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Simulated effects of climate change on the production pattern of winter cauliflower in the UK

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Abstract

Models of the phases of juvenility, curd induction and curd growth, driven by temperature, were developed for Roscoff, Walcheren and Roscoff × Walcheren winter cauliflower types and were linked to enable prediction of the time of curd maturity. Because some crop types in Cornwall (west of UK); Lincolnshire (east of UK) responded differently to weather, separate models were developed for each location. These models were then applied to each cauliflower type at four locations in the UK (Cornwall and Pembrokeshire (west); Kent and Lincolnshire (east)) using four climate impact emissions scenarios and three time-slices (2011–2040, 2041–2070 and 2071–2100). In all forecasts temperatures increased relative to baseline data (1961–1990). The phases of juvenility and curd growth were shortened by increased temperature, while in most cases that of curd induction was increased. The net effect was to advance maturity in all situations except for Roscoff types grown in Cornwall. Maturity was particularly advanced in Pembrokeshire because temperatures were closest to the optimum for curd induction. The effects of location were greater than those of time-slice and scenario and effects on Roscoff × Walcheren types were greater than those on Roscoff or Walcheren types.

Keywords: Temperature; Juvenility; Induction; Curd growth; Maturity; Model simulation

1. Introduction

The UK climate is now at its warmest since measurements began in the 17th century and the last decade has been the warmest in the entire 340 years of central England temperature records (MAFF, 2000). Such changes in temperature affect the growth and

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development of many crops and these effects can be complex in species such as cauliflower, where distinct phases of growth are affected by temperature in different ways. Cauliflowers have three phases of growth: juvenility during which early leaf growth occurs but no induction is possible, curd induction and curd growth. In winter cauliflower the end of juvenility is particularly difficult to determine because it occurs when the plant has more leaves than in other maturity types and so a simple model estimating the end of juvenility was used here. Curd induction requires relatively low temperatures and eventually results in curd initiation so that high temperatures are likely to delay initiation. There is now good understanding of the effect of temperature on the induction of summer and autumn cauliflower (Booij, 1987; Hand and Atherton, 1987; Wurr et al., 1993; Pearson et al., 1994; Grevsen and Olesen, 1994) and several models of induction have been produced (Wurr et al., 1993; Grevsen and Olesen, 1994; Pearson et al., 1994). More recently, there has been specific work studying curd induction in winter cauliflower (Wurr and Fellows, 1998; Reeves et al., 2001) and the latter developed a model, which accurately predicted progress through curd induction on independent data sets. The work described here has used the technique of Reeves et al. (2001) to produce models of curd induction on three different types of winter cauliflower and has also developed models of their curd growth using similar techniques to those of Wurr et al. (1990). The separate models of juvenility, induction and curd growth were then linked to simulate what might happen to winter cauliflower in different parts of the UK using a range of climate change scenarios. This information is relevant to future commercial production because winter cauliflower is grown in distinct parts of the UK, which have slightly different climates and production seasons. For example, in Cornwall, where cauliflower crops mature throughout the winter, frost can cause damage to curds close to maturity and higher temperatures will minimise potential damage.

2. Materials and methods

A number of transplantings of experimental crops (Table 1) were made in 1998–2000 in both Cornwall and Lincolnshire to provide crop samples indicating the stage of crop development of Roscoff (‘Medaillon’), Roscoff × Walcheren (‘Renoir’) and Walcheren (‘Tivoli’) types. Plants were raised and crops fertilised and managed according to local practice. In Lincolnshire all three maturity types were grown, while in Cornwall only Roscoff and Roscoff × Walcheren types were grown.

2.1. Crop sampling

Sequential samples of 10 guarded plants were taken about 3 weeks after planting and then every fortnight in the 1998/1999 season and every 3 weeks in the following two seasons. The plants were dissected and the diameter of the apex was measured orthogonally to the nearest 0.04 mm and the state of the apex was recorded as vegetative or initiated. Once all curds were initiated a more detailed sample was taken. The total number of leaves and the apex diameter were recorded. Hourly air temperature and solar radiation were recorded using data loggers.

Table 1
Details of experimental crops

Experimental trial	Basal fertiliser (kg/ha)			Planted	First top dressing (kg/ha)		Second top dressing (kg/ha)	
	N	P	K		N	Applied	N	Applied
Scorrier, Cornwall 1998/1999 (plants raised by Fentongollen farms)	60	78	250	13 June	66	28 December	None	–
				2 July				
				15 July				
				28 July				
				24 August				
Long Hedges, Lincolnshire 1998/1999 (plants raised by J.T. Woods of Fishtoft)	51	11	68	4 July	44	3 March	None	–
				25 July				
				11 August				
				4 September				
Scorrier, Cornwall 1999/2000 (plants raised by Fentongollen farms)	60	79	300	10 June	78	30 September	None	–
				30 June				
				12 July				
				28 July				
				13 August				
Friskney, Lincolnshire 1999/2000 (plants raised by S.C. Shaw and Son of Friskney)	150	140	160	29 June	83	18 January	None	–
				13 July				
				26 July				
				23 August				
				1 September				
Scorrier, Cornwall 2000/2001 (plants raised by Fentongollen farms)	60	79	300	13 June	75	18 October	75	20 November
				6 July				
				14 July				
				29 July				
Friskney, Lincolnshire 2000/2001 (plants raised by S.C. Shaw and Son of Friskney)	–	–	–	3 July	40	3 February	None	–
				18 July				
				1 August				
				14 August				

2.2. Development of the models used

Both model fitting and simulation modelling were carried out using the GenStat computer package (GenStat Committee, 2000). The nonlinear model for curd induction was fitted using the *fitnonlinear* command in GenStat giving an algorithm of a modified Gauss–Newton method (GenStat Committee, 2000). The model for curd growth was assessed for goodness-of-fit using the residual sums of squares (see, for example, Draper and Smith, 1981).

2.2.1. Model for juvenility

The juvenile phase was defined as ending when the apex diameter of the plant was 0.2 mm, since Wurr and Fellows (1998) observed that a change in response to temperature in two Roscoff cauliflower selections had occurred at this point suggesting a phase change. The time when the apex diameter was 0.2 mm was estimated using linear interpolation of apex diameter measurements. A simple empirical model was then fitted to the data describing the interval from transplanting to an apex diameter of 0.2 mm using a thermal sum of day-degrees with a base temperature of 0 °C in a similar way to Grevsen and Olesen (1994) and Olesen and Grevsen (2000). For Roscoff and Roscoff × Walcheren types the model was fitted to data from Cornwall and Lincolnshire separately.

2.2.2. Model for curd induction

The model proposed by Reeves et al. (2001) was fitted. During the induction phase the rate of change of the logarithm of the apex diameter, D, is a function, f, of temperature, T, where temperature is itself a function of time, t:

$$\frac{d \ln(D)}{dt} = f(T(t)) \tag{1}$$

$$\ln(D(t)) = \ln(D_v) + \kappa \int_{t_v}^{t_c} f(T(x))\, dx \tag{2}$$

where D_v is the apex diameter at the start of induction, t_v the time of the start of the induction phase, t_c the time of curd initiation, defined as occurring at a mean apex diameter of 0.6 mm (Salter, 1969), and κ is the scaling parameter. A continuous asymmetric function of temperature was used here, based on a gamma distribution:

$$f(T) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} T^{\alpha-1} e^{-T/\beta} \quad \text{for } T > 0 \tag{3}$$

To reduce the correlation between the parameter estimates and to give a more meaningful parameterisation, the gamma distribution was redefined in terms of the mode, ζ (the optimum temperature for curd induction), which is equal to $\beta(\alpha - 1)$ and the distance from the mode to the points of inflexion, η, which is equal to $\beta\sqrt{\alpha - 1}$ and affects the range of inductive temperatures to which plants respond.

2.2.3. Model for curd growth

Once a curd is initiated, it enters the curd growth phase, which was described by fitting quadratic relationships between the natural logarithm of curd diameter and accumulated ambient day-degrees >0 °C from curd initiation:

$$\ln(c) = b_0 + b_1 x + b_2 x^2 \tag{4}$$

where c is the curd diameter, x the day-degrees accumulated from curd initiation and the coefficients b_0, b_1 and b_2 can vary for the location of the crops.

2.3. Temperature scenarios

The latest UK Climate Change Impacts Programme (UKCIP)[1] report (Hulme et al., 2002) presents a set of four alternative scenarios of how climate change may affect the UK. They are called low, medium–low, medium–high and high, respectively, and relate to four scenarios of future global emissions of greenhouse gases. They are presented for three time periods: 2011–2040 (called the 2020s), 2041–2070 (called the 2050s) and 2071–2100 (called the 2080s) and are presented at a resolution of 50 km. These grid squares contained winter cauliflower growing regions in the counties of Cornwall, Lincolnshire, Kent and Pembrokeshire. The 30-year average (1961–1990) was used by UKCIP as a baseline temperature for all predictions involving climate change scenarios and is therefore used here also. The method described by Parton and Logan (1981) was used to estimate hourly temperatures from daily minimum and maximum temperatures for use in the juvenility models and in Eqs. (1) and (4).

2.4. How the models were used

The juvenility, induction and curd growth models described were linked together as appropriate for crops of Roscoff, Roscoff × Walcheren and Walcheren types. The juvenility model switched to the induction model at an apex diameter of 0.2 mm, which in turn switched to the curd growth model after curd initiation at 0.6 mm. This sequence of models was then run until curds with a nominal diameter of 120 mm, a typical supermarket specification for curd diameter, were produced. Model coefficients for Cornwall were used to make predictions for Cornwall and Pembrokeshire (west side of UK), and coefficients for Lincolnshire were used for Lincolnshire and Kent (east side). Predictions were made for each variety, using a single typical planting date of 15 July, together with the simulated weather data from the climate scenarios already described, to determine the timing of the end of juvenility, curd initiation and curd maturity for each area relative to the baseline data.

3. Results

3.1. Effects on temperature

Fig. 1 shows monthly baseline daily mean temperatures and those for each time-slice and every location, for the high emissions scenario only. Effects on temperature change were at a

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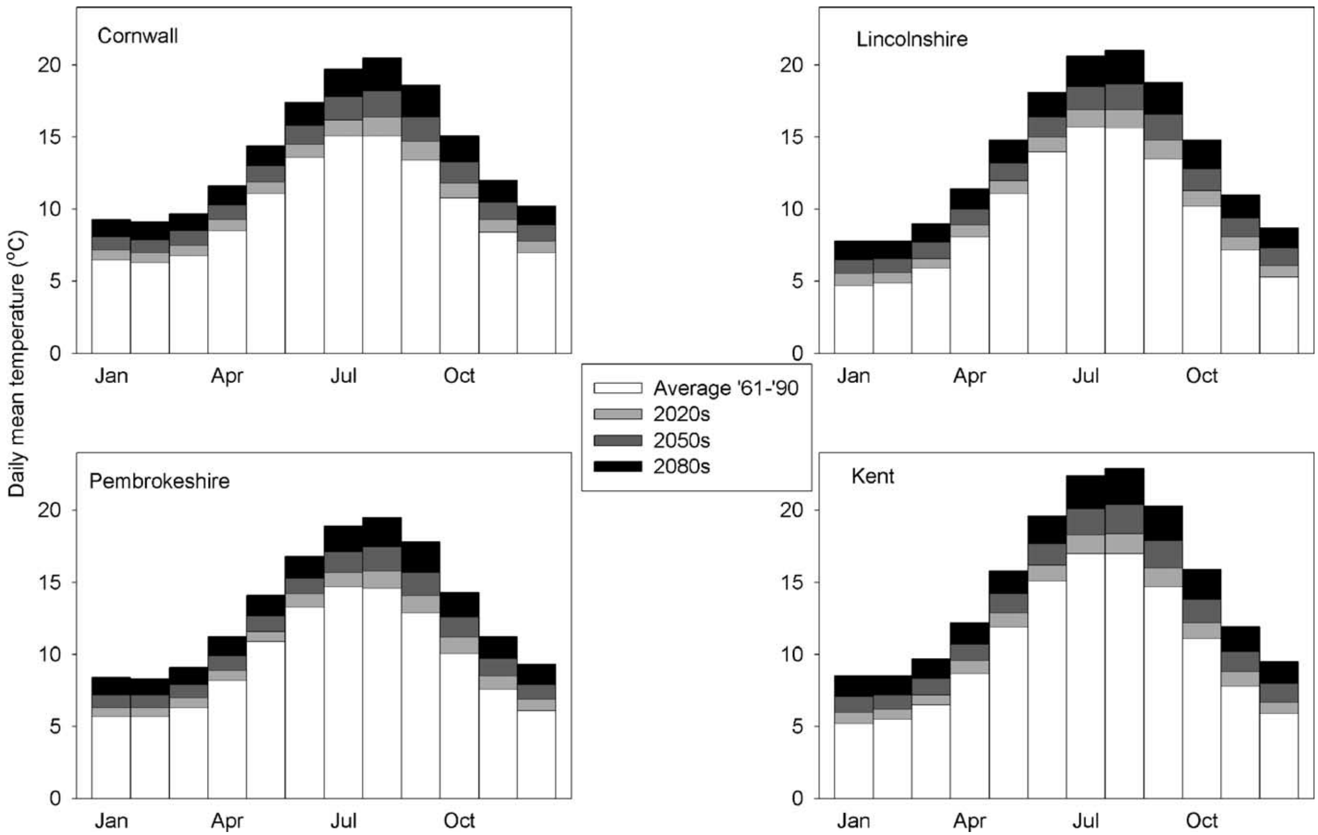

Fig. 1. Monthly mean temperatures under the high emissions scenario in Cornwall, Lincolnshire, Pembrokeshire and Kent showing baseline (1961–1990) data together with UKCIP estimates for the 2020s, 2050s and 2080s.

maximum with the high emissions scenario and were lowest with the low emissions scenario. In all cases temperature increased with time, though this varied according to the month, and some of these increases are considerable, with a rise of up to 5.9 °C forecast for Kent in August. The highest mean temperatures were in Kent and the lowest in Pembrokeshire.

3.2. Model for juvenility

The average thermal sums of day-degrees >0 °C (DD), describing the interval from planting to an apex diameter of 0.2 mm, were 1023 and 1075 DD for Roscoff and Roscoff × Walcheren types respectively in Cornwall. In Lincolnshire the respective sums for Roscoff, Roscoff × Walcheren and Walcheren types were much lower: 449, 451 and 452 DD.

3.3. Model for curd induction

Table 2 shows the results of using hourly air temperatures from 1998 to 2000 to fit the model to data from each maturity type and location. For the Roscoff type, ζ, the modal (optimum) temperature, was similar for both locations, but η (the distance from the point of inflexion), indicating the spread of the gamma curve, was 1.2 °C greater for Lincolnshire. For Roscoff × Walcheren, both coefficients differed with location. The modal temperature,

Table 2
Results from fitting models to experimental data

Varietal type	% variance accounted for		Estimate of coefficient	Cornwall	Lincolnshire
	Cornwall	Lincolnshire			
Model for curd induction					
Roscoff	90.6	95.1	ζ	6.41	6.34
			η	1.54	2.74
			k	0.106	0.023
Roscoff × Walcheren	84.0	76.4	ζ	8.99	6.48
			η	1.59	2.94
			k	0.016	0.013
Walcheren	–	77.0	ζ	–	8.92
			η	–	1.50
			k	–	0.010
Model for curd growth					
Roscoff[a]	94.4		b_0	−0.415	
			b_1	0.00751	
			b_2	−0.00000252	
Roscoff × Walcheren	90.2		b_0	−0.198	−0.515
			b_1	0.00630	0.00540
			b_2	−0.0000018	−0.0000003
Walcheren	92.3		b_0	–	−0.350
			b_1	–	0.00447
			b_2	–	0.0000003

[a] Same model for both locations.

ζ, was 2.5 °C higher for Cornwall (9.0 °C) than for Lincolnshire (6.5 °C). The coefficient, η, was 1.4 °C greater for Lincolnshire than for Cornwall. For the Walcheren type the modal temperature was 8.9 °C.

3.4. Model for curd growth

Regression models describing curd growth were fitted to each of the three maturity types separately using Eq. (4) and showed that the relationship between ln curd diameter and thermal time was curvi-linear. Table 2 shows that in all cases the models fitted well and gives estimates of the coefficients. For the Roscoff × Walcheren type, analyses confirmed that a single model fitting separate lines for each site should be used and the most appropriate models for all types were found to have a base temperature of 0 °C. For the Roscoff type the effect of crop location was not significant.

3.5. Climate change scenarios

3.5.1. Phases of development

As an example of the potential effects of climate change on the duration of juvenility, induction and curd growth, Table 3 presents results from the model for the Roscoff type grown in Cornwall. This shows the effect of the four UKCIP scenarios and the three time-slices

Table 3
For a Roscoff type grown in Cornwall, the effect of scenario and time-slice on the timing of the end of juvenility, curd initiation and curd maturity relative to base line data

Scenario	Time-slice			
	2020s	2050s	2080s	Mean
(a) End of juvenility (day of 0.2 mm)				
High	−6	−14	−21	−14
Medium/high	−6	−12	−18	−12
Medium/low	−6	−11	−14	−10
Low	−6	−9	−13	−9
Mean	−6	−12	−17	−11
(b) Curd initiation (day of 0.6 mm)				
High	7	28	45	27
Medium/high	6	26	36	23
Medium/low	6	20	28	18
Low	5	16	26	16
Mean	6	23	34	19
(c) Curd growth (day of 120 mm)				
High	−6	7	10	4
Medium/high	−7	9	5	2
Medium/low	−7	3	6	1
Low	−7	1	8	1
Mean	−7	5	7	2

The negative value indicates advancement.

on the timing of the end of juvenility, curd initiation and curd maturity, relative to baseline data. A positive value indicated that the event would occur later than baseline data, while a negative value indicated that it would occur earlier than baseline data. Table 3a shows that in the 2080s juvenility will end 17 days earlier than using baseline data compared to 6 days earlier in the 2020s. The high scenario will advance the end of juvenility the most (14 days) and the low scenario the least (9 days). However, in the 2020s there will be no effect of scenario. In contrast, curd initiation (Table 3b) is delayed by all time-slices and scenarios but particularly in the 2080s (34 days delay) and under the high emissions scenario (27 days delay). However, curd growth (Table 3c) will be accelerated by the higher temperatures so that the net effect on curd maturity will be that in the 2020s it will be advanced by 7 days, while it will be delayed by 5 days in the 2050s and 7 days in the 2080s. The net effect of emissions scenarios is small with the high scenario delaying maturity by 4 days while the low and medium/low scenarios would only delay it by 1 day. Fig. 2 then indicates the duration of juvenility, induction and curd growth for every scenario and shows how a later time-slice shortens juvenility and curd growth but that the main effect is on the duration of curd induction. This increased with a later time-slice and as the scenario changed from low to high.

3.5.2. *Emissions scenarios effect on time of curd maturity*

Table 4 shows the net effect of the four emissions scenarios on the time of crop maturity of (a) a Roscoff type, (b) a Roscoff × Walcheren type and (c) a Walcheren type at different

Table 4
Effect of emissions scenarios on the time of maturity in different locations

Scenario	Location				
	Cornwall	Pembrokeshire	Lincs	Kent	Mean
(a) Roscoff type					
High	4	−13	−7	−5	−5
Medium/high	2	−14	−8	−4	−6
Medium/low	1	−14	−5	−3	−5
Low	1	−17	−6	−2	−6
Mean	2	−14	−7	−4	−6
(b) Roscoff × Walcheren type					
High	−12	−27	−9	−11	−15
Medium/high	−13	−27	−9	−10	−15
Medium/low	−13	−27	−8	−9	−14
Low	−14	−26	−7	−9	−14
Mean	−13	−27	−8	−10	−14
(c) Walcheren type					
High	–[a]	–[a]	−8	−7	−8
Medium/high	–[a]	–[a]	−7	−7	−7
Medium/low	–[a]	–[a]	−6	−5	−6
Low	–[a]	–[a]	−6	−4	−5
Mean	–[a]	–[a]	−7	−6	−7

[a] Not grown in these locations.

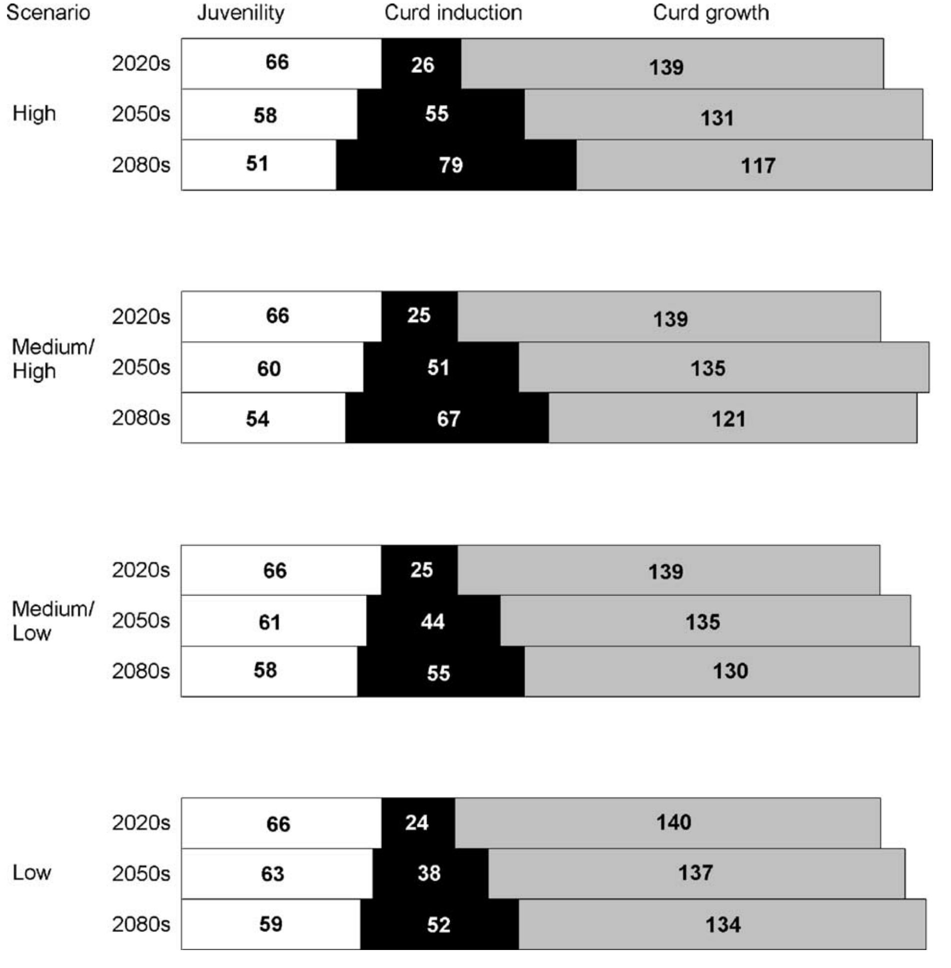

Fig. 2. An example of the effect of different climate change scenarios and time-slices on the duration (days) of the phases of juvenility, curd induction and curd growth for a Roscoff type in Cornwall.

locations in the UK using the most appropriate models for each combination of location and varietal type. In Cornwall maturity of the Roscoff type was slightly delayed (2 days) but on average all scenarios advanced curd maturity, particularly in Pembrokeshire. Maturity of the Roscoff × Walcheren type was advanced in all locations but particularly in Pembrokeshire (−27 days) while the Walcheren type was also advanced in both locations where it is grown. Overall the effect of location was much greater than that of scenario.

3.5.3. Time-slice effects on time of curd maturity

For the Roscoff type in Cornwall the model for the 2020s showed earlier maturity (−7 days) but by the 2050s and 2080s this changed to delayed maturity (Table 5). On average across locations, all time-slices advanced maturity but this was reduced by a later time-slice.

Table 5
Effect of time-slice on the time of maturity in different locations

Time-slice	Location				
	Cornwall	Pembrokeshire	Lincs	Kent	Mean
(a) Roscoff type					
2020s	−7	−16	−6	−2	−7
2050s	5	−16	−6	−3	−5
2080s	7	−11	−8	−6	−5
Mean	2	−14	−7	−4	−6
(b) Roscoff × Walcheren type					
2020s	−13	−21	−3	−6	−11
2050s	−14	−30	−9	−11	−16
2080s	−12	−31	−12	−13	−17
Mean	−13	−27	−8	−10	−14
(c) Walcheren type					
2020s	–[a]	–[a]	−5	−4	−4
2050s	–[a]	–[a]	−7	−5	−6
2080s	–[a]	–[a]	−9	−9	−9
Mean	–[a]	–[a]	−7	−6	−7

[a] Not grown in these locations.

With the Roscoff × Walcheren type maturity of all crops was advanced and this increased with later time-slice. Effects were greatest in Pembrokeshire (−27 days) and least in Lincolnshire (−8 days). For the Walcheren type maturity of all crops was advanced and this effect increased with time. On average, effects on the Roscoff × Walcheren type were greater than on the other two types.

4. Discussion

Recent fluctuations in the time of maturity of winter cauliflower, driven by weather, have created commercial uncertainty, which will increase imports unless some sound means of predicting the timing of crop maturity is developed. The problem has been addressed here by developing simple models of the phases of juvenility, curd induction and curd growth, which are driven by temperature and can be used to estimate when different varietal types will mature. In addition, the models can be used to estimate the effect on cauliflower production of the latest climate change scenarios (Hulme et al., 2002), which suggest fundamental changes in our climate during the next 100 years.

A conventional approach to simulating the effects of climate change would be to use single models for juvenility, induction and curd growth, irrespective of location. However, our data showed that there were interactions between the production system and the environment in Cornwall and Lincolnshire but we do not know why. Where this occurred our approach was to use separate models according to location because we want to simulate what might happen in practice with climate change. It would be simpler to run simulations using a single model but this would not necessarily represent what happens in practice. Unfortunately, we had no plant measurements at transplanting to determine whether transplants were a different size and whether this was the cause of apparently different juvenile periods. However, plants were raised according to commercial practice in both locations by a local plant raiser so they certainly represent what happens in practice.

The UKCIP report (Hulme et al., 2002) points out that warming will be greater in summer and autumn than in winter and spring and there may be greater warming during nights in winter and days in summer. These differential responses are likely to particularly affect curd induction of winter cauliflower, which has a relatively low optimum temperature and is best described by a gamma function (Reeves et al., 2001). As Wurr and Fellows (2000) observed, it is important to take account of the temperature responses of different genotypes and this paper represents a quantitative approach to this problem using sound practically-based physiological models.

Wellington (1954) demonstrated that the difference in the time of curd maturity from year to year could be 3 months. While there will continue to be temperature variations between years and decades the overall trend is for higher temperatures, whichever scenario is used. This will reduce the risk of frost damage to curds as they approach maturity. It is also likely that there will be changes in winter rainfall but the effect of precipitation is ignored here because the models are driven solely by temperature.

The models used for juvenility, curd induction and curd growth have been linked together as Olesen and Grevsen (1993) and Wurr et al. (1995) did when describing climate change impacts on summer/autumn cauliflower. Attempts by many workers to determine the duration of the juvenile phase in cauliflower have been fraught with difficulty and our use of different models for juvenility in Cornwall and Lincolnshire merely represents what others have found and done. Juvenility can conveniently be estimated in terms of the number of leaves formed. However, crops are known to vary in the timing of the end of the juvenile phase (Booij, 1990) and indeed Olesen and Grevsen (2000) adjusted the length of the juvenile phase to fit observed dates of curd initiation. Our model is unproven but uses the same approach as Grevsen and Olesen (1994) and Olesen and Grevsen (2000) and is based on findings by Wurr and Fellows (1998) that during the juvenile phase apex diameters expanded rapidly with temperature up to a diameter of about 0.2 mm. After this there was a different response to temperature suggesting that a phase change had occurred at an apex diameter of 0.2 mm. Here, the fitted thermal sums up to this diameter for crops grown in Lincolnshire were less than half those of crops grown in Cornwall. The reasons for this are not clear though they may be connected with differences in the size of transplants in the two locations. The models used for curd induction fitted well and are based on those determined by Reeves et al. (2001) who reported temperature optima of 11.7 and 9.4 °C in the two open pollinated varieties they studied. Here optima between 6 and 9 °C were found for the three hybrid types and higher or lower temperatures will slow induction and delay curd initiation. Thus, with winter cauliflower, planted in mid-July, ambient temperatures ensure that induction will be delayed with temperature increase. This is not surprising since Wellington (1954) thought that cooler temperatures advanced curd initiation while Wurr et al. (1996) showed that increased temperatures delayed initiation. The models describing curd growth again fitted well and are similar in type to the commercial models used for summer/autumn cauliflower (Wurr et al., 1990).

Here we have used UKCIP information to look at effects of climate change in four locations which cover the majority of UK winter cauliflower production and the models suggest that there will be dramatic effects on crop timing. The UKCIP data (Fig. 1) show that the temperature lift within a single scenario varies according to location, time-slice and month. The effect on the time taken for crops to reach maturity may appear inconsistent but is really quite logical. The whole growth period combines the distinct phases of juvenility, induction and curd growth and each of these has a different response to temperature. During juvenility there is a linear response; curd induction is described by a gamma function (an overturning) relationship, and curd growth is described by a quadratic relationship. Since all these relationships also differ with varietal type it is hardly surprising that effects on the time of maturity vary but this represents the genotype × environment interactions which occur in practice.

Fig. 1 illustrates how dramatically temperatures are expected to increase with time and Fig. 2 illustrates effects on the duration of the three phases of a Roscoff type grown in Cornwall. It shows how the phases of juvenility and curd growth are both shortened by the higher temperatures associated with a later time-slice, while there was the opposite effect on curd induction. The duration of curd growth was much greater than juvenility and induction. Under the low emissions scenario the duration of juvenility exceeded that of induction but under the high emissions scenario induction increased in length, particularly in the 2080s. However, effects of the increase in the duration of induction on the time to maturity were buffered because of the reduction in the lengths of the juvenile and curd growth phases. Fig. 2 and Table 3 also show that, in general, effects of time-slice on phase duration are greater than those of scenario, which were relatively small. The example of a Roscoff type grown in Cornwall in Fig. 2, is actually atypical of other types and locations in suggesting a delay in maturity (Table 4). However, it must be remembered that all timings are relative to the baseline data of 1961–1990 and that current temperatures are above those of the baseline data.

Effects of scenario and time-slice were small whereas the largest effects were those of location. Maturity was particularly advanced in Pembrokeshire because its temperatures (Fig. 1) were lower than elsewhere and therefore closer to the optimum for induction, which was therefore completed most rapidly. Thus, in order to continue to meet market requirements there will need to be either a change in the genotypes grown, and/or later planting, than used currently. Winter cauliflower does not offer the flexibility available with summer/autumn types (Wurr et al., 1995) of a range of planting dates because traditionally the target time for planting all varieties is the middle of July. Another alternative would be for a move from traditional areas of production to cooler locations because of the dominant effect of location on the time of maturity.

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