A Systems Approach to Developing a Model that Predicts Crop Ontogeny and Maturity in Broccoli in South-East Queensland

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Abstract

*Farmers need a well planned crop scheduling program to maintain a regular of supply of broccoli (*Brassica oleracea *L. var.* italica *Plenck) to domestic and export markets which extend from May to September for crops in south-east Queensland. However,*

development, time of harvest and crop quality, thereby impacting on marketing commitments which specify the amount, quality and date of supply. Thus, prediction of crop ontogeny is important for crop scheduling and maintaining continuity of supply of broccoli. Two methods are being used to develop a model of phenological development in broccoli. The first method uses a time of sowing experiment which records crop ontogeny for wide range of cultivars and climatic conditions. This method provides a high level of precision in determination of phenological events but has potential problems such as the difficulty of extrapolation from a small scale experiment to commercial crops. The second method uses historical records from a broccoli farm which reflect crop phenological development under commercial practice over a period of three years. This method has the advantage of using a number of crop performance records obtained from a range of prevailing climates but lacks the precision of the first method. Once both models exist, they can be separately validated against the data used to develop the other model. Furthermore, the ongoing year-by-year expansion in farm records represents new validation data for either model. Our three-step approach should lead to a more robust and credible model for predicting crop ontogeny in broccoli and it could also be applicable to other crops.

Introduction

Broccoli (*Brassica oleracea* L. var. *italica* Plenck) has become an important crop in Australia since the introduction of hybrid cultivars in the early 1970s. A four-fold increase in the area planted and a five-fold increase in production has occurred from 1982 to 1992 (Deuter 1995: 155). The area under broccoli production in Australia in

1994/95 was 5,673 hectares and in Queensland 1,190 hectares. The major broccoli growing districts in south-east Queensland are the Lockyer Valley, Darling Downs and Granite Belt. From July 1995 to June 1996, 8,183 Mt were exported from Australia with a gross (FOB) value of A$17.6 million. The production and distribution systems are strongly market orientated and farmers attempt to provide a regular supply of broccoli of specified quantity and quality to the domestic and export markets.

The need to maintain a regular supply of quality broccoli was a concern for a large commercial farmer on the Darling Downs, 200 km west of Brisbane. The farmer approached the University of Queensland to investigate the problem. This paper describes the resulting approaches to problem definition and research.

Production and Distribution System

A well-planned production program, or crop scheduling program, is essential to maintain continuity of supply of broccoli to domestic and export markets which extend from May to September for crops in south-east Queensland (Figure 1). Our farmer produces broccoli during this period by making over 30 separate sowings at 3-6 day intervals from early March to late May. Fertilisers are applied at rates determined from soil tests and rainfall is supplemented with furrow irrigation.

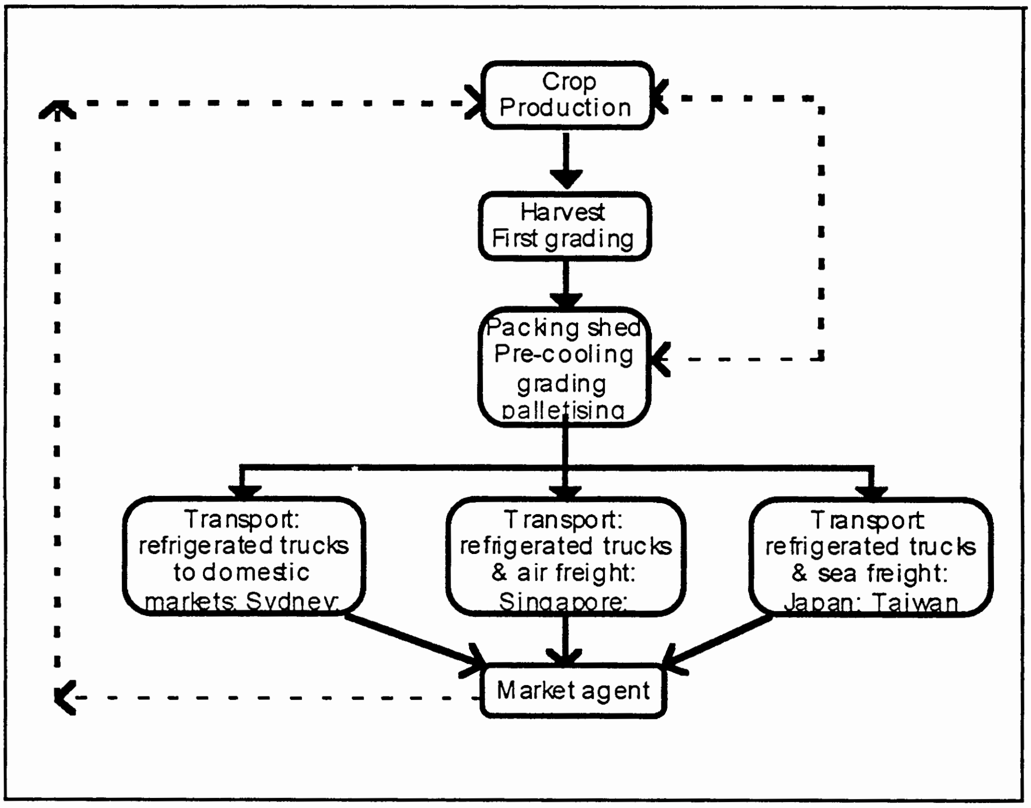

Figure 1: System for production and marketing of broccoli. The solid lines show the flow of broccoli through the system and the broken lines show the flow of information

When the broccoli reaches optimum harvest time, it is sequentially hand harvested and transported in bulk bins to the packing shed. In effect, harvesting is the first step in grading as immature heads or over mature heads are not cut. At the packing shed, the broccoli is pre-cooled in a cold room, then further graded and packed into cartons destined for specific markets. The cartons are palletised and transported by refrigerated trucks to domestic central markets or to ports for export. Broccoli exported to Japan and Taiwan is sea freighted whereas broccoli exported to Singapore and Malaysia is air freighted. Market agents for both the domestic and export markets provide feedback to the farmer on the quality and timeliness of arrival of each consignment (Figure 1). The information on timeliness and consistency of supply is especially valuable for export farmers who have to make advance bookings for air or sea transport and advise overseas customers of arrival dates. Difficulties arise when export orders are delayed or cancelled. Long-term cold storage to even out supply is not possible because fresh broccoli is highly perishable.

Closer analysis of the production and distribution systems, in conjunction with the farmer, identified the crop production component (Figure 1) as the major cause of irregular supply. The other components were tightly controlled and potential problems were minimised by good communication, personnel management and preventative maintenance. In an attempt to maintain regular harvests, farmers stagger sowing dates with cultivars of different maturity times (Pearson and Hadley 1988). However, such a production plan is usually based on average climatic conditions and is likely to fail when variable climatic conditions occur. For example, very cold winters in 1994 and 1995 delayed broccoli harvest on the Darling Downs and some growers were unable to supply their overseas customers on schedule. On the other hand, periods of warmer than average weather hasten crop development leading to over supply and low market prices.

Our conclusion that production was the most critical component was based on the farmer's experience and reports from the literature. Crop development is strongly affected by temperature (Wurr *et al.* 1991, 1992, 1995). Further, the good farm records for 1994 to 1996 (including planting and harvest dates of each planting) could be used for detailed analysis. Thus, we decided to concentrate on studies of crop scheduling and ontogeny to improve accuracy in predicting broccoli maturity, harvest time and supply.

Prediction of Broccoli Ontogeny and Maturity

Broccoli farmers need to know in advance of a change in time of crop maturity arising from variable climatic conditions so that their forward-marketing arrangements can be modified to reduce irregular supply. To this end, a computer model that predicts crop ontogeny could be a useful aid to management. A model of broccoli phenology can be developed with the measurement of broccoli ontogeny in different environments. Most research on crop scheduling involves time of sowing experiments with a range of cultivars. The choice of cultivar is important because they vary in maturity time and adaptability to prevailing temperatures. Thus, a cultivar needs to be matched with sowing time to ensure a regular supply of marketable broccoli heads (Titley 1981, 1985, 1987). Accurate prediction of crop ontogeny will also allow a farmer to supply irrigation, agro-chemicals and fertiliser according to phenological events. For example, if floral initiation occurs earlier, side-dressings of fertiliser may be applied earlier during the vegetative phase.

Unfortunately, little work has been done on crop scheduling and prediction of optimum harvest time for the popular cultivars of broccoli currently used in Australia. Typically, a model of phenology is based on heat sums of average daily temperature (maximum + minimum/2) accumulating between base, optimum and maximum temperatures (Angus *et al.* 1981a, Arnold 1959, Holzworth and Hammer 1992) for each phenological interval, namely sowing to emergence, emergence to floral initiation and floral initiation to harvest maturity (Diputado and Nichols 1989, Fyffe and Titley 1989). In our studies, a 3-hour broken linear temperature response (Holzworth and Hammer 1992) can be used (Figure 2) as defined by the following equation:

if (t <= b)	then Rate = 0	
if (t > b AND t <= c)	then Rate = a*[(t-b)/(c-b)]	
if (t > c AND t <= d)	then Rate = a*[1-(t-c)/(d-c)]	
if (t > d)	then Rate = 0	(Equation 1)

where:
a = R_{opt} (Optimum rate of development (days^{-1}) or Thermal time), b = Base temperature (T_{min}), c = Optimum temperature (T_{opt}), and d = Maximum temperature (T_{max})

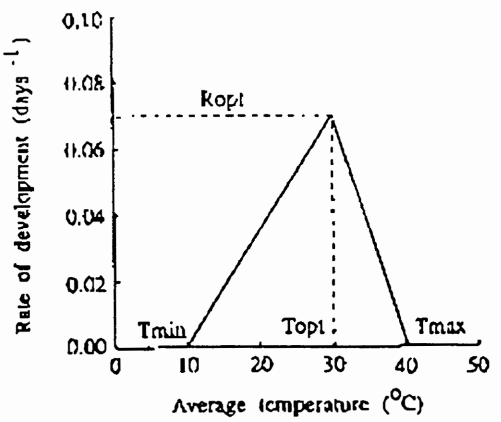

Figure 2: Three-hour broken linear temperature response (Holzworth and Hammer 1992)

Many researchers working on the effect of temperature on broccoli have assumed that photoperiod does not have a modifying effect on floral initiation or flowering of broccoli (Miller *et al.* 1995, Miller 1988, Marshall and Thompson 1987a, b). However, some Japanese researchers have reported that low temperature treatment (17°C) under long-day (16-hour) conditions promoted floral initiation more effectively than the same temperature treatment under short-day (8-hour) conditions (Fujime *et al.* 1988). If the crop is sensitive to photoperiod, another parameter can be incorporated into the general model. A broken linear photoperiod response (Angus *et al.* 1981b, Birch 1996, Holzworth and Hammer 1992) with the following equation (Figure 3) can then be used:

if (pp <= h) Rate = e-f*(h-pp))
if (pp > h) Rate = e-g*(pp-h))
if (Rate < 0) Rate = 0 (Equation 2)

where:
e = R_{opt} (Optimum rate of development ($days^{-1}$) or Thermal time), f = Slope of the first line, g = Slope of the second line, h = Critical photoperiod

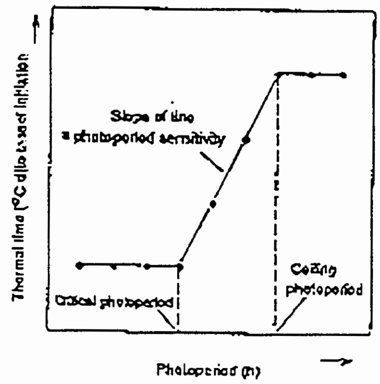

Figure 3: Broken linear photoperiod response (Angus *et al.* 1981b, Birch 1996, Holzworth and Hammer 1992)

This paper describes and compares two methods for collecting the data that underpin a model of broccoli phenology. Thereafter, both approaches depend on a parameter optimisation program such as DEVEL (Holzworth and Hammer 1992), to derive the temperature and photoperiod parameters of equations 1 and 2.

Method 1: Time of sowing experiment

The traditional approach is to develop a model from an experiment that records crop phenological development for a wide range of cultivars and climatic conditions (Birch 1996, Goyne 1993, pers. comm.). Typically, these experiments consist of several cultivars sown at 7 to 14 day intervals over the normal sowing period for a crop, that is March to May for broccoli in south-east Queensland. Further, the impact of photoperiod on ontogeny (equation 2) can be assessed by conducting the experiment under normal and extended photoperiods. Plants can be randomly removed every three days, dissected under a stereoscopic microscope and the development stage of the apex compared to standard micrographs, until the apex rating has reached at least 5 on a scale of 1 to 7 (Moncur 1981). The timing of floral initiation can then be determined when the graph of apex rating against time from emergence reaches 3. Daily climatic data should be recorded during the experiment. Then, it is relatively simple to match the climatic data and crop records for each phenological interval and use DEVEL to derive the temperature and photoperiod parameters of equations 1 and 2. Such an experiment is being conducted at Gatton College in 1997. Three cultivars (Fiesta, Greenbelt, Marathon) were sown at 10-day intervals from early March to late May (8 sowings) under natural and extended photoperiods (16 hours).

This method provides a high level of control over the experimental treatments and precision in determination of phenological events. It also allows comparisons between cultivars since more than one cultivar is sown on each occasion. However, there are some disadvantages with the method. Since such experiments are labour intensive, requiring numerous and frequent field measurements, they are usually run for one season only, which may or may not include unusual climatic events that impact on broccoli development. Another potential problem is extrapolation from a small scale experiment to commercial crops which may grow at a different location and receive different inputs of irrigation or fertiliser than the experimental crop. Due to the cost and potential problems of the experimental approach, an alternative method which uses farm records is being investigated.

Method 2: Records from a commercial broccoli farm

Farmers often keep good records of sowing times, cultivars and harvest dates in order to manage their crop scheduling program. Further, since these records accrue year-by-year, the historical data reflects crop development under commercial practice over a wide range of within year and between year variations in climate. Such records could be used in the development of a model of crop phenology provided accurate records of prevailing climate also exist. Fortunately, meteorological stations are relatively common in south-east Queensland and an automatic weather station can be easily installed on a farm to establish a calibration between farm climatic data and the nearest long-term meteorological station. Thus, crop records from a farm can be matched to prevailing climatic conditions with a reasonable assurance.

An opportunity to use this method has been provided by a farmer who operates a commercial broccoli farm near Brookstead on the Darling Downs, 200 km west of Brisbane. Crop records are available for 1994 to 1996. An automatic weather station was installed in 1996 to provide a calibration against nearby meteorological stations at Anchorfield and Cecil Plains, thereby allowing the matching of three years of crop records to either actual or calculated farm climatic data.

Conceptually, the main advantage of this method is the large number of crop performance records (over 80 planting times) obtained from a range of prevailing climates. Thus, a phenological model based on the historical data should reflect the commercial real-life environment. It is also a cost effective method since it uses existing data. However, the method has some disadvantages associated with commercial practices. For example, identification of phenological events such as emergence and floral initiation does not occur. Thus, these separate phenological events must be pooled into a relatively crude single stage model from sowing to first harvest. Further, crop records are inconsistent if time of harvest is influenced by prevailing markets, such as the need to fill an order to Japan which requires a head size of 100 - 120 mm diameter, rather than the market in Singapore which requires a head size of 80 - 100 mm diameter. Finally, since a farmer believes that each cultivar has an optimum period of sowing, only one cultivar is usually sown at each sowing time, thereby restricting the number of comparisons between cultivars across the same climatic conditions.

Discussion

Having adopted these methods to develop a model of phenological development in broccoli, we regard the two methods to be complementary. Since the model based on farm records uses existing data, it has to be developed first. Parameters from this model become a hypothesis or concept that can be further tested and refined by developing the model based on results from a time of sowing experiment. Once both models exist, and since they are derived from independent data sets, they can be separately validated against the data used to develop the other model. That is, data from the time of sowing experiment can be used in the validation of the model derived from farm records, and vice versa (Boote *et al.* 1996). Furthermore, the ongoing year-by year expansion in farm records represents new validation data for either model. It is also relatively easy to make additional observations on farm crops to test the accuracy of the predictions of emergence and floral initiation with the model obtained from the time of sowing experiment.

We contend that this three-step approach to model development uses all available data and will be superior to the common two-step approach where a model is developed by method 1 above, and validated against results from an independent experiment rather than a commercial farm. Our three-step approach should lead to a more robust and credible model. Furthermore, since farmers are involved in all steps of model development and validation, they should readily accept or 'own' the model finally chosen.

A sensitivity analysis can also be conducted on the broccoli phenology model to test the effect of incremental changes of climatic factors such as temperature on crop ontogeny. With the development of advanced weather forecasting systems, it has become possible to predict the dates of 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). If short-term seasonal weather can be predicted with reasonable accuracy in the near future, farmers can re-schedule their sowings using the crop phenology model and still maintain continuity of supply. For example, the problem of flooding the market due to predicted periods of warmer weather close to harvest may be reduced to a certain extent with the adjustment of planting times earlier in the season. The crop phenology model may also be used to simulate the potential impact of long term climatic trends such as increased temperatures associated with global warming (Wurr *et al.* 1996) on the ontogeny and maturity of broccoli.

Whilst this study involves broccoli, we believe that the 3-step approach described should be applicable to other brassica crops, and possibly other vegetable (e.g. lettuce) and field crops produced by a sequence of regular sowings during the growing season.

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