of Brisbane for 60 sowings of five cultivars (‘Fiesta’, ‘Greenbelt’, ‘Marathon’, ‘CMS Liberty’ (Petoseed, USA) and ‘Triathlon’ (Sakata, USA)) over two growing seasons (1997 and 1998). Details of the sowing dates are presented in the first paper of this series (Tan et al., 2000). Further testing of Model 1 was conducted on additional data from 76 sowings (Table 1) in 1994, 1995 and 1996 (in addition to the 1997 and 1998 sowings). Since timing of emergence and floral initiation were not recorded for these sowings, emergence was assumed to be 5 days after sowing, which was the average duration for crops grown in 1997 and 1998, and Model 1 could be tested.

2.4. Farm records

In addition to crop records for ‘Fiesta’ from 1996 to 1998 seasons (3 years), and for ‘Greenbelt’ and ‘Marathon’ from 1994 to 1997 seasons (4 years) mentioned earlier in this paper, crop schedules for sowing and harvest dates for ‘Greenbelt’ and ‘Marathon’ were also obtained for 1991 and 1993 from the same farm.

2.5. Titley’s experiments

To confirm robustness of our Model 1, it was further tested by re-analysing data of Titley (1985), who helped to establish the broccoli industry in the Lockyer Valley in the 1980s (Titley, 1987). Briefly, three cultivars, ‘Premium Crop’
Table 1
Sowing dates of three broccoli cultivars (‘Fiesta’, ‘Greenbelt’ and ‘Marathon’) grown on a commercial farm in Brookstead from 1994 to 1996

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Sowing date</th>
<th>Month</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Fiesta’</td>
<td>4, 13, 23, 28</td>
<td>February</td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>4, 9, 14, 22, 29</td>
<td>March</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4, 11, 15, 22</td>
<td>April</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13, 20, 30</td>
<td>May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3, 10, 12</td>
<td>June</td>
<td></td>
</tr>
<tr>
<td>‘Greenbelt’</td>
<td>27</td>
<td>January</td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td>7, 11, 17, 28</td>
<td>February</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16, 21, 25, 31</td>
<td>March</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13, 18, 24</td>
<td>February</td>
<td>1995</td>
</tr>
<tr>
<td></td>
<td>6, 10, 16, 21, 25, 30</td>
<td>March</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18, 25, 29</td>
<td>February</td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>6, 11, 18, 27</td>
<td>March</td>
<td></td>
</tr>
<tr>
<td>‘Marathon’</td>
<td>4, 8, 14, 19, 25</td>
<td>April</td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td>1, 8, 17, 25</td>
<td>May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3, 12, 20, 28</td>
<td>June</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4, 10, 16, 21, 27</td>
<td>April</td>
<td>1995</td>
</tr>
<tr>
<td></td>
<td>12, 25, 31</td>
<td>May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7, 15, 23</td>
<td>June</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>March</td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>1, 13, 19</td>
<td>April</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17, 28</td>
<td>May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1, 5</td>
<td>June</td>
<td></td>
</tr>
</tbody>
</table>

(Arthur Yates, Australia), ‘Selection 160’ and ‘Selection 165A’ (Henderson Seeds, Australia), were sown on 19 sowing dates at Gatton College at approximately 20-day intervals from March 1979 to March 1980 (1979–1980 sowings) using a randomised complete block design with four replicates. The same cultivars were grown on a commercial basis for export to southeast Asia in 1983 and 1984 (1983–1984 sowings). The 1979–1980 sowings were used for fitting $T_{\text{base}}$, $T_{\text{opt}}$, using DEVEL (Holzworth and Hammer, 1992), and calculating thermal time duration for EHM (Model 1) for the three cultivars. The 1983–1984 sowings were used as independent data to validate Model 1.

2.6. Data analysis

In addition to the detailed descriptions given in the first paper of this series (Tan et al., 2000), the following analyses are specific to this paper. Analysis of variance (ANOVA) was completed for thermal time duration of EHM to test the independent and interactive effects of photoperiod extension, sowing date and
cultivar, using the general linear model (GLM) procedure of SAS version 6.12. Regressions were calculated using SAS. RMSD, equivalent to the prediction error (Mikkelsen, 1981), was used to compare models.

3. Results

3.1. Time from sowing to harvest maturity

A quadratic model accounted for 76, 49 and 12% of the variance in the chronological duration from sowing to harvest maturity for ‘Fiesta’ (Fig. 1a), ‘Greenbelt’ (Fig. 1b) and ‘Marathon’ (Fig. 1c), respectively, sown from 1991 to 1998. Cold winters in 1994 and 1995 delayed maturity substantially whereas in a warmer year, such as 1993, maturity was advanced for ‘Greenbelt’ and ‘Marathon’. These quadratic models for EHM based on chronological time can be used to plan a crop sowing schedule but lack accuracy for predicting harvest dates.

3.2. Photoperiod, cultivar and sowing date effects

ANOVA for the EFI and FIHM intervals were presented in the first paper of this series (Tan et al., 2000). Effects of photoperiod extension, cultivar, sowing date and their interactions on chronological and thermal time (°C day) duration of EHM are summarised in Table 2. Photoperiod effect was not significant ($P > 0.05$). The most notable interaction was between cultivar and sowing date. Later sowings significantly ($P < 0.01$) increased the chronological duration of EHM, more so with ‘Fiesta’ than ‘Greenbelt’ and ‘Marathon’ (Fig. 2). This temporal trend is similar to the quadratic models in Fig. 1. Thermal time durations of ‘Fiesta’, ‘Greenbelt’ and ‘Marathon’ were 1334, 1272 and

<table>
<thead>
<tr>
<th>Effect</th>
<th>PP</th>
<th>SD</th>
<th>CV</th>
<th>PP×SD</th>
<th>PP×CV</th>
<th>SD×CV</th>
<th>PP×SD×CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronological time</td>
<td>n.s.</td>
<td>**</td>
<td>**</td>
<td>n.s.</td>
<td>n.s.</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>LSD (P = 0.05)</td>
<td>–</td>
<td>2.19</td>
<td>0.71</td>
<td>–</td>
<td>–</td>
<td>2.74</td>
<td>2.84</td>
</tr>
<tr>
<td>Thermal time</td>
<td>n.s.</td>
<td>**</td>
<td>**</td>
<td>n.s.</td>
<td>n.s.</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>LSD (P = 0.05)</td>
<td>–</td>
<td>28.49</td>
<td>9.46</td>
<td>–</td>
<td>–</td>
<td>35.90</td>
<td>37.85</td>
</tr>
</tbody>
</table>

* $P < 0.01$.
** $P < 0.05$.
*** Not significantly different ($P = 0.05$).
and were the sum of thermal time durations of EFI and FIHM for each cultivar.

### 3.3. Evaluation of models against independent farm data

The coefficient of determination, slope of the line and intercept for Model 4 (Figs. 3 and 4) were better than those for Model 1 (Fig. 3). This improvement was
probably due to the breakdown into components of the distinct phenological intervals which improved the precision of predictions for individual sowings. The RMSD of Model 4 (3.3) was similar to that for Model 1 (3.0). Although Model 4 best predicted the chronological duration of EHM, Model 1 can be used instead of Model 4 in cases where timing of floral initiation is not known.

Model 1 predicted 73% of the variation for the pooled analysis with 136 sowings of five cultivars (‘Fiesta’, ‘Greenbelt’, ‘Marathon’, ‘CMS Liberty’ and ‘Triathlon’) over five years (1994–1998) (Fig. 5). The slope of the line and the intercept were similar to those in Fig. 3, showing that the model can be applied reliably over an extensive data set (Fig. 5).

Table 3
Duration (mean±s.e.) from emergence to floral initiation (EFI), from floral initiation to harvest maturity (FIHM) and from emergence to harvest maturity (EHM) for three broccoli cultivars (‘Fiesta’, ‘Greenbelt’ and ‘Marathon’) expressed as thermal time (°C day) grown at UQ, Gatton, as estimated from optimisation routines using DEVEL. Thermal time was calculated from base and optimum temperatures of 0 and 20°C, respectively.

<table>
<thead>
<tr>
<th>Thermal time duration</th>
<th>Cultivar</th>
<th>‘Fiesta’</th>
<th>‘Greenbelt’</th>
<th>‘Marathon’</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFI</td>
<td></td>
<td>670±3.36</td>
<td>612±5.43</td>
<td>627±5.90</td>
</tr>
<tr>
<td>FIHM</td>
<td></td>
<td>664±5.50</td>
<td>660±5.05</td>
<td>678±6.96</td>
</tr>
<tr>
<td>EHM</td>
<td></td>
<td>1334±5.95</td>
<td>1272±6.78</td>
<td>1305±9.61</td>
</tr>
</tbody>
</table>
Fig. 3. Comparison between predicted and observed duration (days) from emergence to harvest maturity for independent data from five broccoli cultivars (‘Fiesta’ (●), ‘Greenbelt’ (■), ‘Marathon’ (▲), ‘CMS Liberty’ (▼), and ‘Triathlon’ (●)) grown on a commercial farm in Brookstead in 1997 and 1998, using a single emergence to harvest maturity model (Model 1). Predicted duration was calculated using $T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C, respectively.

Fig. 4. Comparison between predicted and observed duration (days) from emergence to harvest maturity for independent data from five broccoli cultivars (‘Fiesta’ (●), ‘Greenbelt’ (■), ‘Marathon’ (▲), ‘CMS Liberty’ (▼), and ‘Triathlon’ (●)) grown on a commercial farm in Brookstead in 1997 and 1998, using a combined emergence to floral initiation and floral initiation to harvest maturity model (Model 4). Predicted duration was calculated using base and optimum temperatures of 0 and 20°C, respectively.
When timing of floral initiation was known, Model 3 (FIHM) (Tan et al., 2000) predicted harvest maturity with greater precision than Model 1 (EHM) (Fig. 3). More predicted values in Model 3 fall closer to the 1:1 line than in Model 1 although the RMSD of both models were similar. Precision was improved since variation in the duration of EFI was removed.

3.4. Evaluation of Model 1 against Titley’s data

$T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C were derived using DEVEL, for all three cultivars in the 1979–1980 sowings, these temperatures falling within the 10% confidence interval for individual cultivars during EHM. Thermal time durations of EHM, (calculated using $T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C) for ‘Premium Crop’, ‘Selection 160’ and ‘Selection 167A’ were 1355±17, 1305±22, and 1486±25°C day ($n=19$), respectively. The coefficient of determination for predicted values, using estimated temperature coefficients in Model 1 accounted for 91% of the observed data for chronological duration of EHM for independent commercial crop data (Fig. 6), in the pooled analysis with three cultivars (‘Premium Crop’, ‘Selection 160’, ‘Selection 165A’) from 1983 to 1984 sowings. Most of the points fall close to the 1:1 line and RMSD for the pooled data was 2.5 days.

Fig. 5. Comparison between predicted and observed duration (days) from emergence to harvest maturity for independent data from five broccoli cultivars (‘Fiesta’ (●), ‘Greenbelt’ (■), ‘Marathon’ (▲), ‘CMS Liberty’ (▼), and ‘Triathlon’ (◆)) grown on a commercial farm in Brookstead in 1994, 1995, 1996, 1997 and 1998, using a single emergence to harvest maturity model (Model 1). Predicted duration was calculated using $T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C, respectively.
4. Discussion

Traditionally, curvilinear relationships, like those in Fig. 1, have been used to plan a sowing and marketing schedule (Tan et al., 1997) but variations in prevailing weather conditions can cause deviations from the plan. Incidentally, the convex curves of Fig. 1 become concave curves in the northern hemisphere where progressive sowings experience warmer rather than cooler environments (Wurr et al., 1991).

The single EHM model approach (Model 1), which was also used by other researchers (Titley, 1987; Marshall and Thompson, 1987) can be used by growers and researchers to predict harvest dates from emergence, and plan sowing schedules. A sowing schedule might be planned using mean weekly temperatures, but by progressively applying the model with daily temperatures, deviation between the actual and planned predicted harvest date will become apparent. Our Model 1 adequately predicted chronological duration of EHM for five cultivars of commercial field-grown broccoli over five growing seasons (RMSD of 4.4 days). This compares favourably with the Scottish model which predicted the duration from sowing to harvest maturity within ±7 days for nine out of 10 crops (Marshall and Thompson, 1987). Fitted values from 1979 to 1980 sowings at UQ, Gatton (Titley, 1985) confirmed that $T_{\text{base}}$ and $T_{\text{opt}}$ were 0 and 20°C, respectively for additional cultivars grown all year round, and thermal time of EHM was cultivar specific. Model 1 was further validated by independent data from 1983 to
1984 sowings, showing that our model is quite robust, as it could be applied to different cultivars grown more than 10 years earlier. The simple thermal time, modified thermal time, and non-linear rectangular hyperbola models described by Titley (1987) only accounted for 23, 64 and 85% of the variation, respectively when tested on the same independent data from 1983 to 1984 sowings (Titley, 1985, 1987). Our single EHM model (Model 1) accounted for 91% of the variation and hence, is an improvement on the models developed by Titley (1985, 1987). Based on these data, it is reasonable to apply $T_{\text{base}}$ and $T_{\text{opt}}$ of 0 and 20°C, respectively, to the EHM interval for other broccoli cultivars.

Although Model 3 can be applied independently of Model 2, the latter is still useful for predicting floral initiation. With the development of advanced weather forecasting systems, it has become possible to predict the likely date of the first and last frost, and the number and severity of frosts in north-eastern Australia with increasing accuracy using the southern oscillation index (SOI) (Stone et al., 1996). Broccoli plants are more sensitive to freezing injury and high temperatures ($\geq 35^\circ$C) during floral initiation (Bjorkman and Pearson, 1998; Tan et al., 1998, 1999). It will be possible to combine crop models, such as that proposed here and advanced weather forecasting, to examine risks of crop exposure to high and low temperatures at critical stages (e.g. floral initiation) of crop development. It would then be possible to adjust sowing dates or management options to minimise frost or heat damage.

Precision in predicting harvest maturity can be improved (RMSD of 1.9 (UQ, Gatton), 2.9 (Brookstead) days) by using the FIHM model (Model 3) when timing of floral initiation (Tan et al., 1998) is known, since the variation which occurred during EFI is removed. Our Model 3 is precise and gives predictions of comparable accuracy to maturity models developed at Wellesbourne, UK and Aarslev, Denmark, which reported RMSD of 1.73–3.26 days (Wurr, 1992) and 4–5 days (Grevsen, 1998), respectively. Our Model 3 only requires maximum and minimum daily temperatures, thermal time requirement and timing of floral initiation data. It does not need the solar radiation and sensitivity of individual cultivars to solar radiation data used in the Wellesbourne maturity models (Wurr et al., 1991; Tan et al., 2000). This may be because of the non-limiting radiation conditions in southeast Queensland, meaning predictive models do not need to take account of low radiation effects.

The ontogeny models developed in this study would also be useful in determining the timing of cultural practices that are related to crop ontogeny, such as fertiliser application, irrigation and crop protection (Theunissen and Sins, 1984). Moreover, they may also be adapted to simulate the potential impact of long term climatic trends such as increased temperatures associated with global warming on broccoli ontogeny and maturity (Wurr et al., 1996).

The present study confirms our hypothesis that where base and optimum temperatures are similar in each phenological interval, both a combined EFI and
FIHM model (Model 4), and a single EHM thermal time model (Model 1) can adequately predict harvest maturity.

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References


