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ORIGINAL PAPER

Relationship between temperature and cauliflower (*Brassica oleracea* L. *var. botrytis*) growth and development after curd initiation

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Abstract Two experiments were conducted to assess the response of cauliflower (*Brassica oleracea* L. *var. botrytis*) cv. ''Nautilus'' F1 hybrid to different constant temperatures after curd initiation by keeping the plants in six different temperature-controlled glasshouse compartments with heating set point temperatures of 6, 10, 14, 18, 22, and 26 °C (±4 °C) at the School of Plant Sciences, The University of Reading, UK during winter 1998–1999 and summer 1999. Many of the growth parameters increased with increasing mean growing temperature up to an optimum temperature and then declined with further increases in temperature. Therefore, cauliflower's growth and development after curd initiation could be resolved into linear or curvilinear function of effective temperatures calculated with optimum temperatures between 19 and 23 °C. It is suggested that future warmer climates will be beneficial for winter cauliflower production rather than summer cauliflower production.

Keywords Cauliflower · Curd · Temperature · Effective temperature · Growth · Development · Relationship · Radiation conversion coefficient

Introduction

Generally, both plant growth and development require temperatures to be within particular limits. Temperature *per se* is not a growth factor supplying energy to plants, but, it indirectly controls the rate of plant growth and development including morphogenesis and plant quality by controlling the rate of metabolic activities such as chemical reactions, gas solubility, mineral absorption, and water uptake (Treshow 1970). Variations in optimum temperature requirements for maximum metabolic activity of plants are reported between species and even among populations and individuals of a single species (Treshow 1970; Krug 1997). Plant growth rate also varies greatly within temperature limits. For example, plant growth rate increases rapidly from 0 to 15 °C, and increases steadily from 15 to 30 °C for many species of tropical origin (Preece and Read 1993). Above 30 °C, growth rate usually declines because of increased rate of respiration than photosynthesis and above 40 °C, thermal induced death occurs (Preece and Read 1993).

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However, for many plants, the optimum growth temperatures range from 20 to 30 °C (Preece and Read 1993). It has also been reported that different plant organs and stages of plant development have different optimum temperatures (Treshow 1970). Temperature deviation from optimum level decreases enzyme activities causing a reduction in metabolic processes, which ultimately suppress plant development (Treshow 1970).

Cauliflower (*Brassica oleracea* L. *var. botrytis*) is a temperature sensitive determinate vegetable crop. Its growth periods (germination to transplanting, transplanting to curd initiation and curd initiation to harvest) respond differently to environmental variables (Booij 1987; Hadley and Pearson 1998). The optimum monthly temperature for curd formation is between 14 and 20 °C (Swiader et al. 1992; Baloch 1994). Curd formation is very sensitive to temperature extremes, which may cause several types of market defects. Quality of curds becomes poor above 20 °C and there may be no curd formation above 25 °C (Swiader et al. 1992). If the apex is exposed to warm or hot conditions during the curd initiation stage, the diameter of the apex does not increase and may even shrink (Wiebe 1972; Nowbuth and Pearson 1998) or regresses to vegetative growth (Swiader et al. 1992; personal observations). Fujime (1983) and Swiader *et al.* (1992) reported that high temperatures during curd development might result in loss of compactness and development of ricey and fuzzy curds.

Curd growth following the initiation of the floral apex is strongly dependent on prevailing air temperature. Previous work carried out by Salter (1960, 1969) shows a close linear relationship between logarithm of curd size and accumulated day-degrees. This suggests that the time to curd maturity is determined by the accumulated temperature. Further studies (Wurr et al. 1990; Pearson et al. 1994) confirmed this close relationship between curd growth and accumulated temperature. Data presented by Wurr et al. (1990) showed that the growth rate of curds up to 20 mm in diameter was linearly related to temperature up to 18 °C, with indications of supra-optimal temperature effects at 23 °C. However, further studies of temperature on curd growth by Pearson et al. (1994) showed that the effect of temperature on curd relative growth rate of cvs. ''Jubro'', ''Revito'', and ''White Fox'' increased linearly up to an optimum of 16, 21, and 25 °C, respectively, and declined thereafter. They re-plotted their data against effective temperatures rather than accumulated degree-days and found less variation compared with plotting against mean temperatures. However, the data of Pearson et al. (1994) were collected from field grown crops, where temperature changed both diurnally and seasonally. Therefore, this study was conducted in controlled temperature glasshouses to assess more accurately the effects of temperature on cauliflower's growth and development after curd initiation and to confirm whether the application of the effective temperature model developed by Pearson et al. (1994) was appropriate to describe curd growth of cauliflower.

Materials and methods

Cauliflower cv. ''Nautilus'' F1 hybrid seeds (Tozer seeds Ltd, Pyports, Cobham, Surrey, UK) were sown singly in modular trays containing 135 cells (each cell 30 mm × 30 mm × 45 mm deep) containing a peat-based, seed and modular compost (SHL; William Sinclair Horticulture Ltd, Lincoln, UK) on 11 September 1998 (Experiment 1) and placed in a growth room (18 ± 2 °C) for germination and early seedling development, provided with 50 μmol m^{-2} s^{-1} PAR by using Warm white fluorescent tubes (58 W, 1200 mm; GE Lighting, UK) supplemented by tungsten bulbs in a ratio of 20% calculated by the nominal wattage at plant height. At the fourth leaf stage, on 15 October 1998, randomly selected seedlings were potted individually by hand into 2 l pots (6 in.) containing the same SHL compost mixed with 25% perlite and placed in a heated glasshouse set at 15 ± 4 °C until curd initiation. The daylength was extended to 14 h by using high-pressure sodium lamps (SON/T; Camplex 400 W ''Planta'' light, UK) providing 110 μmol m^{-2} s^{-1} (PAR) at plant height during winter 1998–1999 experiment.

About 3 weeks after potting, a sample of three plants was harvested twice a week until 100% curd initiation. At each harvest, plants were dissected to measure the apex diameter and finally a clearly domed apex of approximately 0.6 mm was considered to be curd initiation (Salter 1969; Wiebe

1975; Hadley and Pearson 1999). On 15 December 1998 after curd initiation, 96 plants were selected randomly, and transferred 16 plants to each of six different temperature-controlled glasshouse compartments with heating set point temperatures of 6, 10, 14, 18, 22, and 26 °C (±4 °C) at the School of Plant Sciences, The University of Reading, UK. Actual recorded mean growing temperatures for 4 weeks after curd initiation were 8.8, 12.3, 17.5, 20.6, 23.3, and 27.5 °C (Fig. 1a).

During the spring of 1999 (Experiment 2), the experiment was repeated in the same way as described above. Seeds were sown on 6 February 1999 and grown in glasshouse (heating set point temperature 18 °C) until the fourth leaf stage. On 24 March 1999, seedlings were potted individually by hand into pots and placed in a temperature-controlled glasshouse at heating set point temperature of 15 ± 4 °C. After curd initiation, on 5 May 1999, 10 plants were transferred to each of the six temperature controlled glasshouse compartments where recorded actual mean growing temperatures for the 4 weeks were 9.8, 13.0, 19.1, 21.5, 24.5, and 25.5 °C (Fig. 1b).

Six and seven plants were harvested in experiments 1 and 2, respectively, after 4 weeks. Fresh and dry weights of plant components (leaf, stem, and curd) were measured using a portable Sartorius balance (Model No 1212 MP; Sartorius AG, Goettingen, Germany). Leaf area [measured in cm^2 by using a calibrated leaf area meter (Delta-T Devices Ltd, Cambridge, UK)], stem length, and curd length and diameter were also recorded. Average photosynthetically active radiation (PAR) for 4 weeks after curd initiation was recorded using a calibrated 0.7-m long tube solarimeter (in house manufacture, Szeicz et al. 1964). The solarimeters were calibrated for PAR assuming that 0.5 of solar radiation is PAR (Stanhill and Fuchs 1977) and that 1 J of natural PAR contains 4.56 µmol (McCartney 1978). Measurements were made in each of the six different temperature-controlled glasshouse compartments during the winter 1998–1999 and the summer 1999 experiments, as shown in Fig. 1(c,d). The amount of radiation intercepted was considered to be directly proportional to leaf area, because plants were sufficiently distant from each other to avoid shading effects and moreover, it was also assumed that there was no self-shading between the leaves of the same plant. Therefore, radiation conversion coefficient (e, g mol^{-1}) for yield (curd) was calculated as follows:

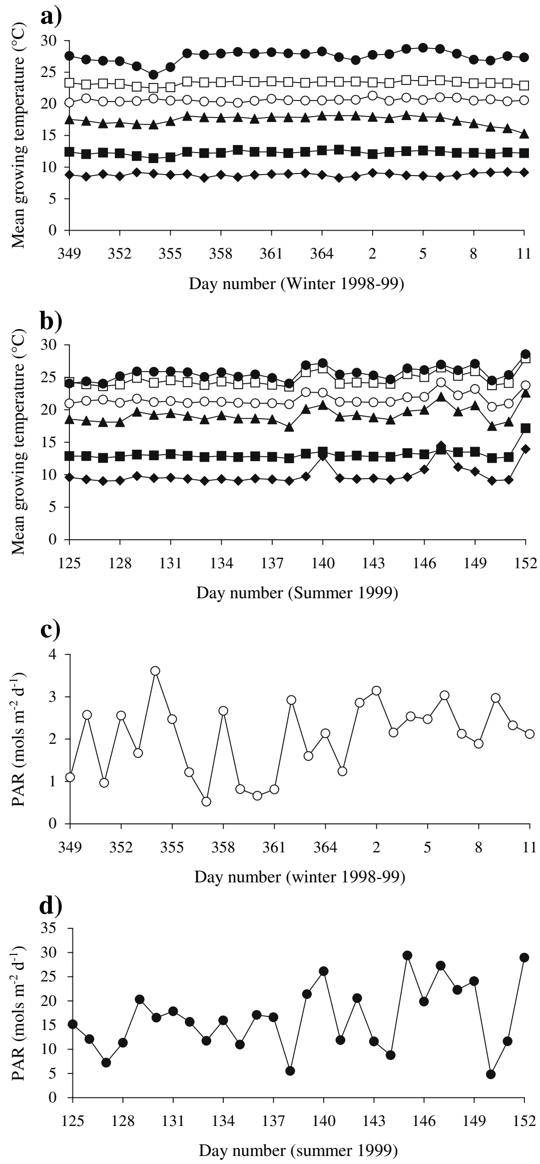


Fig. 1 Actual mean growing temperatures (°C) in six different temperature-controlled glasshouse compartments (◆ –6 °; ■, –10 °C; ▲, –14 °C; ○, 18 °C;□, 22 °C; ●, 26 °C) and photosynthetically active radiation (mol m^{-2} day^{-1}) during the winter, 1998–1999 (a, c) and summer 1999 (b, d) experiments

$$\text{Radiation conversion coefficient} = \text{Curd dry weight (g)}/\text{PAR intercepted}(\text{mol m}^{-2})$$

where

$$\text{PAR intercepted} = \text{Average LA}(\text{m}^2) \times \text{mean PAR}(\text{mol m}^{-2}\text{day}^{-1}) \times \text{Experimental period (days)}$$

where

$$\text{Average LA} = (\text{leaf area at final harvest} - \{\text{leaf area at curd initiation})/2$$

Data were analysed (Gomez and Gomez 1984), using SAS (Version 8) and Genstat 5 computer statistical software packages. Microsoft Excel XP spreadsheet was used for regression analysis (Gomez and Gomez 1984) and graphs.

Results

General observations

Except for radiation conversion coefficient for yield under low incident radiation, all growth parameters describing the growth of the cauliflower plant after curd initiation were significantly higher in the high incident radiation levels (16.5 mol m^{-2} day^{-1}) occurring during the summer 1999 experiment than in low incident radiation levels (2 mol m^{-2} day^{-1}) during the winter 1998–1999 experiment. In addition, many of the growth parameters increased with increasing mean growing temperature up to an optimum temperature and then declined with further increases in temperature. Therefore, the effective temperature approach of Pearson et al. (1994) was applied here to analyse the data. Effective temperatures were calculated for sub-optimal and supra-optimal temperatures, using the following formula (Pearson et al. 1994):

$$T_e = T_o - |T_o - T_a|$$

where T_e, T_o, and T_a are effective temperature, optimum temperature, and actual temperature respectively. The optimum temperature (T_o) was the value that gave the lowest residual sum of squares in the relationship between the growth parameters and effective temperature (Pearson et al. 1994). Visual inspection of plots of residual sum of squares against optimum temperatures (Table 1) showed that the minimum residual sum of squares varied very little within a range of between ±0.5 and ±0.7 around the optimum temperatures for all studied cauliflower variables after curd initiation (data not shown). Thus, the optimum temperatures for all variables should not be considered as more accurate than ±0.5. The concept of effective temperature assumes that supra-optimal temperatures are equivalent to sub-optimal temperatures in terms of developmental rate. Figure 2 (*source*: Pearson 1992) explains the principles of effective temperature.

Directly measured growth parameters

Vegetative growth

Cauliflower leaf area, stem length, fresh and dry weights (g) of leaf and stem at 4 weeks after curd initiation were significantly higher ($p < 0.01$) in the high incident radiation conditions during the summer 1999 experiment than in the low incident radiation conditions during the winter 1998–99 experiment in each temperature treatment (Figs. 3 and 4). During the winter 1998–1999 experiment, leaf area, stem length, fresh and dry weights of leaf and stem increased ($p < 0.01$) with increase in mean growing temperature from 8.8 to 20.6 °C (leaf area, fresh and dry weights), 23.3 °C (stem length), and 17.5 °C (stem fresh and dry weights) reaching a maximum value and declined thereafter with further increase in temperature up to 27.5 °C, whereas, during the summer 1999 experiment, leaf area, stem length, fresh and dry weights of leaf and stem increased ($p < 0.01$) with increase in mean growing temperature from 9.8 to 13 °C (leaf area, fresh and dry weights) and 21.5 °C (stem length, fresh and dry weights) and declined thereafter with further increase in mean growing temperature up to 24.5 °C. However, during the summer 1999 experiment, there was an indication of increase in leaf area, fresh and dry weights of leaf and stem at 25.5 °C (Figs. 3 and 4). Therefore, during the winter 1998–1999 experiment, all vegetative growth components (leaf area, stem length, fresh and dry weights of leaf and stem) showed positive linear relationship with increase in effective temperature with an optimum temperature (Table 1 and Figs. 3 and 4), whereas, during the summer 1999 experiment, stem length and stem fresh

Table 1 Regression coefficients for the effect of effective temperature on cauliflower growth and development after curd initiation during winter 1998–1999 and summer 1999

Estimator	Season	a	b	c	T_{opt}	r^2	p
Leaf fresh weight	Winter	67.59 (±9.82)	3.7 (±0.72)		18.7	0.87	<0.01
Leaf dry weight	Winter	6.09 (±0.71)	0.3 (±0.05)		19.3	0.90	<0.01
Leaf area	Winter	1291 (±155.9)	81.48 (±11.2)		19.0	0.93	<0.01
Stem fresh weight	Winter	12.05 (±2.2)	0.81 (±0.16)		18.6	0.86	<0.01
	Summer	42.3 (±4.1)	1.62 (±0.24)		21.3	0.92	<0.01
Stem dry weight	Winter	1.26 (±0.23)	0.08 (±0.02)		18.6	0.85	<0.01
Stem length	Winter	14.35 (±0.75)	0.17 (±0.04)		23.1	0.80	<0.05
	Summer	19.99 (±1.18)	0.23 (±0.07)		22.5	0.75	<0.05
Curd length	Winter	1.46 (±0.08)	0.04 (±0.005)		21.1	0.95	<0.01
	Summer	–1.24 (±0.65)	0.38 (±0.04)		22.0	0.96	<0.001
Curd diameter	Winter	–0.15 (±0.41)	0.18 (±0.025)		21.7	0.93	<0.01
	Summer	–2.62 (±0.8)	0.64 (±0.05)		21.9	0.98	<0.001
Curd fresh weight	Winter	–6.16 (±1.44)	0.88 (±0.09)		21.3	0.96	<0.001
	Summer	–167.6 (±28.6)	17.32 (±1.83)		20.2	0.96	<0.001
Curd dry weight	Winter	–0.64 (±0.14)	0.09 (±0.01)		21.1	0.96	<0.001
	Summer	–10.01 (±1.85)	1.12 (±0.12)		20.7	0.96	<0.001
Plant fresh weight	Winter	74.34 (±11.93)	5.32 (±0.85)		19.1	0.91	<0.01
	Summer	136.9 (±21.5)	19.1 (±1.37)		20.3	0.98	<0.001
Plant dry weight	Winter	6.78 (±0.92)	0.47 (±0.06)		19.5	0.93	<0.01
	Summer	27.28 (±2.36)	0.77 (±0.15)		20.0	0.87	<0.01
Curd weight ratio	Winter	–0.035 (±0.01)	0.006 (±0.0008)		21.5	0.93	<0.01
	Summer	–0.219 (±0.05)	0.026 (±0.003)		20.9	0.95	<0.001
Relative curd growth rate	Winter	–0.229 (±0.05)	0.04 (±0.01)	–0.0011 (±0.0002)	21.1	0.96	<0.01
	Summer	–0.115 (±0.03)	0.033 (±0.004)	–0.0008 (±0.0001)	20.6	0.99	<0.001
Relative plant growth rate	Winter	–0.025 (±0.01)	0.005 (±0.002)	–0.0001 (±0.0001)	19.0	0.95	<0.05
	Summer	–0.0201 (±0.0025)	0.005 (±0.0004)	–0.0001 (±0.00001)	18.9	0.995	<0.001
Radiation conversion coefficient	Winter	–0.139 (±0.05)	0.022 (±0.003)		24.2	0.95	<0.01
	Summer	–0.196 (±0.04)	0.022 (±0.003)		20.3	0.95	<0.001

a, b, c, T_{opt}, r^2 and p are the intercept, the linear coefficient, quadratic coefficient, optimum temperature (°C), the coefficient of determination and probability respectively. Values in the parentheses are the standard errors. Differences in optimum temperatures of less than 0.7 °C are not likely to be significant

weight increased with increase in effective temperature with an optimum temperature of 22.5 and 21.3 °C respectively (Table 1 and Fig. 4). During summer 1999, leaf area, leaf fresh weight, leaf and stem dry weight showed no significant relationship with effective temperatures (Figs. 3b,d,f and 4f).

Curd growth

Curd growth parameters (curd length, diameter, fresh, and dry weights) were significantly higher ($p < 0.01$) in the high incident radiation conditions during summer 1999 than in the low incident radiation conditions during winter 1998–1999 (Figs. 5 and 6). Curd length, diameter, fresh and dry weights at 4 weeks after curd initiation increased with increase in mean growing temperature up to 20.6 and 19.1 °C during the winter 1998–1999 and summer 1999 experiments respectively (except curd diameter which increased up to 21.5 °C during the summer 1999 experiment), and declined thereafter (Figs. 5 and 6). Therefore, curd growth parameters increased linearly with increase in effective temperature with an optimum temperature during both the winter

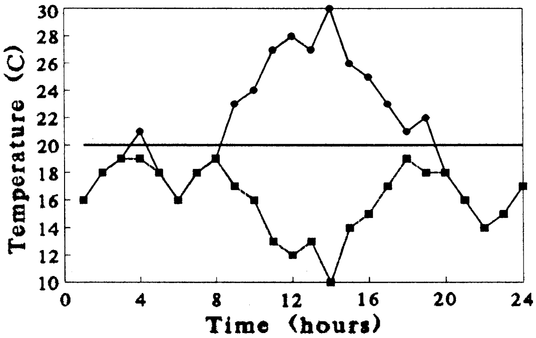


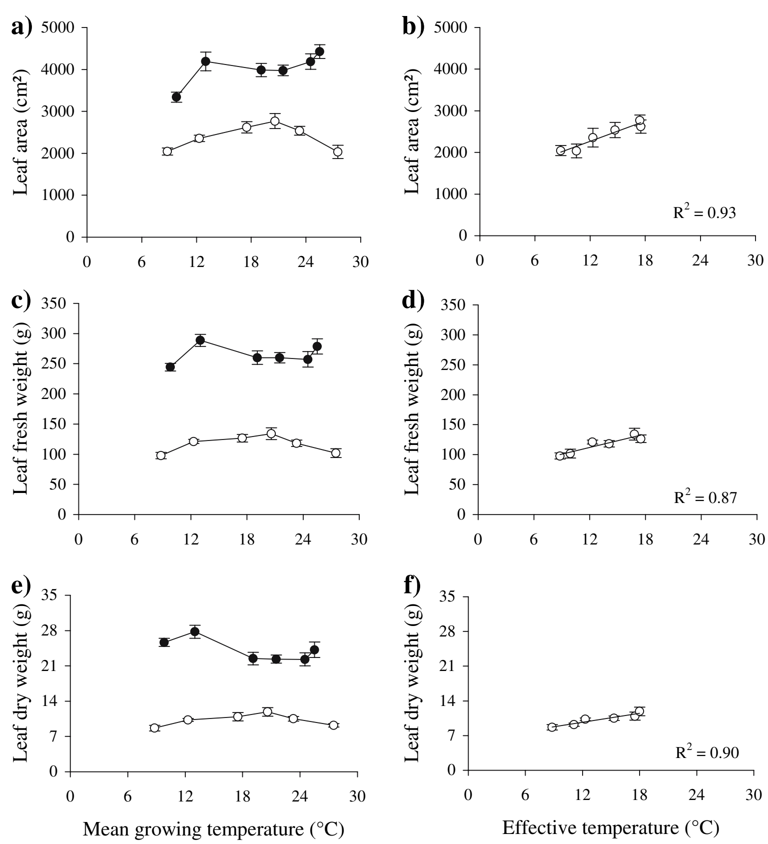
Fig. 2 A schematic diagram demonstrates the principles of effective temperature. The solid line (●—●) represents mean hourly actual temperature over a 24-h period, whilst the broken line (■- - -■) shows the corresponding hourly effective temperatures where the optimum temperature is 20 °C (Pearson 1992)

1998–1999 and summer 1999 experiments (Table 1 and Figs. 5 and 6). However, curd length at 8.8 °C during the winter 1998–1999 experiment appeared to be aberrant and was not included in the data as it was felt that inclusion would be more erroneous from not including it in the regression analysis. No satisfactory reason can be given for this result at 8.8 °C.

Plant growth

Above ground plant fresh and dry weights (g) at 4 weeks after curd initiation were significantly higher ($p < 0.01$) in high incident radiation condition during the summer 1999 experiment than in low incident radiation condition during the winter 1998–1999 experiment (Fig. 6c–f). Moreover, plant fresh and dry weights increased ($p < 0.01$) with increase in mean growing temperature up to 20.6 and 19.1 °C during the winter 1998–1999 and the summer 1999 experiments, respectively, and declined thereafter with a further increase in temperature. When data for the plant fresh and dry weights were regressed against effective temperatures, both plant fresh and dry weights (g) increased ($p < 0.01$) linearly with an increase in effective temperature

Fig. 3 Effect of actual mean growing temperature (°C) and effective temperature (°C) on leaf area (a, b), leaf fresh weight (c, d), and leaf dry weight (e, f) after curd initiation during winter 1998–1999 (○) and summer 1999 (●). Error bars represent 2 × standard errors of the means



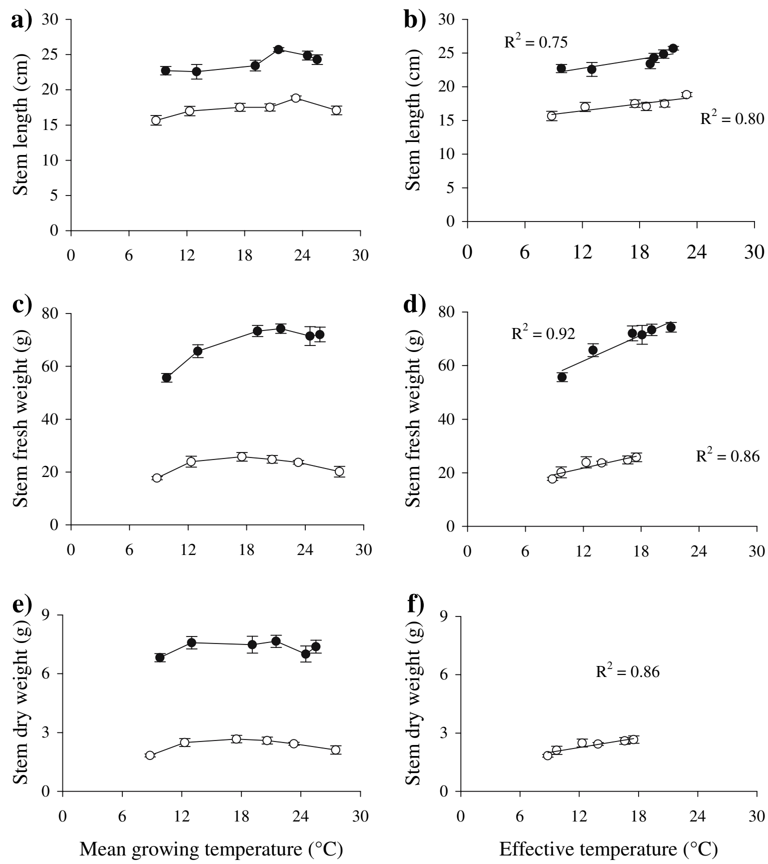


Fig. 4 Effect of actual mean growing temperature (°C) and effective temperature (°C) on stem length (a, b), stem fresh weight (c, d) and stem dry weight (e, f) after curd initiation during winter 1998–1999 (○) and summer 1999 (•). Error bars represent 2 × standard errors of the means

with an optimum temperature (Table 1) during the winter 1998–1999 and the summer 1999 experiments (Fig. 6).

Derived growth parameters

Partitioning of dry matter

Leaf weight ratio was higher ($p < 0.05$) in low incident radiation conditions during the winter 1998–1999 experiment than in high incident radiation conditions during the summer 1999 experiment (Fig. 7). During the winter 1998–1999 experiment, leaf weight ratio declined from 0.82 at 8.8 °C to 0.75 at 23.3 °C, whereas, during the summer 1999 experiment, leaf weight ratio declined more steeply from 0.76 at 9.8 °C to 0.56 at 24.5 °C (although there was an indication of small increase above 25 °C). There was no difference between the leaf weight ratio of both the winter 1998–1999 and summer 1999 crops. In addition, temperature did not affect the stem weight ratio during both the winter 1998–1999 and the summer 1999 experiments (Fig. 7). In contrast, curd weight ratio was higher during the summer 1999 than during the winter 1998–1999 experiment (Fig. 7). During the summer 1999 experiment, curd weight ratio increased from approximately 0.03 at 9.8 °C to 0.28 at 19.1 °C and decreased thereafter to 0.18 at 25.5 °C. Similarly curd weight ratio increased from approximately 0.006 at 8.8 °C to 0.08 at 20.6 °C and decreased thereafter to 0.06 at 27.5 °C during the winter 1998–1999 experiment. By regressing data against effective temperatures, curd weight ratio increased with increase in effective temperatures with optimum temperatures of 21.5 and 20.9 °C during the winter 1998–1999 and summer 1999 experiments respectively (Table 1 and Fig. 7). In addition, mean rate of curd weight ratio increase per 1 °C increase in effective temperature was over three times higher during the summer 1999 than the winter 1998–1999 experiment (Table 1 and Fig. 7).

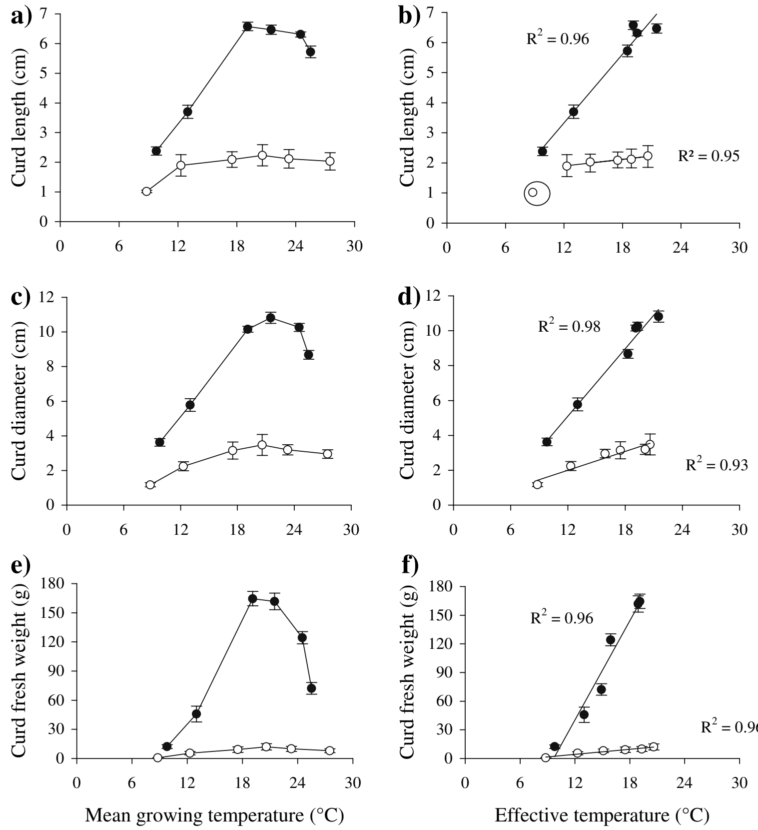


Fig. 5 Effect of actual mean growing temperature (°C) and effective temperature (°C) on curd length (a, b), curd diameter (c, d), and curd fresh weight (e, f) after curd initiation during winter 1998–1999 (○) and summer 1999 (●). Error bars represent 2 × standard errors of the means. Circled data point is considered aberrant (b)

Relative growth rate

Relative curd growth rate (g g^{-1} day^{-1}) was higher ($p < 0.05$) in high incident radiation conditions during the summer 1999 experiment than in low incident radiation conditions during the winter 1998–1999 experiment (Fig. 7). In addition, during the summer 1999 experiment, relative curd growth rate increased from 0.128 g g^{-1} day^{-1} at 9.8 °C to 0.214 g g^{-1} day^{-1} at 19.1 °C and declined thereafter to 0.195 g g^{-1} day^{-1} at 25.5 °C. Similarly, during the winter 1998–1999 experiment, relative curd growth rate increased ($p < 0.01$) from 0.031 g g^{-1} day^{-1} at 8.8 °C to 0.126 g g^{-1} day^{-1} at 23.3 °C and declined thereafter to 0.116 g g^{-1} day^{-1} at 27.5 °C (Fig. 7). Relative curd growth rate showed a curvilinear response to effective temperatures (°C) with an optimum temperature of 21.1 and 20.6 °C during the winter 1998–1999 and the summer 1999 experiments respectively (Table 1 and Fig. 7).

In contrast, plant relative growth rate during the summer 1999 experiment was not significantly higher than during the winter 1998–1999 experiment (Fig. 8). During the summer 1999 experiment, plant relative growth rate increased from 0.015 g g^{-1} day^{-1} at 9.8 °C to 0.022 g g^{-1} day^{-1} at 21.5 °C and declined thereafter with a further increase in temperature to 0.019 g g^{-1} day^{-1} at 25.5 °C. Similarly, plant relative growth rate increased from 0.009 g g^{-1} day^{-1} at 8.8 °C to 0.023 g g^{-1} day^{-1} at 20.6 °C and declined thereafter with a further increase in temperature to 0.014 g g^{-1} day^{-1} at 27.5 °C during the winter 1998–1999 experiment. Plant relative growth rate showed a curvilinear response to effective temperatures with an optimum temperature of approximately 19 °C during the winter 1998–1999 and summer 1999 experiments (Table 1 and Fig. 8).

Radiation conversion coefficient

In contrast, the radiation conversion coefficient for the curd (yield) was consistently higher in low incident radiation condition (2 mol m^{-2} day^{-1}) during the winter 1998–1999 experiment than in high incident radiation conditions (16.5 mol m^{-2} day^{-1})

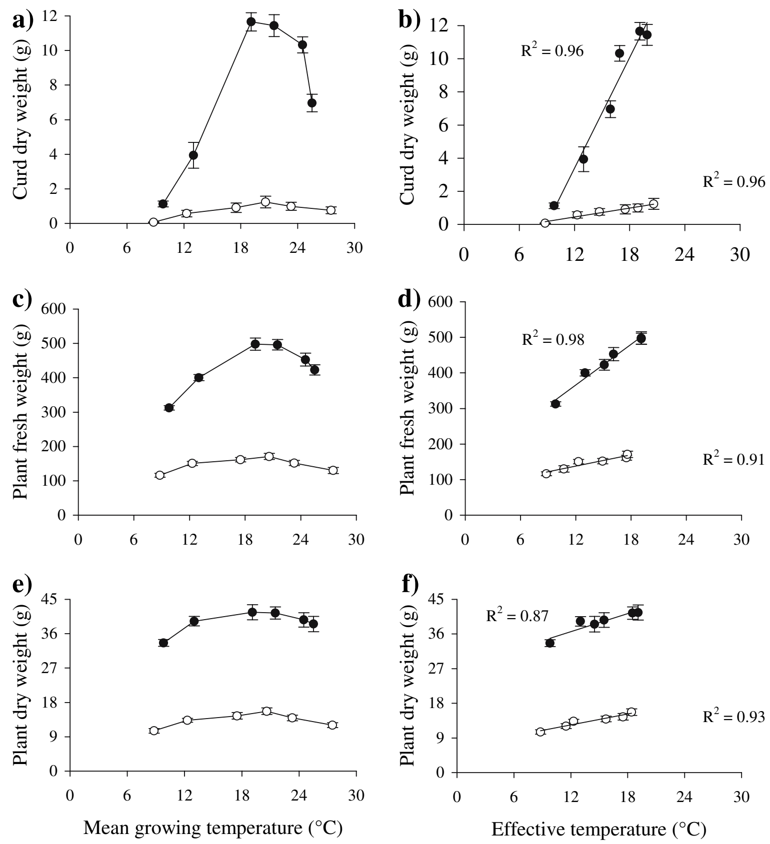


Fig. 6 Effect of actual mean growing temperature (°C) and effective temperature (°C) on curd dry weight (a, b), plant fresh weight (c, d), and plant dry weight (e, f) after curd initiation during winter 1998–1999 (○) and summer 1999 (•). Error bars represent 2 × standard errors of the means

during the summer 1999 experiment, although this difference was not significant (Fig. 8). Radiation conversion coefficient for the curd increased from 0.025 g mol^{-1} at 8.8 °C to 0.303 g mol^{-1} at 20.6 °C and declined to 0.229 g mol^{-1} at 23.3 °C but increased to 0.314 g mol^{-1} at 27.5 °C during the winter 1998–1999 experiment. Similarly radiation conversion coefficient for the curd increased from 0.033 g mol^{-1} at 9.8 °C to 0.231 g mol^{-1} at 19.1 °C and declined thereafter to 0.117 g mol^{-1} at 25.5 °C during the summer 1999 experiment (Fig. 8). Radiation conversion coefficient also increased linearly with increase in effective temperatures (°C) with optimum temperatures of 24.2 and 20.3 °C during both the winter 1998–1999 and the summer 1999 experiments respectively (Table 1 and Fig. 8). Radiation conversion coefficient at 23.3 °C during winter 1998–1999 was excluded from regression analysis, as it appeared aberrant.

Discussion and conclusion

The results of the present investigation indicate that all the cauliflower growth parameters increased in size and weight with increase in mean growing temperatures after curd initiation up to an optimum and declined thereafter. Because the response of cauliflower growth parameters to mean growing temperatures (°C) appeared symmetrical both above and below the optimum value, measurements were successfully analysed in terms of effective temperatures (Pearson et al. 1994).

Pearson et al. (1994) assumed that relative growth rate was linearly related to temperature, both above and below the optimum temperature. This assumption was not confirmed in this study because relative growth rates (RCGR, PRGR) showed a curvilinear response to effective temperatures. However, all other growth parameters were found to be a linear

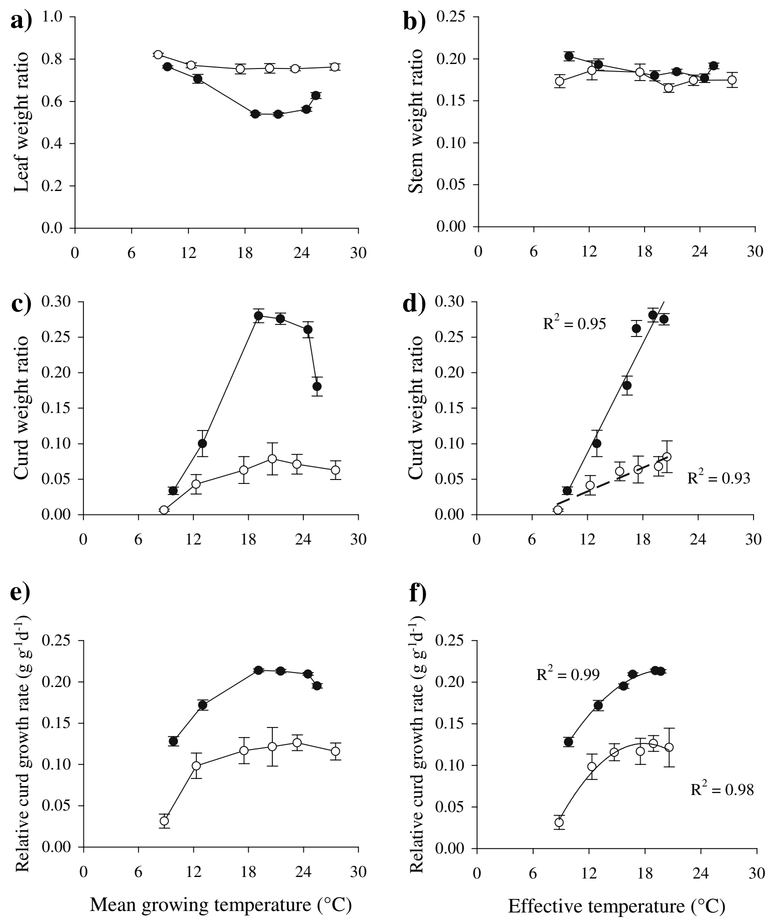


Fig. 7 Effect of actual mean growing temperature (°C) and effective temperature (°C) on leaf weight ratio (a), stem weight ratio (b), curd weight ratio (c, d), and relative curd growth rate (e, f) after curd initiation during winter 1998–1999 (○) and summer 1999 (●). Error bars represent 2 × standard errors of the means

function of effective temperatures with optimum temperatures in the range of 19–23 °C. The optimum temperature for curd growth noted here is close to the optimum value of 21 °C for curd growth reported by Pearson et al. (1994) for cv. ''White Fox''. They also found optimum temperatures of 16 and 25 °C for two other cultivars ''Jubro'' and ''Revito'' respectively. The difference in optimum temperatures for the curd growth of different cultivars can be attributed to varietal difference but the effect of different growing conditions cannot be discounted because data for cvs. ''Nautilus'' and ''White Fox'' were collected from crops grown in controlled environments while data for cvs. ''Jubro'' and ''Revito'' were sampled from field grown crops. This needs to be confirmed in the future work. However, the optimum temperatures for curd growth (21–22 °C) were generally higher than for the growth of vegetative components (19 °C) except for stem length. This finding concurs with Treshow (1970) who reported that different plant organs have different optimum growth temperatures.

The effective temperature model (Pearson et al. 1994) can be applied whenever the relationship between crop growth and temperature is linear and symmetrical both above and below the optimum temperature. This model could also be applicable to already published data of many other species such as lettuce (Thompson et al. 1979), pearl millet (Garcia-Huidobro et al. 1982), faba beans (Ellis et al. 1988), and carrot (Hussain 1999).

Cauliflower plants curd dry matter accumulation was more efficient under low radiation levels during winter compared with the plants grown under higher radiation levels during summer leading to higher radiation conversion coefficients of the plants under low radiation than high radiation levels. This is in accordance with the results of Rahman et al. (2007) and Kasim and Dennett (1986), who found that the

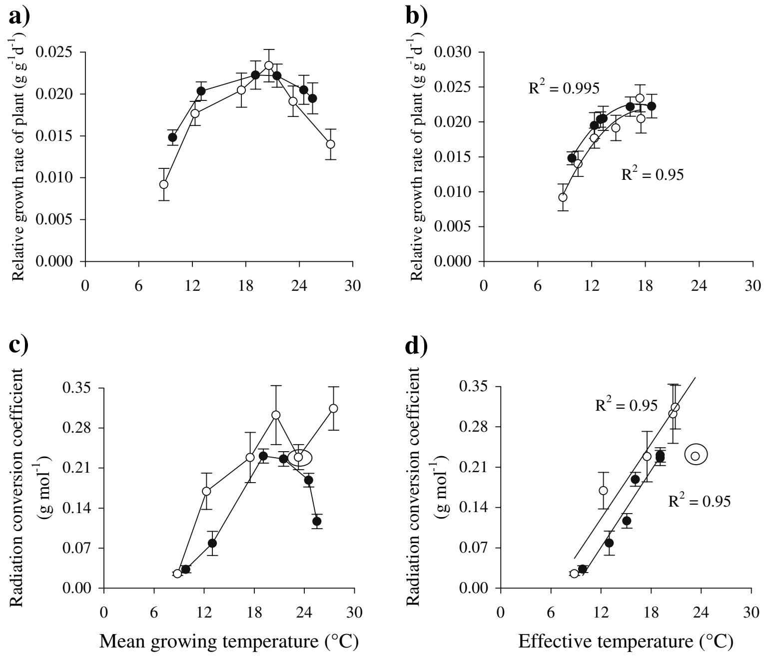


Fig. 8 Effect of actual mean growing temperature (°C) and effective temperature (°C) on relative growth rate of the plant (a, b) and radiation conversion coefficient for the curd (c, d) after curd initiation during winter 1998–1999 (○) and summer 1999 (●). Error bars represent 2 × standard errors of the means. Circled data points are considered aberrant (c, d)

radiation conversion coefficient for cauliflower plants and faba beans (*Vicia faba*) increased as the radiation level decreased.

An approximate rise in global mean temperatures of 2.1–4.8 °C is expected by the end of 21st century due to increases in CO_2 concentrations and other greenhouse gases (UKCIP 2002). Annual changes in average temperature in the UK are expected between 1 and 5 °C by the 2080s depending on region and scenario which will cause greater summer warming in the southeast than the northwest regions and greater warming in summer and autumn than in winter and spring season (UKCIP 2002). This rise in mean temperature will extend the spring and autumn seasons, which will favour cauliflower production because during this period, the daily mean temperatures will rise in the sub-optimum temperature regions and the radiation levels will be much lower for this temperature in the spring and autumn. However, in summer, the daily mean temperature will become more supra-optimal which will cause reduction in summer cauliflower production. Wheeler et al. (1995) have shown no interaction between CO_2 concentrations and temperature on the logarithm of total above ground cauliflower biomass accumulation whereas, the effects of increased CO_2 concentrations on curd growth were greater at warmer temperatures. For example, increases in curd dry weight at 13 and 15 °C grown at 531 μmol mol^{-1} CO_2 was 27 and 71%, respectively, compared to 328 μmol mol^{-1} CO_2. It suggests that future climate change will favour the cauliflower production in autumn, winter and spring seasons rather than in summer season because daily mean temperatures during summer will become more supra-optimal.

In conclusion, cauliflower's growth and development after curd initiation could be resolved into linear or curvilinear function of effective temperatures calculated with optimum temperatures between 19 and 23 °C. In addition, future warmer climates will be beneficial for winter cauliflower production rather than summer cauliflower production.

References

Baloch AF (1994) Vegetable crops. In: Horticulture. National Book Foundation, Islamabad, Pakistan, pp 514–515

Booij R (1987) Environmental factors in curd initiation and curd growth of cauliflower in the field. Neth J Agric Sci 35:435–445

Ellis RH, Summerfield RJ, Roberts EH (1988) Effects of temperature, photoperiod and seed vernalization on flowering in faba bean (*Vicia faba* L.). Ann Bot 61:17–27

Fujime Y (1983) Studies on thermal conditions of curd formation and development in cauliflower and broccoli, with special reference to abnormal curd development. In: Memoirs of The Faculty of Agriculture Kagawa University, No. 40. Miki-tyo, Kagawaken, Japan, pp 117–123

Garcia-Huidobro J, Monteith JL, Squire GR (1982) Time, temperature, and germination of pearl millet (*Pennisetum typhoides* S. and H.). I. Constant temperature. J Exp Bot 33:288–296

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research, 2nd edn. John Wiley and Sons Ltd., Singapore

Hadley P, Pearson P (1998) Effects of environmental factors on progress to crop maturity in selected brassica crops. Acta Horticult 459:61–70

Hadley P, Pearson S (1999) Physiology. In: C. Gomez-campo (ed) Biology of *Brassica Coenospecies*, pp 359–373

Hussain I (1999) Evaluation of carrot (*Daucus carota* L.) germplasm variability under different environmental conditions. PhD Thesis, The University of Reading, UK

Kasim K, Dennett MD (1986) Radiation absorption and growth of *Vicia faba* under shade of two densities. Ann Appl Biol 109:639–650

Krug H (1997) Environmental influence on development, growth and yield. In: The physiology of vegetable crops. Cab International, pp 101–180

McCartney HA (1978) Spectral distribution of solar radiation II. Global and diffuse. Q J R Meteorol Soc 104:911–926

Nowbuth RD, Pearson S (1998) The effect of temperature and shade on curd initiation in temperate and tropical cauliflower. Acta Horticult 459:79–86

Pearson S (1992) Modelling the effects of temperature on the growth and development of horticultural crops. PhD Thesis, The University of Reading, UK

Pearson S, Hadley P, Wheldon AE (1994) A model of the effects of temperature on the growth and development of cauliflower (*Brassica oleracea* L. botrytis). Sci Horticult 59:91–106

Preece JE, Read PE (1993) The biology of horticulture: an introductory textbook. John Wiley and Sons, Inc

Rahman HU, Hadley P, Pearson S, Dennett MD (2007) Effect of incident radiation integral on cauliflower growth and development after curd initiation. Plant Growth Regul 51:41–52

Salter PJ (1960) The growth and development of early summer cauliflower in relation to environmental factors. J Horticult Sci 35:21–33

Salter PJ (1969) Studies on crop maturity in cauliflower: I. Relationship between the times of curd initiation and curd maturity of plants within a cauliflower crop. J Horticult Sci 44:129–140

Stanhill G, Fuchs M (1977) The relative flux density of photosynthetically active radiation. J Appl Ecol 14:317–322

Swiader JM, McCollum JP, Ware GW (1992) Producing vegetable crops. Interstate Publishers, Inc., Danville, IL

Szeicz G, Monteith JL, dos Santos JM (1964) A tube solarimeter to measure radiation among plants. J Appl Ecol 1:169–174

Thompson PA, Cox SA, Sanderson RH (1979) Characterization of the germination response to temperature of *Lactuca sativa*. Ann Bot 43:319–334

Treshow M (1970) Environment and plant response. McGraw-Hill Book Company

UKCIP (2002) Climate change scenarios for the United Kingdom. The UKCIP02 Scientific Report, pp 16–18

Wheeler TR, Ellis RH, Hadley P, Morison JIL (1995) Effects of CO_2, temperature, and their interactions on the growth, development and yield of cauliflower (*Brassica oleracea* L. *botrytis*). Sci Horticult 60:181–197

Wiebe HJ (1972) Effect of temperature and light on growth and development of cauliflower. III. Vegetative phase. Gartenbauwissenschaft 37:455–469

Wiebe HJ (1975) Effect of temperature on the variability and maturity date of cauliflower. Acta Horticult 52:69–75

Wurr DCE, Fellows JR, Sutherland RA, Elphinstone ED (1990) A model of cauliflower curd growth to predict when curds reach a specified size. J Horticult Sci 65:555–564