Report to the Horticultural Development Council

Commercial Validation of Prediction Systems for Calabrese Maturity

S.Pearson and P.Hadley

Department of Horticulture,

School of Plant Sciences,

Whiteknights,

University of Reading,

Reading,

RG6 2AS.

Summary

The objectives of this study were to validate the systems developed at Reading University to predict the maturity date and yield of calabrese. Maturity dates for 50% of the crop were predicted in three different ways; i) using a simple relationship between thermal time and spear growth, ii) using a model incorporating the effects of temperatures, supra-optimal temperatures, light integral and plant densities and iii) using a relationship to predict spear initiation from planting date combined with the second model (ii).

With the more complex relationship (ii) inconjunction with the actual meterological data and measured spear diameter at maturity the mean deviation, for 40 crops of calabrese was +0.5 days and a prediction error, spre, of 3.45 days. The simple thermal time relationship (i) produced similar results, with a mean deviation of +0.2 days and spre of 3.87 days. This could be used an alternative technique when light integral data required for the second model (ii) is not available.

At Reading we have placed great emphasis on producing accurate predictions of crop yields which can be used in practice by growers as opposed to simple estimations of crop maturity dates. Calabrese crop yields were predicted on a daily basis throughout the season for a large South Lincolnshire cooperative growing 10 different varieties in 120 differing fields. Predictions of crop yield were reasonably accurate and stable over a three week prior to maturity. The system also had the flexibility to consider a large number of fields from many differing growers.

Introduction

Accurate prediction of the maturity dates give growers considerable economic advantages in organising supermarket contracts, labour and cold storage space in advance of the forthcoming supply. The development of techniques to forecast maturity of crop plants has received much attention over recent years. Salter (1969) first suggested that predictions of cauliflower crop maturity were possible based on his findings that the diameter of a cauliflower curd was logarithmically related to the number of accumulated day degrees. Calabrese maturity was first examined by Marshall and Thompson (1987) in Scotland. However, their analysis did not allow for the effect of vernalization (vernalization is where a period of cold hastens floral development) on spear initiation and was only applicable to direct drilled crops. Subsequently, Wurr et al., (1991) examined spear growth in a wide range of calabrese varieties grown through-out the season. They showed that the logarithm of spear diameter was related, curvilinearly, to accumulated effective day degrees. A simple technique was developed whereby predictions of 50% crop maturity could be made from measurements of spear samples taken during early crop growth.

Independently, at Reading, a similar technique was developed to predict the maturity of cauliflowers. At Reading, however, the emphasis has been placed on presenting these predictions of crop maturity in a practical manner for use by the grower. The grower is presented not only with maturity predictions but also his forthcoming crop yield. Predictions are not provided in terms of dates as this gives growers little useful information, especially when they are confronted with a large number of maturity dates for each different field and variety (Pearson et al. in prep.). The problems of identifying the size and timing of a peak only from predictions of 50% crop maturity dates and harvesting spreads are highlighted in Table 1. However, using a computer program initially developed at Reading for cauliflower crops, the information in table I can be converted into meaningful predictions of crop yield, see fig 1, which can easily be used by growers.

Table I. The data set used to produce figure 1 to demonstrate the yield prediction technique.

Grower	Variety	Plant Day No	Area	50% Harvest Day no	Days From 10 to 90% Cut
1	A	1	7	15	6
1	A	19	6	33	18
1	B	19	2	38	14
1	B	29	3	46	14
1	C	4	1	26	18
2	A	30	4	51	6
2	B	10	8	30	14
2	B	15	5	32	12
2	B	20	7	38	18
2	C	17	1	41	18
3	B	5	3	29	20
3	B	13	1	33	14
3	C	2	4	20	16
3	C	19	3	35	18
3	C	29	5	60	18
4	A	8	2	19	10
4	A	12	6	31	12
4	A	13	2	34	14
4	B	1	5	22	16
4	B	21	5	37	12
5	A	13	3	28	10
5	A	19	5	48	10
5	B	2	2	19	16
5	C	5	7	27	12
5	C	11	3	55	10

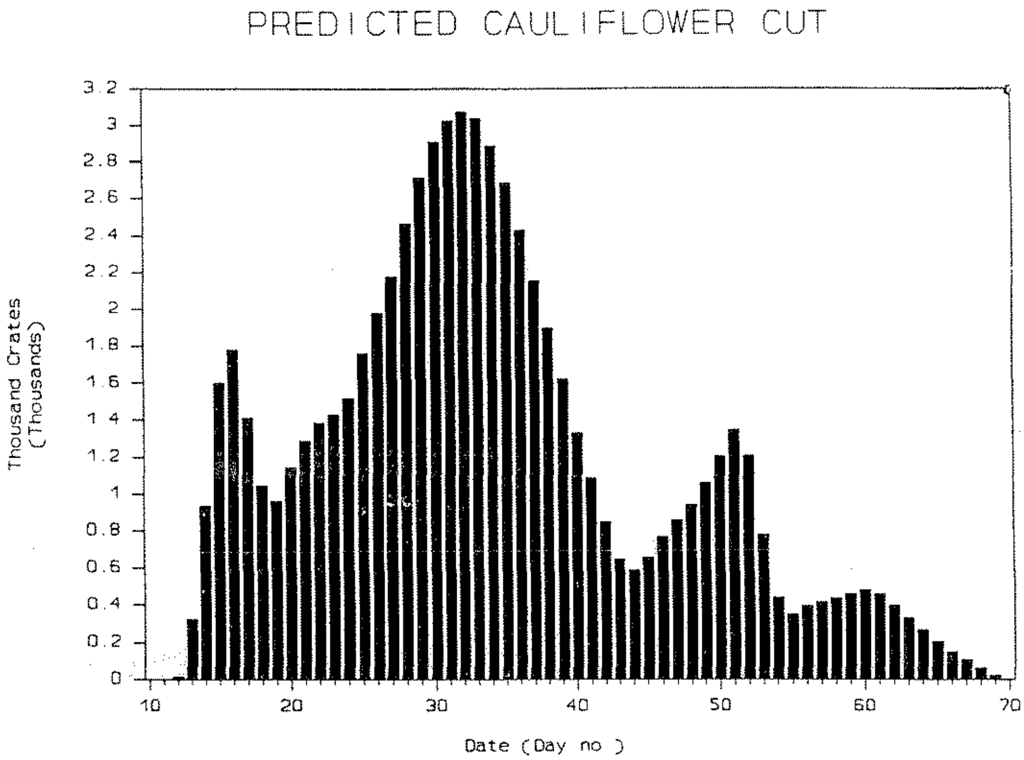


Figure 1. The forecast daily supply (crates per day) of cauliflower, determined by the yield prediction system from data shown on table I.

The objectives of this present study were to validate our Reading models and relationships on commercial techniques crops of calabrese. In order to thoroughly test the models over a wide range of conditions two diverse geographical locations in Scotland and South Lincolnshire were used.

Theory

Relationships to Predict Spear Growth.

i). Thermal Time

Two different techniques have been developed at Reading to predict the spear growth of calabrese (Pearson and Hadley, in Prep). The first technique is based on thermal time. This is an environmental time scale, perhaps better known as accumulated day degrees. Plants respond to the amount of accumulated temperature they have received. Thus, if the temperature is high plants accumulate temperature units, day degrees, quickly and as a result develop at a fast rate. However, if the temperatures are low the plants develop slowly. The number of day degrees to which a plant responds over a 24 hour period is equal to the difference between the daily mean temperature and the plants base temperature below which development ceases, with the proviso that the optimum temperature for growth is not exceeded. For example, if the plants base temperature is 1°C and the average temperature on a day is 10°C the plant will have accumulated 9 day degrees (d°C).

For spear growth of calabrese the first technique requires a linear relationship between the rate of spear expansion and temperature, (fig 2). This is the only accurate method by which the thermal time required for spear maturity and the base temperature can be derived. This derived thermal time constant determines the number of day degrees required for the spear diameter to expand logarithmically by 1. Using long-term average temperature data, the thermal time required for a spear to reach a certain diameter can be converted into the

Fig 2a

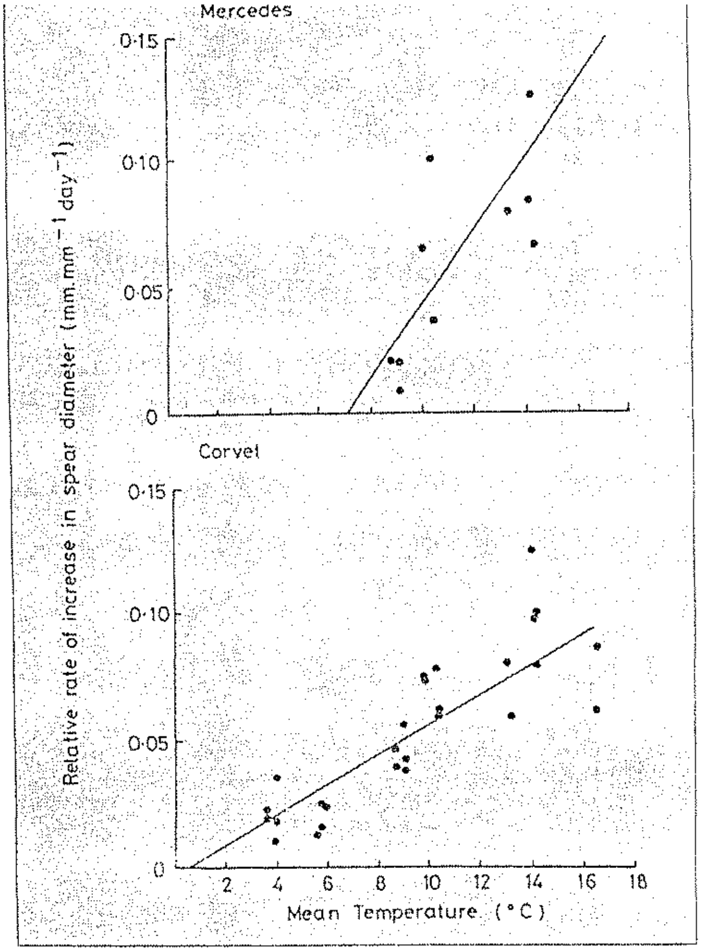


Fig 2b

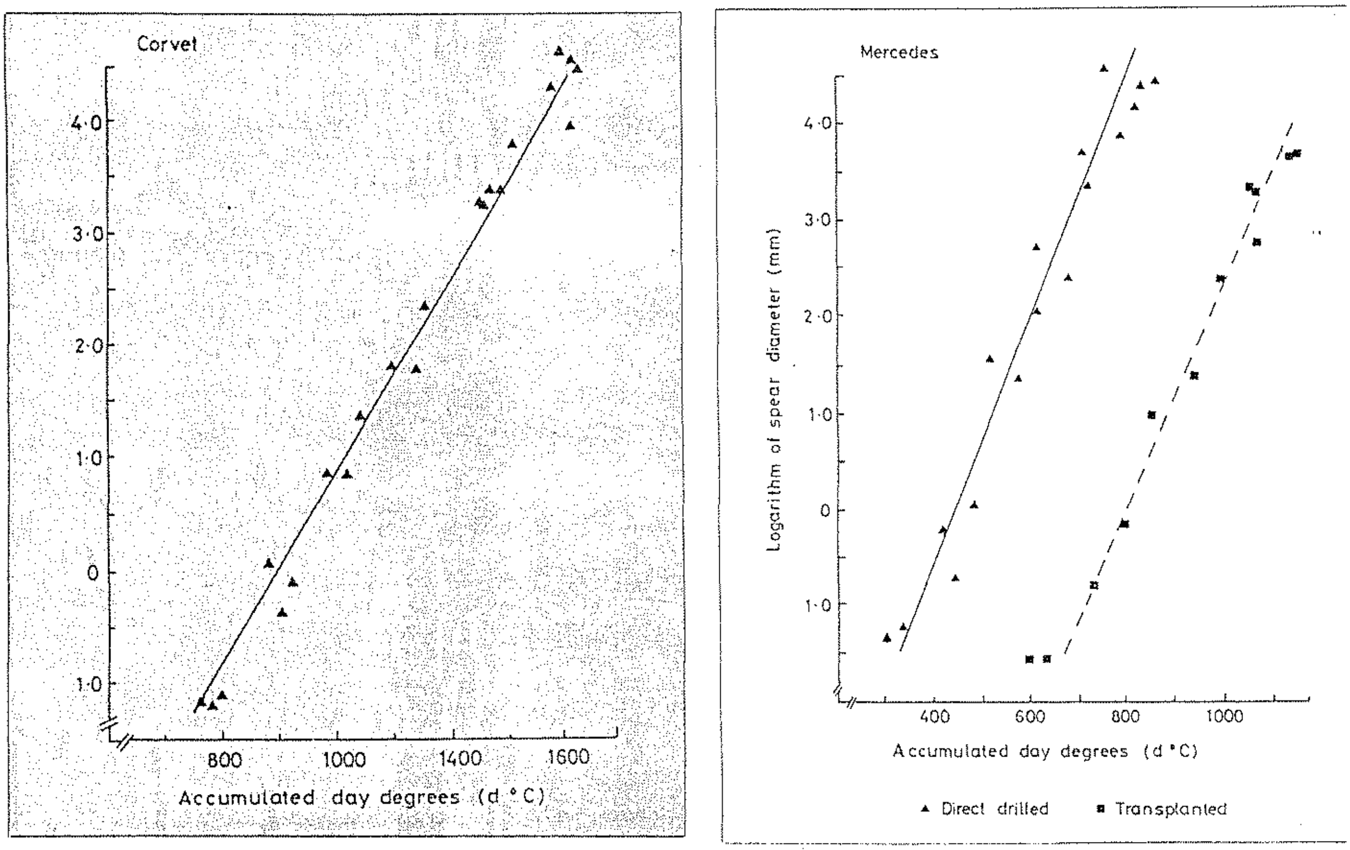


Figure 2a. The relationship between spear growth rates and mean temperature, reprinted from The Grower.

Figures 2b. The relationship between accumulated day degrees and the logarithm of spear diameter for calabrese cultivars Corvet and Mercedes, deterimed from the same data shown on figure 2a.

expected days to maturity. This relationship was established from data, collected at Reading (Pearson and Hadley, 1988), for calabrese cultivars Corvet and Mercedes grown under plastic covers, fig 2a. Corvet had a lower base temperature than cv. Mercedes, 0.6°C as opposed to 5.4°C. However, when both cv's were grown above their base temperatures cv Mercedes spears expanded at a greater rate per degree centigrade than cv. Corvet.

Alternatively, thermal time required for spear expansion could have been determined by plotting the accumulation of day degrees against the increase in logarithm of spear diameter. However, the advantage of our (rate) approach is that the analysis reveals the error in the models, whereas the latter (integrated) method obscures much of the variation in the data. The differences in the two techniques for determining thermal time are illustrated in figs 2a and 2b with data from cv Mercedes. Although based on the same data set our method (rate) in this instance accounted for 67% of the variation in the rate of spear growth, compared with 98% for the alternative integrated method. Although an apparently impressive result it must be remembered that it is derived from a relationship between 2 cumulative values which are already highly correlated. For example, fig 3 shows two series of accumulated randomly generated numbers plotted against each other. The linear relationship subsequently plotted through these points statistically and erroneously accounts for a high proportion of the apparent variation, 89 % in this instance. Thus, it would appear from figure 3 that the two series of accumulated randomly generated numbers are related, even though by definition they cannot be. Of course, when the non cumulative original data are plotted by definition no relationship would be seen. Thus, the true variation in the calabrese data will only therefore be revealed if rates of spear growth are plotted against other environmental variables. Although this point might appear trivial it is important when comparing the errors in different models and for our understanding of the effects of the environment on spear growth.

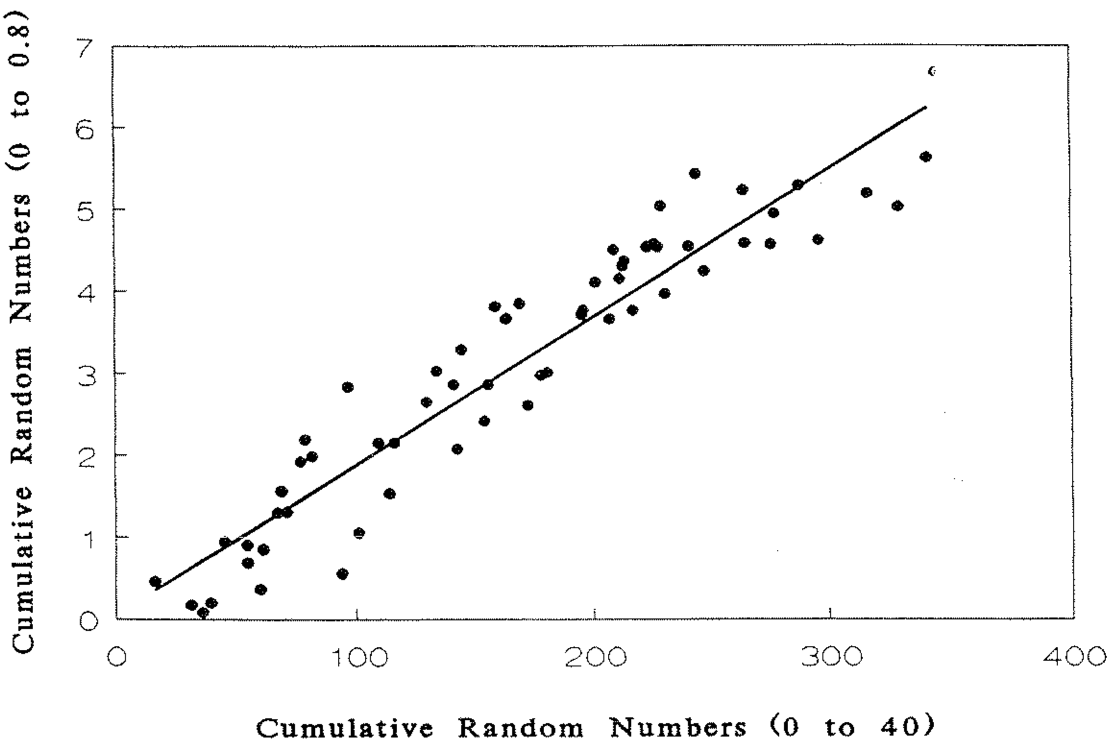


Figure 3. The relationship between 4 series of cumulative random numbers, for the fitted line $r^2 = 0.89$.

ii). A Model Incorporating the Effects Sub and Supra-optimal Temperatures, Light Integral and Plant Density.

The advantage of thermal time relationships described above (section i) is that only two values, the base temperature and thermal time, need to be determined experimentally. However, the thermal time method does assume that spear growth rate does not decline towards spear maturity and that the model incorporates no influence of light and plant density on spear growth rate. Both Marshall and Thompson (1987) and Wurr et al., (1991) previously showed that light might effect spear growth. Our second approach, although more complex, includes such variables in the model. This model for the determination of spear growth rates incorporates the effects of sub-optimal temperature ($P>0.05$), supra-optimal temperatures (i.e. those exceeding 17°C), light integral ($P>0.01$) and plant density into a single linear relationship. The data used to construct the model were collected from numerous crops of calabrese. The data used to produce the model was independent of the data gathered in Scotland and South Lincolnshire. Our one relationship is used for the prediction of all the varieties.

Again the advantage of this technique is that a statistical confidence can be assigned to the influence of each variable (such as light and temperature) in the model. As plant density was incorporated into the model only one equation was needed to predict the spear maturity for calabrese grown under a range of environmental conditions and spacings. Plant density effects the model by determining the final size of the spear at any given crop density and also the rate at which spear growth declines as the spear approaches maturity. The model accounted for 55% of the variation in the spear growth rate with the sample data.

The solution of the model, which is by integration of the daily growth rates, requires the input of plant density and historical or actual temperature and light data to predict spear maturity date. Initially the model is solved in conjunction with historical meterological data and updated with actual temperature and light measurements as time progresses.

iii) Prediction of Spear Initiation

One of the objectives of our research at Reading is to develop a predictive system where spear samples of the crop do not need to be taken. This could be achieved by predicting spear initiation. The initial but somewhat limited data indicate that rate of progress to spear initiation is related to temperature, with an optimum of 20°C. Interestingly, the optimum temperature for spear initiation appears to be higher than that for spear growth, 17°C. Techniques similar to those described for the prediction of flowering in Chrysanthemum by Pearson et al.,(In Press) have been extended for the prediction of initiation of calabrese spears. As data were only available for cultivar Corvet it was necessary to make some simple assumptions on initiation times for other widely used commercial cultivars. Based on typical maturity patterns Cruiser was assumed to initiate 3 days earlier, Shogun 5 days later and the remaining cultivars on identical dates to Corvet.

Commercial Prediction of Daily Crop Yields

The system developed for predicting cauliflower yield, illustrated in fig 1, was also used for calabrese. The 10, 50, 90% harvest cutting spreads are calculated for each crop by the methods described above. The number of mature spears in a crop is assumed to be normally distributed over the cutting period. Thus the number of spears maturing in a crop increases up to the 50% maturity date and thereafter decrease rapidly towards the 90% cutting date. It can be shown that the number of spears maturing in a crop on a daily basis is equivalent to the area, for each day, under the distribution curve. In the illustration, figure 4, the area ABCD represents the number of mature spears on day x and CDEF the number of mature spears in the crop on day x+1. The day to day expected cuts for any single field are determined by calculating the area under the curve daily through-out the cutting period. Growers may have many fields of calabrese. Thus, in order to determine the expected yield of their whole enterprise this process must be repeated for the whole acreage planted. The

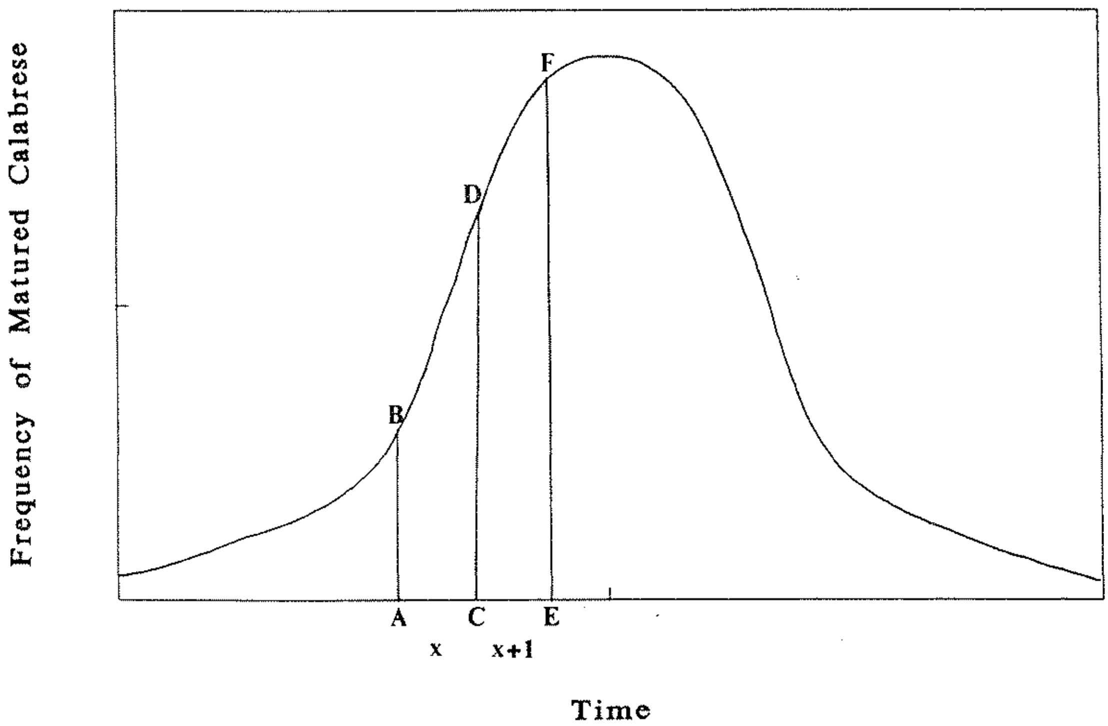


Figure 4. The maturity distribution of a calabrese crop. The area ABCD represents the number of spears mature on day x.

forecast yield is then determined by adding, on a day to day basis, the contributions from each field within the enterprise. This produces an output similar to the one shown in figure 1. Growers can now see at a glance the magnitude of their forthcoming supply.

Materials and Methods

Spear samples were collected from 20 crops of calabrese grown at sites in Scotland and South Lincolnshire. The Scottish site was in Fife at an altitude of approximately 30m above sea level. The South Lincolnshire site at sea level was centred around Old Leake. The sampling was conducted throughout the season on a wide range of commercially important cultivars grown at differing plant densities. At each sampling time 25 spears were randomly selected from each field and measured in two directions, 90° from each other, using a vernier scale. Plant densities were determined by counting the number of plants growing along a 10m row within the crop, multiplication by 0.1 (to convert to plants per meter row) and by the row width gave the plant density. Unfortunately the plant density data obtained in South Lincolnshire appeared to be erroneous, with unrealistically high plant densities. The error was due to incorrect measurement of the average row width, by not allowing for wheeling. Consequently this data was not used and the spear crop density in South Lincolnshire was assumed to be 9.9 plants m^{-2} for spears and 3.5 plants m^{-2} for crowns. These values were obtained from the estimates of the number of transplants used by the growers.

At the initial sampling growers estimates of the target size at maturity were recorded. Actual spear sizes at maturity were measured by re-sampling fields following the start of the harvest. The percentage of the crop cut was determined from the proportion of plants harvested from a sample of 100. Fifty percent maturity dates were determined by addition or subtraction of a set number of days to the final sampling date depending on the percentile of plants cut at that time, see table II. A summary of the crops sampled is shown in table III together with their 50% maturity dates.

Table II. The conversions, based on the percentile of harvested plants, to convert the sample date at maturity to the 50% maturity date.

Percentile of Harvested Plants	Adjustment to Final Sampling Date
0-10	+4
10-20	+3
20-30	+2
30-40	+1
40-60	0
60-70	-1
70-80	-2
80-90	-3
90-100	-4

Crop Number	Cultivar	Plant Date	Density ($pl.m^{-2}$)	Sample Date	Target.Diam (mm)	Maturity Date[1]	Percentage Mature	Diam (mm)
1	S.G.1	4 Apr	9.9	5 Jun	80	27 Jun	80	88.5
2	Greenbelt[3]	17 Apr	3.5	21 Jun	150	11 Jul	45	136.7
3	Caravel	7 Jun	9.9	1 Aug	85	7 Aug	75	95.5
4	Cruiser	13 May	9.9	9 Jul	85	17 Jul	60	86.1
5	Cruiser	17 Jun	9.9	9 Aug	85	29 Aug	75	82.3
6	Caravel	17 Jun	9.9	9 Aug	85	29 Aug	40	94.9
7	Marathon	17 Jun	3.5	9 Aug	150	30 Aug	5	158.3
8	Arcadia	17 Jun	3.5	9 Aug	150	28 Aug	15	173.4
9	Marathon	26 Jun	3.5	15 Aug	150	6 Sep	10	163.9
10	Cruiser	1 Jul	9.9	23 Aug	85	12 Sep	40	108.4
11	Marathon	2 Jul	3.5	15 Aug	150	12 Sep	20	168.3
12	Cruiser	15 Jul	9.9	4 Sep	85	12 Sep	5	101.3
13	Cruiser	8 Jul	9.9	22 Aug	85	11 Sep	20	107.0
14	Arcadia	9 Jul	3.5	4 Sep	150	18 Sep	30	172.1
15	Shogun	4 Jul	3.5	4 Sep	150	18 Sep	10	174.4
16	Caravel	4 Jul	9.9	29 Aug	85	24 Sep	40	98.5
17	Shogun	18 Jul	3.5	4 Sep	150	14 Oct	20	170.4
18	Shogun	17 Jul	3.5	5 Sep	150	5 Oct	20	179.6
19	Cruiser	17 Jul	9.9	5 Sep	85	7 Oct	10	158.0
20	Marathon	23 Jul	3.5	11 Sep	150	16 Oct	20	145.7

Table III. A summary of the experimental data.

a) South Lincolnshire

Crop Number	Cultivar	Plant Date	Density ($pl.m^{-2}$)	Sample Date	Target.Diam (mm)	Maturity Date[1]	Percentage Mature	Diam (mm)
1	Shogun		3.53	28 May	220	23 Jun	10	185
2	Skiff		5.51	28 May	130	25 Jun	51	112
3	Skiff		5.03	31 May	130	24 Jun	45	129
4	Greenbelt		4.13	31 May	220	24 Jun	12	146
5	Caravel		5.18	4 Jun	130	26 Jun	45	108
6	Marathon		3.91	4 Jun	220	1 Jul	28	187
7	Shogun		3.88	7 Jun	220	4 Jul	55	183
8	Caravel		5.10	7 Jun	130	28 Jun	60	104
9	Skiff		5.10	13 Jun	130	4 Jul	65	119
10	Skiff		4.98	13 Jun	130	3 Jul	57	117
11	Skiff	2 May	5.50	20 Jun	130	10 Jul	59	107
12	Marathon	21 Apr	3.80	25 Jun	220	12 Jul	28	196
13	Skiff	2 May	4.84	25 Jun	130	22 Jul	41	119
14	Marathon	14 May	3.54	25 Jun	220	25 Jul	75	201
15	Marathon	29 Apr	3.51	26 Jun	220	17 Jul	36	179
16	Marathon	22 Apr	3.41	26 Jun	220	16 Jul	28	189
17	Marathon	28 May	3.54	19 Jul	220	1 Aug	48	155
18	Marathon	20 Jun	3.69	5 Aug	220	28 Aug	13	204
19	Marathon	1 Jul	3.47	21 Aug	220	13 Sep	9	177
20	Shogun	1 Jul	3.40	21 Aug	220	17 Sep	29	184

b) Fife

The initial solution of the models requires the input of historical meteorological data. Initial solutions are then updated as the real measured data are obtained. The historical average temperatures for Fife were assumed to be 1°C lower than those measured at Kirton over the previous 4 years. A differing mathematical fourier series relationship (France and Thornley, 1984) was used to predict historical light integral data at each site.

The maximum and minimum temperature and direct sunlight hours measured over the experimental period for the Scottish site were obtained from RAF Leuchars, the nearest meterological station. In South Lincolnshire hourly measurements of the screened air temperature were taken from an automatic weather station (Skye 400; Skye Instruments) located on one of the cooperatives farms at Freiston. Sunlight hour data was obtained from RAF Conningsby. Light integral data which is required for the model was not available from either of the meteorological sites. However, daily light integral was estimated from the sunlight hour data using a series of well known equations (Dr. Anne Wheldon, University of Reading **pers. com.**).

A number of different validations were performed to test the simple thermal time (i) and more 'complete' (ii) models of spear maturity. The simple thermal time relationship validations were conducted using the actual temperature data and the measured final spear size at maturity. Different values of the thermal time constant were used, 140d°C and 120d°C respectively assuming a base temperature of 0.6°C.

Four validations were performed on the more 'complete' relationship (ii), using a similar protocol to Wurr et al. (1990) for his cauliflower model. Predictions were compared with the actual maturity dates when using;

i) estimated meterological data and the grower estimate of spear size at maturity,

ii) estimated meterological data and the actual spear size at maturity,

iii) actual meterological data and the estimated spear diameter,

iv) the actual meteorological data and spear diameters at maturity.

The mean deviations of the predicted crops from the actual maturity dates and the prediction errors (Spre, as used by Wurr et al., 1990) were calculated for all validations. The prediction errors give a measure of the model's consistency and are thus the most important validation coefficient to consider.

Finally the relationships to predict maturity from the transplanting date without crop sampling were tested. The relationship to predict spear initiation was combined with the complete model, these were solved to produce maturity prediction using the measured meterological data and spear diameter at harvest. Initiation was defined to occur when the apex was 0.6mm in diameter (Salter, 1969).

The commercial yield prediction system was tested by intensively sampling a large proportion of the South Lincolnshire cooperatives fields. Throughout the season the cooperative had 120 crops of calabrese. Up to 50% of their fields were sampled and predicted, the remaining 50% were estimated from forecasts of the sampled fields planted on similar dates. Crops were predicted using only the simple thermal time relationship. For the predictions of maturity date it was assumed that the thermal time constant was on average 140d°C, with some slight varietal variations of ± 5d°C. Thus 140d°C were required for the spear to expand by a logarithm of 1. The yield of crown calabrese crops was set at 900 10lb packs per acre and spear crops 800 10lb packs per acre. Forecasts were updated on-line using temperature data recorded on site. Yield predictions were faxed to the cooperative at weekly intervals. Unfortunately the predictions were disrupted during the third week of November when frost destroyed a considerable proportion of the crops. Estimates from fieldsman at OLGA were that 50% of the mature crops and 33% of the immature crops were destroyed.

Results

The Meteorological Data

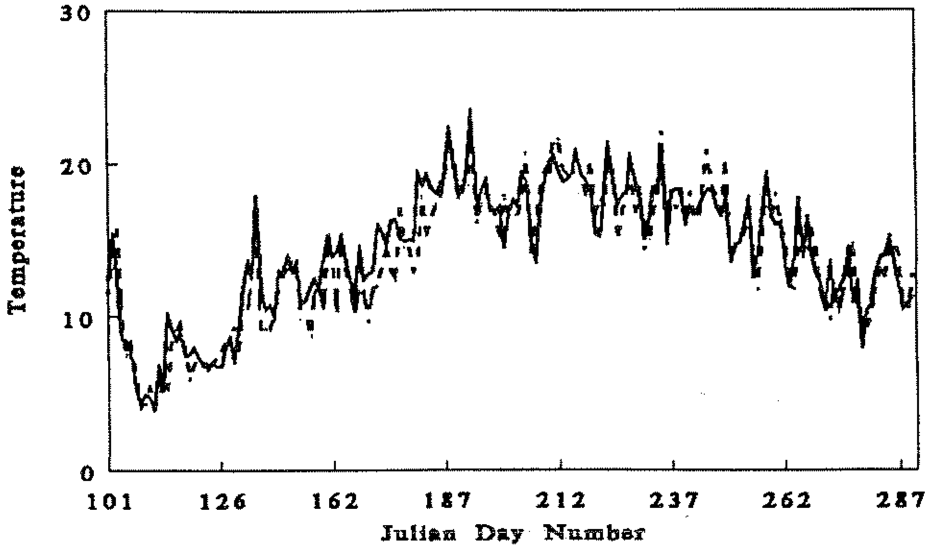
The meteorological data used in the validations is summarised in figure 5a and b. Figure 5a also compares the mean temperature data obtained RAF Conningsby and the cooperative farm in South Lincolnshire. The measurements from the South Lincolnshire site were, on average, 0.4°C higher than those measured at RAF Conningsby. This difference probably reflects the close proximity of the South Lincolnshire site to the sea.
Over the experimental period temperature in South Lincolnshire were 1.96°C higher than in Fife. From the estimates of light integral Fife received 6% less than RAF Conningsby

i. Thermal Time Model

Table IV summaries the validation results of the prediction models. A positive sign on the table indicates that crops matured earlier than predicted whilst a negative sign indicates a later cut. The 140d°C thermal time relationship was +4.1 days late for all crops combined. Predictions for the Scottish crops were +6.2 days late compared with +1.9 days for Lincolnshire. A thermal time 'constant' of 120d°C produced better forecasts with a total deviation of only +0.2 days and a Spre of 3.87days. The actual deviation determined for each crop using the 120d°C relationship is shown in fig 6.

ii. Complete Model

The results of a range of validations with the 'complete' model are shown on Table V. Validations with estimated meteorological data showed similar results when both estimated and actual spear diameter data was used. Deviations and Spre's were similar at both sites. Only one cultivar Arcadia produced consistently late results, however only a sample of 2 was used, one of which matured 8 days early when using the estimated head size and 10



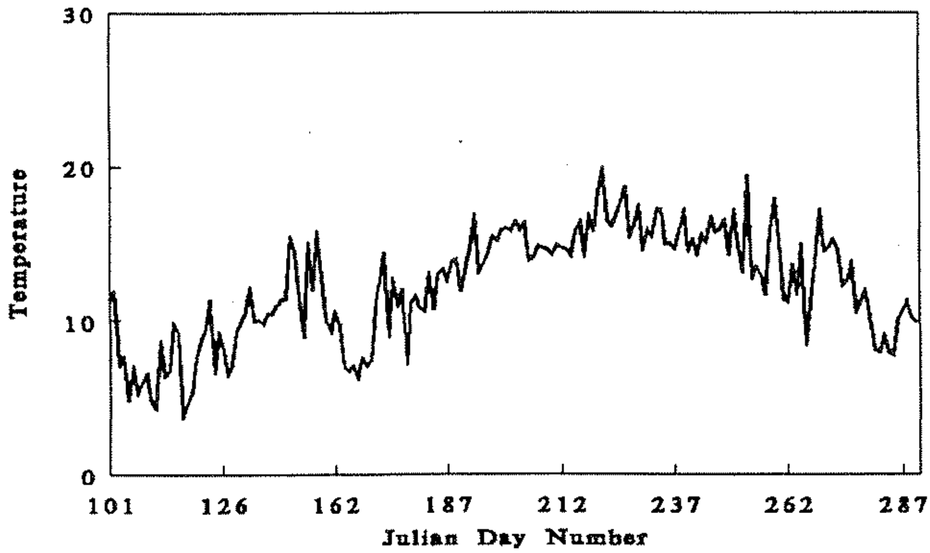
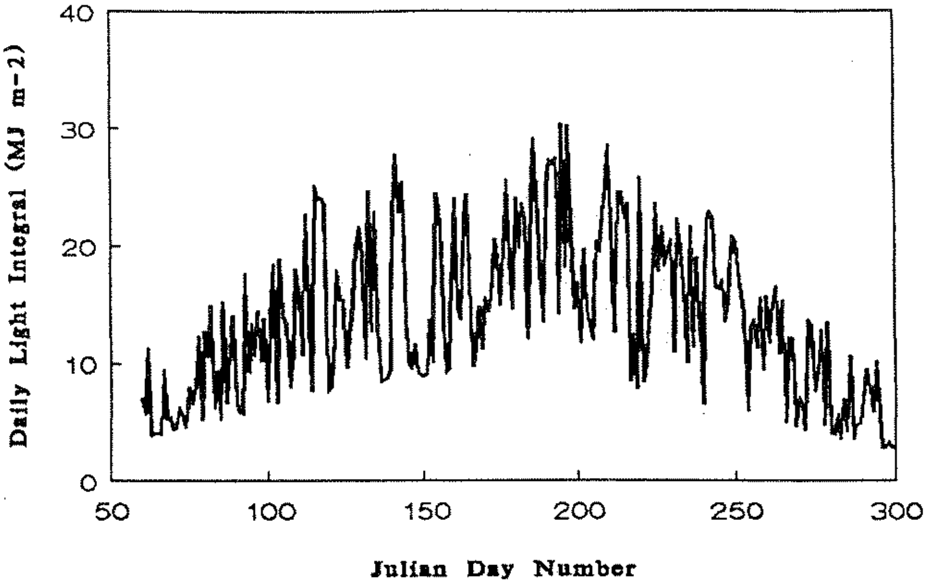


Figure 5a. The measured daily mean temperatures over the experimental period, the upper diagram shows Freiston and RAF Conningsby (broken line), the lower diagram is data from RAF Leuchars.



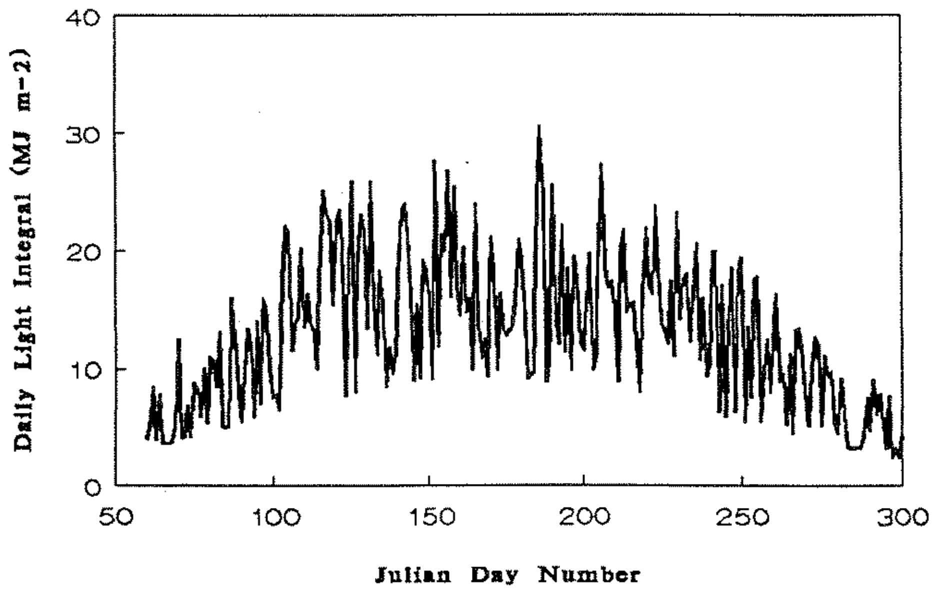
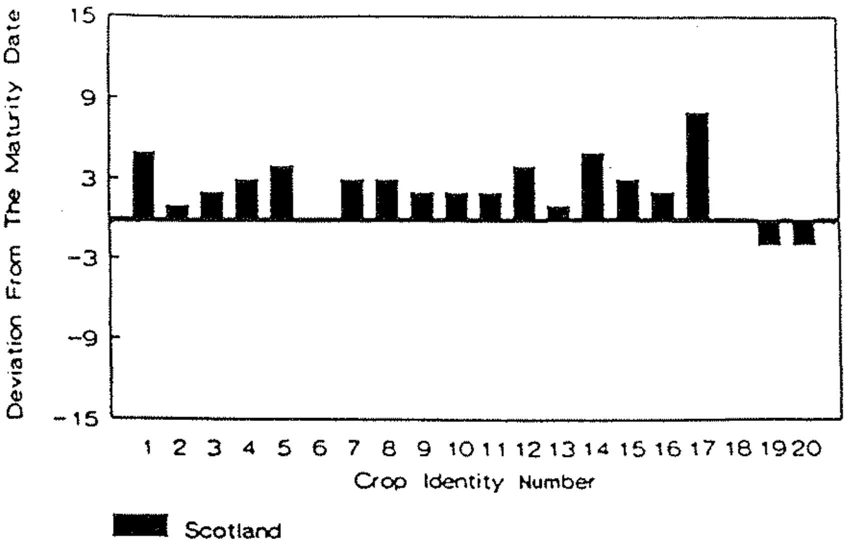


Figure 5b. The estimated daily light integral from RAF Conningsby (upper diagram) and RAF Leuchars (lower diagram) for the experimental period.

Cultivar	Sample number (n)	140°dC		120°dC		Initiation[1]	
		Mean dev.	Spre	Mean dev.	Spre	Mean dev.	Spre
Arcadia	2	+7.0	9.21	+3.5	6.51	-4.5	8.04
Caravel	5	+5.8	6.04	+1.8	2.93	-7.0	11.70
Cruiser	6	+0.3	2.71	-2.51	3.85	-4.7	6.90
Greenbelt	2	+5.0	5.38	+1.5	2.12	---	----
Marathon	12	+4.8	6.19	+0.3	4.04	-4.2	8.58
Shogun	6	+3.0	5.00	-1.3	5.06	-7.2	8.23
Skiff	6	+5.2	5.21	+1.7	1.73	+1.0	6.08
Group							
Spears	20	+3.5	4.66	+0.1	2.92	-4.2	8.11
Crowns	20	+4.5	6.17	+0.3	4.49	-4.9	7.99
South Lincs	20	+1.9	4.18	-1.9	4.39	-6.65	8.75
Scotland	20	+6.2	6.63	+2.2	3.25	-0.7[a]	6.37[a]
Total	40	+4.1	5.54	+0.2	3.87	-4.7	8.04

Table IV. The validation results using the simple thermal time models and the model to predict maturity from transplanting date[1], all in conjunction with the measured final spear diameters and meterological data.

[a] only a sample of ten crops were used.



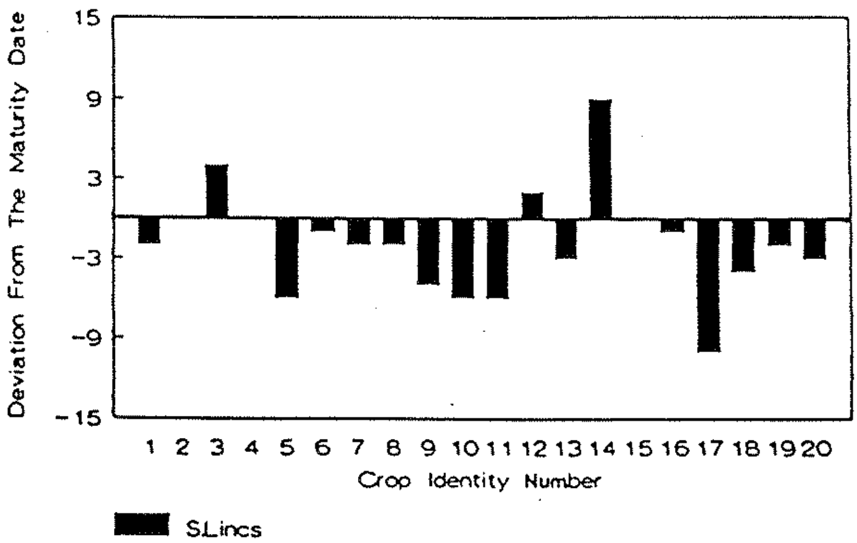


Figure 6. The prediction deviations from the 50% maturity date, for each crop, when the 120d°C thermal time model was applied with the measured final spear diameters and meterological data.

days early when the actual spear diameter was used.

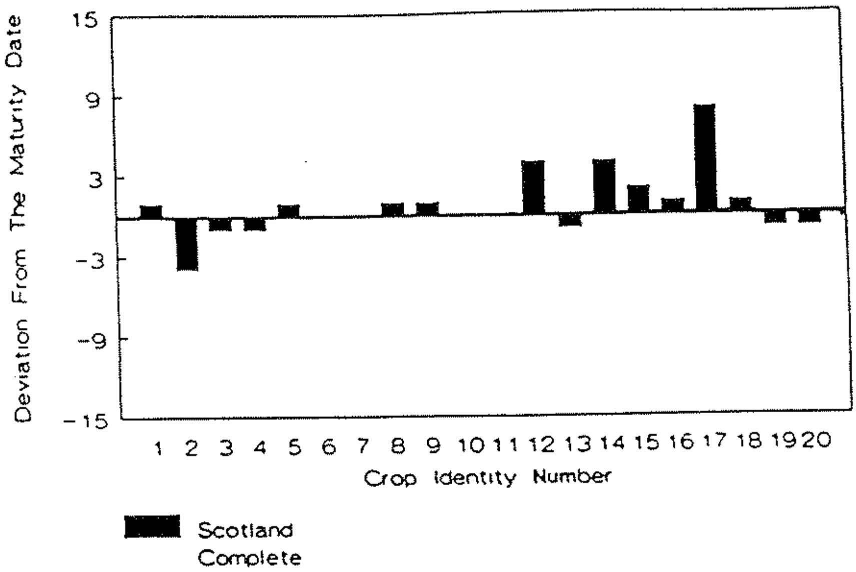
When the 'complete' model was used with actual meterological data and estimated spear diameter the predictions for Fife were 2.3 days late whereas in South Lincolnshire 1.9 days early. However, these differences could be due to an overestimation of the final spear diameter by the Scottish grower compared with an underestimation in Lincolnshire, Table III. When the actual head diameter at maturity was used both sites produced good predictions of the mean deviation from the maturity date. Scottish data spre was lower than Lincolnshire, 2.51 days compared with 4.29. When data from all crops were combined, with the measured spear diameter and actual meterological data the 'complete' model produced the lowest spre, 3.45 days, of all the techniques examined. Only two cultivars had mean deviation greater than 2 days. Arcadia was 5.5 days late 1, of only 2 crops measured was 11 days early. Caravel was 2.8 days late, but this value was skewed by a Lincolnshire crop which was 7 days earlier than expected. It is also believed that the crop in question may have been mistaken, when the maturity sample was taken, for a block of Cruiser planted adjacent to it (Dr M. Brittain **pers. com.**). The individual deviations for all the crops from their maturity dates are shown on figure 7.

iii). The Spear Initiation Model

Table IV shows the validation results for the spear initiation and maturity date model. Only the last 10 Scottish crops were validated as data on planting dates were not available for the first 10. Combined data for all crops produced a mean deviation from the maturity date of -4.7 days, with a considerable Spre of 8.04 days. Much of this error was associated with the South Lincolnshire crops which had a mean deviation of -6.6 days. Predictions for the majority of cultivars were early except cv. Skiff, which was on average 1 day late. This was because all the cv. Skiff crops were grown in Scotland.

Cultivar	Sample number (n)	Est. Met. Est. Head Mean Dev.	Est. Met. Est. Head Spre	Est. Met. Act. Head Mean Dev.	Est. Met. Act. Head Spre	Act. Met. Est. Head Mean Dev.	Act. Met. Est. Head Spre	Act. Met. Act. Head Mean Dev.	Act. Met. Act. Head Spre
Arcadia	2	+2.5	6.04	+4.0	7.21	+3.5	6.51	+5.5	7.77
Caravel	5	-0.4	2.44	-0.4	3.74	+2.6	3.31	+2.8	3.58
Cruiser	6	-3.3	5.21	-0.4	3.46	-2.7	4.47	+0.2	3.31
Greenbelt	2	-2.5	2.91	-5.0	5.83	+2.5	2.91	-0.5	0.71
Marathon	12	-0.1	4.78	-1.2	4.27	+2.1	5.04	-0.7	3.37
Shogun	6	-3.8	5.49	-4.0	5.22	-1.7	4.70	-1.2	3.43
Skiff	6	-4.7	5.56	-5.8	6.51	+0.2	1.35	-0.8	1.77
Group									
Spears	20	-3.1	4.64	-2.6	4.83	-0.3	3.29	+0.4	2.86
Crowns	20	-1.1	4.98	-1.9	5.02	+1.4	4.95	+0.5	3.87
S. Lincs	20	-2.4	4.87	-1.0	4.40	-1.5	4.59	+0.2	4.29
Scotland	20	-1.5	4.79	-3.4	5.51	+2.7	3.95	+0.7	2.51
Total	40	-2.0	4.83	-2.2	4.93	+0.2	4.28	+0.5	3.45

Table V. The validation results for the 'complete' model.



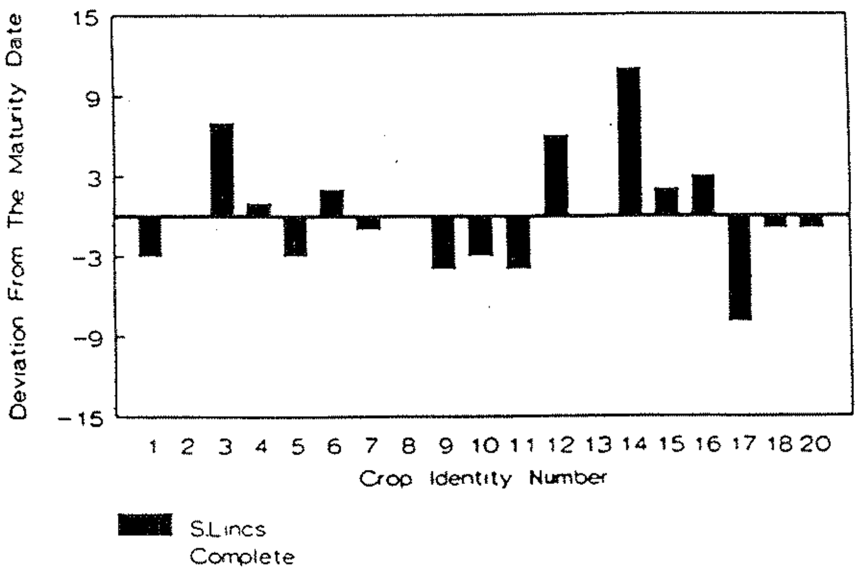


Figure 7. The prediction deviations from the 50% maturity date, for each crop, when the 'complete' model was applied with the measured final spear diameter and meterological data.

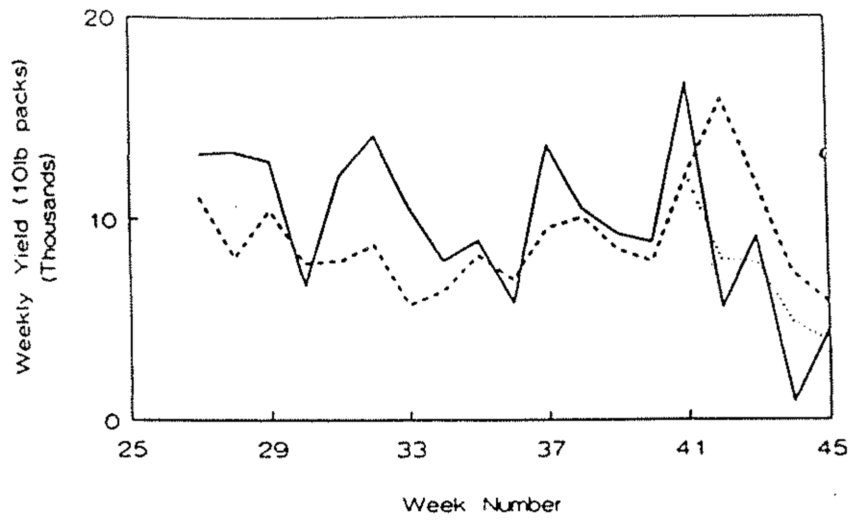
iv). The Yield Prediction System

Figure 8 shows the actual weekly calabrese yields plotted against the predictions with lead times of 1 and 3 weeks. Also shown is the corrected yield, according to fieldsman estimates of loss, for frost damage in week 42. Over the whole season the predicted yield was 78% of the actual yield. Discrepancies arise due to growers underestimates of planted area and yields greater than expected. The importance of accurate data collection cannot be overemphasised. Considering that these predictions were made using the 140d°C thermal time model the results were very reasonable. During weeks 31, 32 and 33 predictions were lower than the actual crop cut. However, if the prediction had been wrong in principle there would have been a large predicted peak to compensate for the lower early yield. This did not occur. Over the last two thirds of the season the predictions produced an accurate indication of yield. During that period the three week lead time prediction appeared more accurate than the one week prediction.

Discussion

The simple thermal time method (i), with a constant of 120d°C, for predicting spear maturity produced good results. The spre was only 0.42 days greater than that of the 'complete' model (ii), when both used the actual meteorological and spear diameters. This indicates that the simple method could be used quite successfully when no light integral data is available at any particular site. Furthermore, the purchase of meteorological data is very expensive and the omission of the light integral from the model would considerably reduce the running costs.

Of all the techniques examined the 'complete' model (ii), incorporating the effects of sub and supra-optimal temperatures, light integral and plant density on spear growth rates, produced the best results. Predictions were encouraging considering that originally the model only claimed to account for 55% of the variation in spear growth rates. This value, 55%, 1 Week



3 Weeks

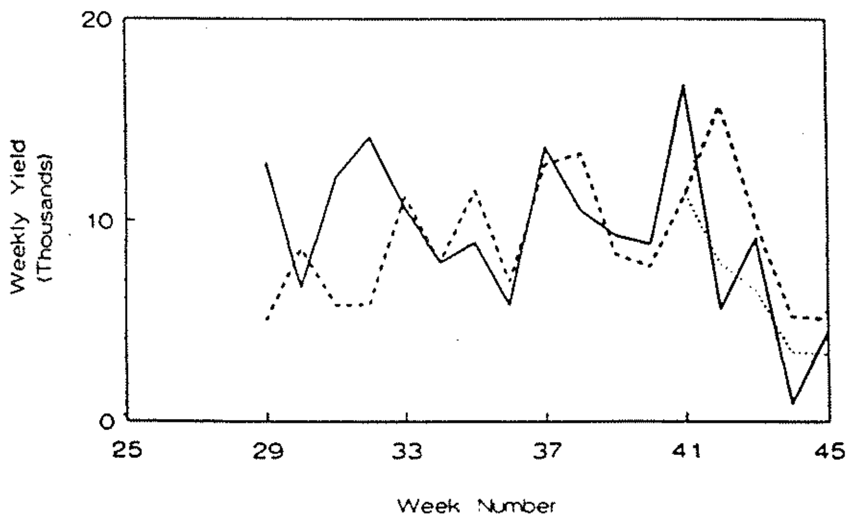


Figure 8. The predicted (broken line) and actual (solid line) weekly yields in South Lincolnshire. The dotted line represents the corrected predicted yield following frost damage. The upper diagram shows data from prediction with a lead time of 1 week and the lower 3 weeks.

was high considering that the original data was collected from field trials where the environmental variables are highly correlated and cannot be easily separated out, for instance a high light integral is linked with high temperature.

The identification of other variables affecting spear growth rates would produce improved predictions of calabrese maturity dates. We believe this could be achieved by more detailed and closely controlled experiments on spear growth, involving controlled temperature glasshouse studies and field shading experiments, facilities for which are available at Reading University. The effects of differing temperatures, at a constant light level, on spear growth could be examined in controlled temperature glasshouses. Whereas, field shading studies would consider the effect of light integral on plants grown under similar temperatures regimes. Shading studies of the spear as opposed to the plant would indicate whether light integral effects on spear growth are due to increased plant photosynthesis or increased spear temperature, due to the incident irradiation it receives. During the forthcoming season the effect of elevated field CO_2 levels on calabrese growth will be investigated along a field temperature gradient tunnel specially designed at Reading University.

Soil moisture deficit as a factor effecting spear growth has not been studied and experiments would provide useful data for incorporation into the spear growth model and growers with field irrigation systems.

The technique used to predict crop maturity from the date of transplanting requires more data than the limited supply we have for cv. Corvet, which is not widely used commercially. Unlike spear growth, initiation probably varies considerably between cultivars which would explain the different maturity dates of cultivars. Investigation of different cultivars in a series of controlled environment studies would give sufficient data on spear initiation to test the derived relationship in the field.

The most important information for a grower is an estimate of the future yields as opposed to simple predictions of crop maturity. Our work at Reading has addressed this problem. The yield predictions performed well even with the 140d°C thermal time model (i). Improvements could be made in subsequent years with better estimates of expected yield, areas planted and the use of the 'complete' (ii) or 120°C model (i). One of the advantages of the yield prediction system is that the large sample size, in terms of fields visited, reduces the effect of 50% maturity date prediction errors. For example if 5 crops are predicted 2 days early and a further 5 fields, 2 days late, the overall yield prediction would be close to the actual. Deviations from the expected yield would only occur when global factors not incorporated into the model, such as soil moisture deficit, systematically delay or hasten all the crops in a given enterprise.

The system developed at Reading University is ideally suited to producing predictions of expected calabrese yield for the whole spectrum of commercial enterprise from individual farms to cooperatives, to whole regions.

Acknowledgements

We gratefully acknowledge the work of David Forsythe and Stephen Herron who collected the data used in the study. Also Dr Louise Sutherland for her useful criticisms of the manuscript.

References

France, J. and Thornley, J.H.M. (1984). *Mathematical models in agriculture.* Butterworths, London.

Marshall, B. and Thompson, R. (1987). A model of the influence of air temperature and solar radiation on the time to maturity of calabrese *Brassica oleracea* var *italica. Annals of Botany.* **60**. 513-9.

Pearson, S. and Hadley, P. (1988). Planning calabrese production. *The Grower.* **110**(9). 21-2

Pearson, S. and Hadley, P. (In Press). A reanalysis of the effects of temperature and irradiance on the time to flowering of chrysanthemum (*Dendranthema grandiflora*). *Journal of Horticultural Science.*

Salter, P.J. (1969). Studies on crop maturity in cauliflower: I. Relationship between the times of curd initiation and curd maturity of plants within a cauliflower crop. *Journal of Horticultural Science.* **44**. 129-40.

Wurr, D.C.E., Fellows, J.R., Sutherland, R.A. and Elphinstone, E.D. (1990). A model of cauliflower curd growth to predict when curds reach a specified size. *Journal of Horticultural Science.* **65**. 555-64.

Wurr, D.C.E., Fellows, J.R. and Hambridge, A.J. (1991). The influence of field environmental studies on calabrese growth and development. *Journal of Horticultural Science.* **66**. 495-504.