

The response of *Corylus avellana* L. phenology to rising temperature in north-eastern Slovenia

Zalika Črepinšek · Franci Štampar ·
Lučka Kajfež-Bogataj · Anita Solar

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Abstract Knowledge of plant–weather relationships can improve crop management, resulting in higher quality and more stable crop yields. The annual timing of spring phenophases in mid-latitudes is largely a response to temperature, and reflects the thermal conditions of previous months. The effect of air temperature on the variability of hazelnut (*Corylus avellana* L.) phenophases (leafing, flowering) was investigated. Meteorological and phenological data for five cultivars were analysed over the periods 1969–1979 (P1) and 1994–2007 (P2) in Maribor, Slovenia. Phenological data series were correlated strongly to the temperature of the preceding months (R^2 : 0.64–0.98) and better correlated to daily maximum and mean temperatures than to daily minimum temperatures. About 75% of phenophases displayed a tendency towards earlier appearance and a shorter flowering duration during P2, which could be explained by the significant temperature changes ($+0.3^\circ\text{C}/\text{decade}$) from December to April between 1969 and 2007. An increase in air temperature of 1°C caused an acceleration in leafing by 2.5–3.9 days, with flowering showing higher sensitivity since a 1°C increase promoted male flowering by 7.0–8.8 days and female flowering by 6.3–8.9 days. The average rate of phenological change per degree of warming (days

earlier per $+1^\circ\text{C}$) did not differ significantly between P1 and P2. An estimation of chilling accumulation under field conditions during 1993–2009, between 1 November and 28 February, showed that all four of these months contributed approximately similar amounts of accumulated chilling units. The growing degree days (GDD) to flowering were calculated by an estimated base temperature of 2°C and 1 January as a starting date, given the most accurate calculations. In general, thermal requirements were greater in P2 than in P1, although this difference was not significant. Longer-time series data extended to other agricultural and wild plants would be helpful in tracking possible future changes in phenological responses to local climate.

Keywords *Corylus avellana* L. · Phenology · Temperature · Chilling accumulation · Heat requirement

Introduction

Phenology is the study of periodic biological events in the plant and animal world that are influenced by the environment, especially temperature changes driven by weather and climate (Lieth 1974). The time of occurrence of characteristic vegetation stages, such as leaf unfolding and flowering, are closely related to the climate of the observed site and the weather during the months before a phenological event. The annual timing of spring phenophases in mid-latitudes is largely a response to temperature, and reflects the thermal conditions of the current year and location (Wielgolaski 1999); the temperature in the previous year's winter is also important. In many studies, good correlations between spring phenophases and air temperatures can be found (Chmielewski 2003; Črepinšek et al. 2006). Phenological events, however, are often modified by

Z. Črepinšek (✉) · F. Štampar · L. Kajfež-Bogataj
Biotechnical Faculty, Agronomy Department,
University of Ljubljana,
Jamnikarjeva 101,
1000 Ljubljana, Slovenia
e-mail: zalika.crepinsek@bf.uni-lj.si

A. Solar
Biotechnical Faculty, Agronomy Department,
Experimental Field for Nut Crops, University of Ljubljana,
Vinarska 14,
2000 Maribor, Slovenia

other factors, such as photoperiod, radiation, air humidity or soil characteristics (Migliavacca et al. 2008; Wielgolaski 1999). With increasing air temperatures, plant development in spring starts earlier in the year (Kramer 1994; Menzel et al. 2006). Over the last few years, an increasing number of studies have revealed earlier onsets of phenological spring phases in many places across Europe (Galan et al. 2005; Menzel et al. 2006; Schleip et al. 2008). Significant changes have also been noted in Slovenia (Črepinšek 2005). The majority of published studies have covered natural vegetation, with only a few investigating agricultural plants, despite their economic value (Chmielewski 2003). Modelling plant phenology has become an important tool in recent years, allowing us to understand the influence of climatic variables on phenological development (Bergant et al. 2002; Chuine et al. 1998; Kramer 1994; Schleip et al. 2008). Understanding crop phenology is fundamental for crop management, in which the timing of management practices such as pest control, irrigation and spraying against diseases is based increasingly on stages of crop development.

Hazelnut production is confined to areas with a mild-to-warm summer and cool winter, similar to those found in most parts of Slovenia. Hazelnut trees have a poor tolerance to heat, moisture and wind stress but tolerate extreme cold, including snow and winter frost as low as -15°C . In deciduous tree crops, including hazelnuts, the dates of flowering and leafing at the end of winter or early spring are a function of the chilling requirements for buds and the heat requirement during the post-rest phase. The requirement for chilling is an adaptive device for preventing the beginning of development at the onset of winter, when the flowers or leaves are likely to be damaged by frost (Larcher 2003). Hazelnut requires more hours of chilling than most other nut species (Wilkinson 2005). The chilling hours requirement differs from cultivar to cultivar and different parts of the plant also have substantially different chilling requirements. Mehlenbacher (1991) reported chilling requirements for 'Tonda Gentile delle Langhe' of 1,050–1,300 h for leaves, 600–800 h for female flowers and 350–600 h for male catkins but generally a period of 1,200 h below 7°C was adequate. In most parts of Slovenia, including the discussed location of Maribor, with its cold winter climate, chilling requirements are essential in order to overcome dormancy in the floral and vegetative buds of hazelnuts (Črepinšek et al. 2009). Since several studies suggest that global temperature is increasing (IPCC 2007), major areas within growing regions might face substantial temperature increases in the future, with a consequent absence of winter chilling. In Slovenia, a positive trend of approximately $0.9^{\circ}\text{C}/50$ years in mean annual temperatures has been recorded, and the minimum daily temperatures have increased at a greater rate than the maximum daily temperatures (Kajfež-Bogataj 2001). These changes, which are more pronounced over the winter

months, together with studies on the impact of climate change in Slovenia (Kajfež-Bogataj and Bergant 2005), indicate that winters with insufficient chilling might appear in subsequent years, especially in the coastal area of Slovenia, which has a warmer, Mediterranean climate.

Corylus spp. requires only a very short period of heat accumulation after vernalisation and there are differences in post-rest heat requirements among genotypes with the same estimated chilling requirement (Mehlenbacher 1991). Hazelnut flowering time varies greatly according to the climate and is very temperature-dependent; it thus varies greatly from year to year (Piskornik et al. 2001). Trees grown in mild regions may flower for months while trees in cold regions for only for a few weeks. Hazelnuts are monoecious, wind-pollinated and self-incompatible. During flowering, both male and female inflorescences can be observed on the same tree (Germain 1994). The peak flowering periods for the two may not overlap on the same cultivar (Baldwin 2004). A situation known as dichogamy is present with almost all cultivars (Mehlenbacher 1991). Male catkins usually precede female flowers (protandry) or the pistillate flowers mature first (protogyny) (Encyclopaedia Britannica 2010). When the catkins extend, pollen is shed and transported by wind to the female flowers. After pollination, the development of reproductive structures is suspended and remains quiescent for 5–6 months. The weather during flowering can alter the flowering times of different cultivars, so it is necessary to plant a number of different pollinisers for successful nut production. The growth and development of the plants and nuts must be well understood with regard to temperature when determining the environments in which hazel can be successfully grown, and appropriate agricultural practices then implemented to maximize production (Baldwin 2004).

The aim of this work was to evaluate the flowering and leafing responses to air temperature of five hazelnut cultivars in north-eastern Slovenia, including the heat requirement for flowering and chilling accumulation during the period from November to February. Moreover, comparison and analysis of historical phenophase dates was performed for two separate periods (1969–1979, 1994–2007) with respect to air temperature changes. The information obtained will provide a better understanding of hazelnut's phenological temperature response, which will be useful for current hazelnut production and will also help in the development of adaptation measures in the light of predicted climate change.

Materials and methods

Meteorological and phenological data

The investigation was carried out in the experimental hazelnut orchard of the Biotechnical Faculty in north-

eastern Slovenia, in Maribor (46°32' latitude N, 15°39' longitude E, altitude 275 m) during the years 1969–1979 and 1994–2007. The climate is continental (Köppen's Cfw), with a mean annual temperature of 9.7°C and mean annual precipitation of 1,046 mm for the period 1961–1990; temperature extremes are 35.8°C and –22.3°C. The warmest month is July, with an average temperature of 19.6°C, and the coldest month is January, with an average temperature of –1.3°C. During the last 18 years (1991–2008), the mean annual temperature has increased to 10.8°C and the amount of precipitation has been reduced to 906 mm (ARSO 2010). Hourly temperatures and daily and monthly mean air temperatures were obtained from the meteorological station in Maribor (46°50' latitude N, 15°70' longitude E, altitude 264 m) of the Environmental Agency of the Republic of Slovenia (ARSO).

Five hazelnut cultivars: 'Daviana', 'Gunslebert', 'Istrska dolgoplodna leska' ('Istrska'), 'Merveille de Bollwiller' ('Bollwiller') and 'Tonda gentile delle Langhe' ('TGDL') were included in the trial. As a part of the germplasm collection, hazelnuts were planted in a single row, 4 m apart, in the early 1950s of the twentieth century. They were trained as bushes, and four to six scaffold branches were maintained in each bush throughout their whole lifespan. Vigorous growth was assured by keeping the surface in the row clean, regular mulching of grass on both sides, and modest fertilisation with nitrogen, potassium and phosphorous.

'TGDL' is one of the most valued cultivars in the kernel market, whereas the others are more suited to the in-shell market. 'Daviana' is an old English cultivar with a medium vigorous tree, a low yield and high susceptibility to big bud-mite. The in-shell nut has an oblong shape and medium size (Manzo and Tamponi 1982). 'Gunslebert' was first introduced in Germany. It is valued for its medium-to-large nuts with good texture and a strong nutty flavour. It is a vigorous growing and highly productive variety (Manzo and Tamponi 1982). 'Istrska' originates from Istria (Croatia). It leafs out and blooms moderately early. It is slightly sensitive to drought. Due to its high and stable yields, this variety is recommended for commercial growing in all Slovene areas suitable for hazelnuts (Solar and Štampar 1997). 'Bollwiller', also called 'Hall's Giant', is a hardy, vigorous and productive variety with large nuts. It leafs out and blooms late and the nuts ripen in mid-September (Manzo and Tamponi 1982). It is well-adapted to the continental climate (Germain and Sarraquigne 2004). 'TGDL' is a famous Italian variety. Due to its quality round nuts, it is used mainly in the confectionary industry (Germain and Sarraquigne 2004). It has very early blooming, leafing and ripening dates (Solar and Štampar 2009). Its nut-weight and productivity are medium, and chilling requirements low (Mehlenbacher 1991).

Phenological observations started in 1969 and have continued until now, with a gap from 1980–1993. Unfortu-

nately, during this period phenological observations were not made for the cultivars used in our study, due to temporarily changed research priorities at the Biotechnical Faculty.

Each recorded phenological date was the average date of at least three plants of the same cultivar. Leafing dates were recorded at phenological stage C (Germain and Sarraquigne 2004), when over 50 % of terminal buds had enlarged and the bud scales have split, exposing the green of the leaves inside (IPGRI 2008). Male flowering was recorded at stages Fm1 (start: 5 % of flowers are open and start to shed pollen), Fm2 (peak: 50 % of flowers are open), Fm3 (end: last flowers are open) and female flowering at stages Ff1 (start: 5 % of flowers are open and have extended stigmas), Ff2 (peak: 50 % of flowers are open), Ff3 (end: last flowers are open) (Germain and Sarraquigne 2004; IPGRI 2008).

Calculation of chilling accumulation

To estimate the average chilling accumulation under our field conditions and to find the most efficient months in relation to chilling accumulation, a chilling-hours model, proposed originally by Weinberger (1950) and still in frequent use today, was used (Luedeling et al. 2009a; Ruiz et al. 2007). This model calculates the number of hours (H) in which the temperature (T) is below 7°C, without considering freezing temperatures. The number of accumulated chilling-hours (CH) at a given time *t* after a fixed starting time is given as:

$$CH_t = \sum_{i=1}^t H; \text{ If } 0^\circ\text{C} < T < 7^\circ\text{C}, \text{ then add } 1, \text{ else } 0 \quad (1)$$

The starting date for chilling accumulation was 1 November, as suggested by other researchers (Luedeling et al. 2009a; Ruiz et al. 2007) since, before that date, in general, the temperatures are too high to contribute notably to chilling accumulation at the Maribor location. On the basis of our historical phenological data and other investigations (Ruiz et al. 2007), chilling accumulation was calculated until the end of February, with time-steps of 15 days.

Determination of heat requirement

The heat requirements for the flowering of hazelnut cultivars were obtained from the sum of daily mean temperatures (Tmean) after determining different base temperatures (Tbase) (–1, 0, 1, 2, 3, 4, 5°C) using the lowest standard deviation method (Jato et al. 2002; Galan et al. 2005).

$$GDD = \sum_{i=1}^t Tmean - Tbase; \text{ If } Tmean < Tbase, \text{ then add } 0 \quad (2)$$

A growing degree day (GDD in °C) is defined as a day on which the mean daily temperature (in °C) is 1° above the

base temperature required for the growth of a particular plant. GDDs were calculated each year from the day after the chilling-period (starting date) to the date on which a single phenophase began. The starting date was determined on the basis of correlation analysis between the mean air temperatures and the phenophase dates. Negative relationships between temperatures in any fixed period (time step of 15 days) and the phenophase dates indicate that warm weather at this time is necessary for earlier flowering or leafing (Emberlin et al. 2007).

Statistical analysis

Differences among cultivars and years were evaluated using analysis of variance and the Duncan multiple range test ($P=0.05$). Relationships between temperature data and phenological events were investigated using correlation and linear regression analysis. Statistical analyses were performed using software environment R, Version 2.9.0. (R foundation for statistical computing, Vienna, Austria) and SPSS version 16.0 for Windows (SPSS, Chicago IL).

Results

Thermal conditions during the 1969–2007 period

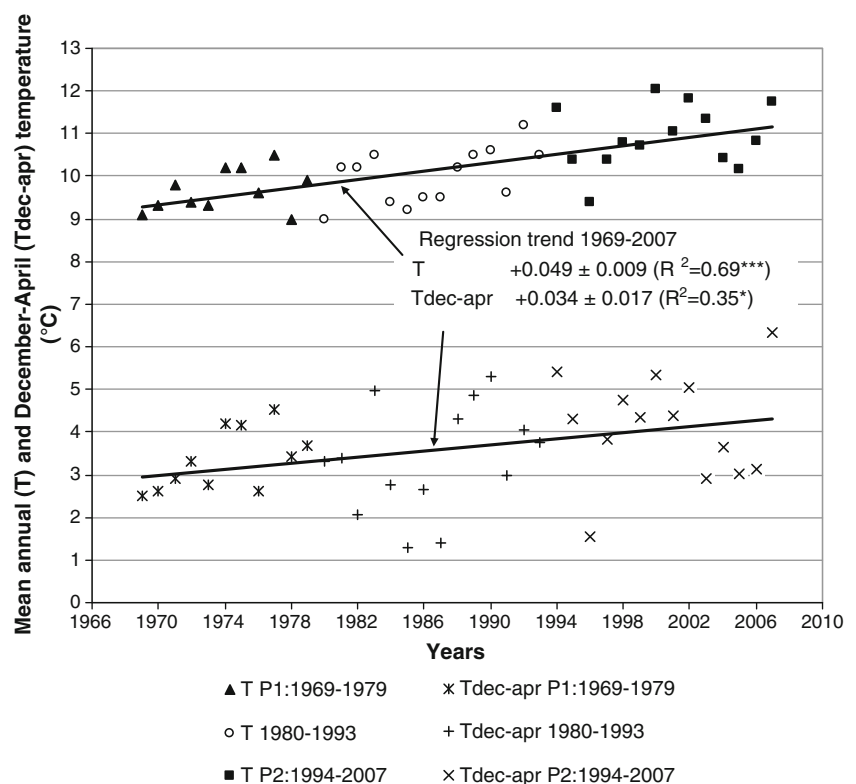
The mean annual temperature was 9.7°C during period P1 (1969–1979) and 10.9°C during period P2 (1994–2007) in

Maribor. Over recent years, a significant increase has been observed in the mean, minimum and maximum temperatures. The linear trend in the mean annual temperature for the period 1969–2008 amounted to +0.49°C for each 10 years ($P<0.001$; Fig. 1). The temperatures from December to April are important for the timing of hazelnut flowering and leafing in our climatic conditions (Solar and Štampar 1997). The mean temperature from the previous December to April of the current year was 3.3°C during P1, and 4.2°C during P2. Significant temperature changes occurred during these months, i.e. average temperatures from December to April were higher in P2 compared to P1 by 0.2°C, 0.4°C, 0.7°C, 0.4°C ($P<0.05$) and 1.9°C ($P<0.001$); the linear temperature trend for the time period from December to April was +0.3°C/10 years ($P<0.05$) for the period 1969–2007 (Fig. 1).

Timing of phenological phases

During P1 and P2, the leafing dates of the studied hazelnut cultivars occurred within the period from 20 March to 10 April (Fig. 2, Table 1). The average difference between the earliest leafing cultivar 'TGDL' and the latest 'Gunslebert' was 17 days in P1 and only 9 days in P2. In particular years, considerable deviations of the leafing dates were observed, depending on weather conditions during the winter and spring months. The earliest and latest dates of leafing differed by about 1 month for 'Daviana', 'Gunslebert',

Fig. 1 Mean annual temperature (T) and mean temperature from the previous December to April of the current year (Tdec-apr) at Maribor for three periods: P1:1969–1979; 1980–1993 (14 year gap between experiments); P2:1994–2007. Regression trends for T and Tdec-apr are given with slope and standard error of the slope (°C/year); linear regression coefficients are significant at * $P<0.05$ and *** $P<0.001$



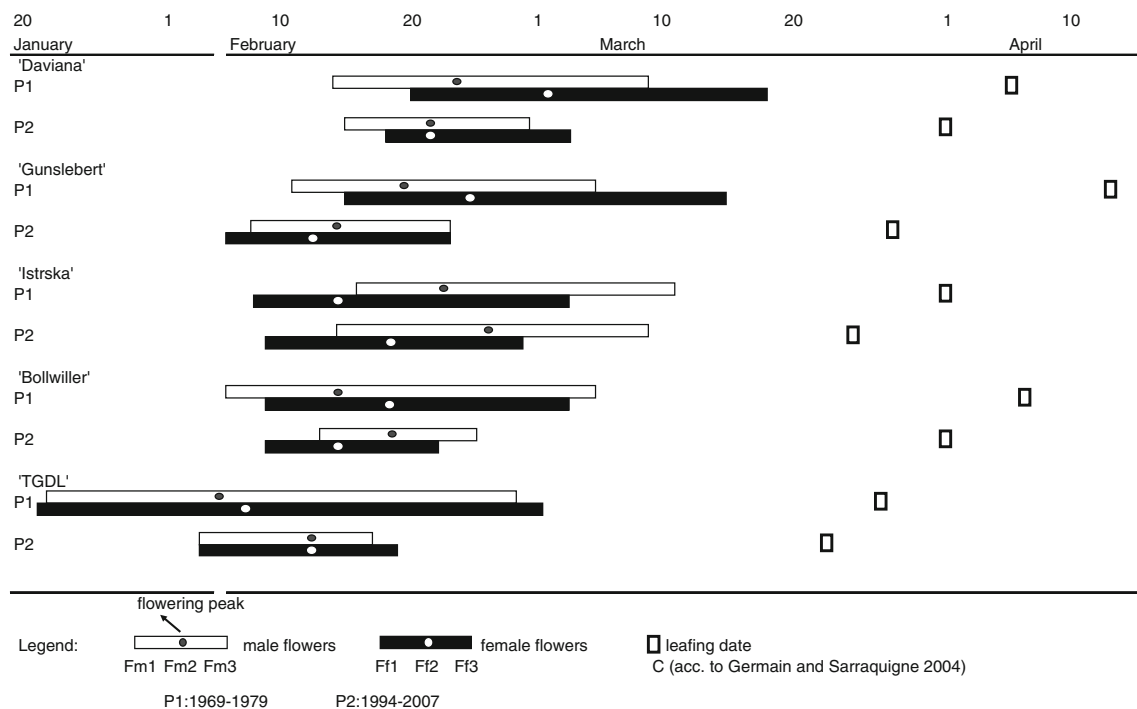


Fig. 2 Average dates of flowering of *Corylus avellana* L. cultivars (male flowers: *Fm1* start, *Fm2* peak, *Fm3* end; female flowers: *Ff1* start, *Ff2* peak, *Ff3* end) and leafing (C) of hazelnut cultivars

'Daviana', 'Gunslebert', 'Istrska', 'Bollwiller' and 'TGDL' for P1:1969–1979 and P2:1994–2007, Maribor, Slovenia

'Istrska' and 'Bollwiller', whereas the variability range was greater (43 days) in the earliest leafing cultivar, 'TGDL'.

Figure 2 shows the floral phenology and dichogamy in different hazelnut cultivars growing in Maribor during P1 and P2. The cultivars 'Daviana', 'Gunslebert' and 'Bollwiller' showed slightly protandrous behaviour in P1, whereas the cultivars 'Istrska' and 'TGDL' showed protogyny in P1.

When looking at the average flowering dates, expressed as the day of the year (DOY) (Table 1), it can be seen that the flowering patterns of 'Daviana' and 'Istrska' were consistent over the two periods, with 'Daviana' showing protoandry and 'Istrska' showing protogyny in both P1 and P2. Protogyny in P1 and homogamy in P2 were expressed by 'TGDL', while 'Gunslebert' and 'Bollwiller' had protoandry in P1, but weak protogyny in P2.

The difference between pollen shedding and the beginning of female flowering was 6 days for 'Istrska' and four for 'Daviana', whereas in the other three cultivars, the mean overlapping of male and female inflorescences was only from 1–2 days. In terms of leafing dates, considerable deviation at beginning of flowering was also recorded for those years with significantly warmer or colder winter months. Flowering dates showed a larger variability compared to leafing dates, with the highest value of 77 days between the earliest and the latest male flowering for 'TGDL'.

The degree of dichogamy varied from year to year for all five cultivars. The earliest pollen shedding appeared in 'TGDL' at the end of January (31 January), whereas the other cultivars started male flowering in the second 10-day period of February, and the latest were 'Daviana' and 'Istrska' on 15 February (Fig. 2). The first female flowers were also noted in 'TGDL' (2 February), the latest was 'Daviana' (19 February). Female flowers were receptive for between 15 days in 'Bollwiller' to 21 days in 'TGDL' and 'Istrska'. The duration of pollen-shedding was similar to that of female flowering; it ranged from 16 days for 'Bollwiller' to 21 days for 'TGDL'. The earliest cultivar, 'TGDL', had the longest flowering duration for both types of inflorescence.

Table 1 shows a comparison of the mean flowering dates, leafing dates and flowering durations between the time periods P1 and P2. About 75% of phenophases showed a tendency towards an earlier appearance and shorter flowering duration, respectively, but only a few of them were significantly earlier, with $*P < 0.05$ or $**P < 0.01$.

Correlations of phenological phases with temperature

Significant negative correlations (with $P < 0.01$) between the start dates (leafing, flowering) of the analysed cultivars and air temperature indicate that higher temperatures at this time will cause earlier phenological occurrence. The majority of

Table 1 Comparison of hazelnut mean dates of flowering of *Corylus avellana* L. cultivars (male flowers: *Fm1* start, *Fm2* peak, *Fm3* end; female flowers: *Ff1* start, *Ff2* peak, *Ff3* end), leafing (*C*) and flowering duration between two periods (P1:1969–1979, P2:1994–2007), with a summary of MANOVA (Roy test). *DOY* Day of the year, *SE* standard error, significant earlier dates are in **bold**

Cultivar	Period	Average date of phenophase as DOY (SE)								Flowering duration F3-F1 in days (SE) Female
		C	Fm1	Fm2	Fm3	Ff1	Ff2	Ff3	Male	
'Daviana'	P1	96 (1.2)	45 (1.4)	54 (1.6)	68 (2.0)	51 (1.4)	61 (0.9)	77 (2.3)	23 (0.7)	25 (0.9)
	P2	91 (1.2)	46 (1.0)	52 (1.5)	59 (1.9)	49 (1.2)	52 (1.3)	63 (1.4)	13 (0.5)	14 (0.4)
'Gunslebert'	P1	103 (1.1)	42 (1.4)	50 (1.4)	64 (2.1)	46 (1.5)	55 (1.6)	74 (1.8)	23 (0.7)	28 (0.9)
	P2	87** (1.0)	39 (1.2)	45 (1.5)	53 (1.7)	37 (0.9)	43 (1.2)	53 (1.6)	14 (0.4)	16 (0.5)
'Istrska'	P1	91 (1.7)	41 (1.3)	53 (1.8)	70 (2.2)	39 (1.1)	45 (1.5)	72 (2.0)	29 (1.0)	32 (1.2)
	P2	84* (0.9)	49 (1.4)	52 (1.3)	59 (1.5)	46 (1.4)	53 (1.5)	60 (1.7)	10** (0.3)	14** (0.4)
'Bollwiller'	P1	97 (1.4)	37 (1.4)	45 (1.6)	64 (1.9)	40 (1.3)	49 (1.5)	62 (2.2)	28 (0.9)	22 (0.7)
	P2	91* (0.9)	44 (1.3)	49 (1.4)	55 (1.8)	40 (1.3)	45 (1.5)	52 (1.6)	12 (0.5)	12 (0.5)
'TGDL'	P1	86 (2.2)	23 (1.1)	36 (1.3)	58 (2.0)	22 (0.8)	38 (1.3)	60 (1.7)	35 (1.1)	38 (1.2)
	P2	82 (1.6)	35 (1.1)	43 (1.4)	47 (1.0)	33 (1.2)	43 (1.2)	49 (7.8)	12** (0.4)	17** (0.4)
MANOVA (Roy test)	Df	Test stat.	Approx F	Num Df		Den Df		Pr(>F)		
Cultivar	4	40.200	491.33	9		110		< 2.2e-16***		
Period	1	1.800	21.40	9		107		0.003402**		
Cultivar:period	4	0.428	5.23	9		110		6.449e-06***		

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

phenophases (73%) were correlated most strongly with maximum air temperatures (Table 2), all the rest with average temperatures, and none with minimum temperatures, suggesting that the chilling requirement at the period best correlated with temperature was already fulfilled. Leafing dates of all cultivars were linked most strongly with maximum temperature from February to March, with coefficients of determination (R^2) ranging from 0.64 to 0.93. Most of the flowering phenophases were also highly correlated ($R^2 = 0.64$ to 0.98), with maximum air temperatures during the period of 2–3 months before their occurrence.

The correlations with temperature for both male and female flowers were stronger for the flowering-peak than for the start or the end of flowering. An increase in air temperature of 1°C caused acceleration in leafing from 2.5 days for 'Daviana' and 'Istrska', to 3.9 days for 'TGDL'. Flowering phenophases showed higher sensitivity to tem-

perature than leafing, since a 1°C increase promoted male flowering by 7.0–8.8 days compared to 6.3–8.9 days for female flowering.

The sensitivity to temperature change of leafing and flowering in terms of earliness per warming of 1° (days/1°C) did not change significantly during the warmer P2 period. For example, for 'Daviana', an increase in air temperature of 1°C caused an advance of 2.6 days in leafing in P1 and 2.5 days in P2 or an advance of 8.2 days in flowering peak in P1 and 8.7 days in P2.

Chilling accumulation in field conditions during the period 1993–2009

Chilling accumulation for the period 1993–2009 between 1 November and 28 February in field conditions for Maribor are shown in Table 3 and Fig. 3. During the winter period 1993/1994–2008/2009, all four months contributed approximately

Table 2 Coefficients of determination (R^2) of phenophases with the best correlated temperature variable (either T_{avg} , T_{max} or T_{min}) and rate of phenological shift (days per °C) of five hazelnut cultivars for two periods (P1:1969–1979, P2:1994–2007). The phenological shift is given for the best correlated temperature variable. *C* Leafing; *Fm2*male flowers peak; *Ff2* female flowers peak; *Ff1* female flowers start, *Fm1* male flowers start; T_{max} average temperature calculated over a 1-, 2- or 3-month period, with daily maximum temperatures; T_{avg} average temperature calculated over a 1-, 2- or 3-month period with daily average temperatures; *SE* standard error

Cultivar		Phenophase	Temperature	Period	R^2	Phenological shift (days/°C) with SE
'Daviana'	P1	C	T_{max}	Feb-Mar	0.74***	-2.6 ± 0.16
		Fm2	T_{avg}	Jan-Feb	0.91***	-8.2 ± 0.65
		Ff2	T_{max}	Jan-Mar	0.86***	-7.5 ± 0.54
	P2	C	T_{avg}	Mar	0.82***	-2.5 ± 0.14
		Fm2	T_{avg}	Jan-Mar	0.89***	-8.7 ± 0.77
		Ff1	T_{max}	Jan-Mar	0.89***	-6.9 ± 0.48
'Gunslebert'	P1	C	T_{max}	Feb-Mar	0.64**	-2.9 ± 0.37
		Fm2	T_{max}	Dec-Feb	0.92***	-8.0 ± 0.72
		Ff2	T_{max}	Dec-Feb	0.98***	-6.3 ± 0.53
	P2	C	T_{max}	Jan-Mar	0.83***	-3.6 ± 0.19
		Fm2	T_{max}	Dec-Jan	0.96***	-7.2 ± 0.62
		Ff2	T_{max}	Dec-Jan	0.98***	-8.2 ± 0.74
'Istrska'	P1	C	T_{max}	Feb-Mar	0.93***	-3.7 ± 0.24
		Fm2	T_{avg}	Dec-Feb	0.96***	-7.9 ± 0.63
		Ff2	T_{avg}	Jan-Feb	0.65**	-8.2 ± 1.23
	P2	C	T_{max}	Feb-Mar	0.66**	-2.5 ± 0.32
		Fm2	T_{avg}	Jan-Feb	0.82***	-7.8 ± 0.71
		Ff2	T_{avg}	Jan-Feb	0.88***	-8.9 ± 0.61
'Bollwiller'	P1	C	T_{max}	Feb-Mar	0.82***	-3.4 ± 0.32
		Fm2	T_{max}	Jan-Feb	0.95***	-7.5 ± 0.59
		Ff1	T_{max}	Jan	0.65**	-6.5 ± 0.79
	P2	C	T_{max}	Mar	0.90***	-3.0 ± 0.18
		Fm1	T_{max}	Dec-Feb	0.96***	-7.6 ± 0.86
		Ff2	T_{max}	Jan-Feb	0.90***	-6.7 ± 0.80
'TGDL'	P1	C	T_{max}	Jan-Mar	0.92***	-3.9 ± 0.35
		Fm2	T_{max}	Jan-Feb	0.64**	-7.0 ± 0.98
		Ff2	T_{max}	Dec-Jan	0.85***	-7.1 ± 0.92
	P2	C	T_{max}	Feb-Mar	0.79***	-3.5 ± 0.44
		Fm2	T_{avg}	Dec-Feb	0.76***	-8.8 ± 1.23
		Ff2	T_{max}	Dec-Feb	0.76***	-6.5 ± 0.77

** $P < 0.01$, *** $P < 0.001$

similar amounts of accumulated chilling units to the sum total. Chilling accumulation differed from year to year, the coefficient of variation (CV) until 28 February was 12.4%. From the years 1993 to 2009, CH ranged from 980 in the winter of 2002/2003 to 1,558 in the winter of 2006/2007. No significant changes were found in chilling accumulation during these periods.

Heat requirements for the beginning of flowering

The method of Jato et al. (2002) was applied with the aim of determining the heat requirement for flowering. We

tested different threshold temperatures (T_{base}) (−1, 0, 1, 2, 3, 4, 5°C) and different starting dates from 1 December onwards, using time steps of 15 days. The results of correlation analysis (Table 2) showed that there is a negative correlation between temperatures from December onwards and hazelnut flowering dates, indicating that warm weather at this time is necessary for earlier flowering. GDD calculated by subtracting the base temperature of 2°C from 1 January onwards resulted in the lowest standard deviation. GDDs, with standard errors and coefficients of variation, are shown in Table 4. For female flowers, the mean GDD for five cultivars was 32°C during P1 and 43°C

Table 3 Chilling accumulation by a fixed date in Maribor during the 1993–2009 period, according to the '0–7°C Model', with a summary of ANOVA, *SE* standard error, *CV* coefficient of variation

Year/date	15 November	30 November	15 December	31 December	15 January	31 January	15 February	28 February
Chill units ('0–7°C Model', 1 hour between 0 and 7°C=1 chill unit)								
93/94	148	205	396	595	814	1,026	1,233	1,331
94/95	132	331	548	684	768	924	1,111	1,371
95/96	292	454	587	754	907	916	978	1,171
96/97	71	270	451	536	597	743	914	1,078
97/98	118	398	666	924	1,132	1,338	1,443	1,549
98/99	180	408	491	614	812	931	1,062	1,266
99/00	183	264	460	568	597	696	917	1,152
00/01	90	263	509	741	893	1,091	1,250	1,436
01/02	229	446	545	635	672	828	1,055	1,296
02/03	157	224	400	554	634	818	889	980
03/04	243	386	645	829	973	1,092	1,266	1,461
04/05	199	408	615	811	1,019	1,119	1,261	1,398
05/06	166	352	591	761	955	999	1,098	1,294
06/07	196	354	543	745	951	1,147	1,352	1,558
07/08	245	448	719	719	838	1,084	1,310	1,448
08/09	54	287	573	780	794	1,083	1,239	1,414
mean	169	344	546	703	835	990	1,149	1,325
SE	16.5	20.6	23.1	27.7	39.0	41.8	42.4	41.1
CV	39.1	24.0	16.9	15.8	18.7	16.9	14.8	12.4
ANOVA								
Source of variation	df		F		P-value		F crit	
Years	15		12.02		< 0.001***		1.76	
Dates	7		341.80		< 0.001***		2.09	

during P2. The difference in GDD between P1 and P2 was significant with 'Bollwiller' and 'TGDL' ($P<0.01$). GDD ranged among the cultivars from 19.8°C for 'TGDL' to 53.9°C for 'Daviana', the coefficients of variation being

from 12.9% to 23.7%. For male flowers, the mean GDD for five cultivars was 27.3°C during P1 and 44.5°C during P2, and the difference in GDD between P1 and P2 was significant with 'TGDL' ($P<0.001$). The lowest GDD for

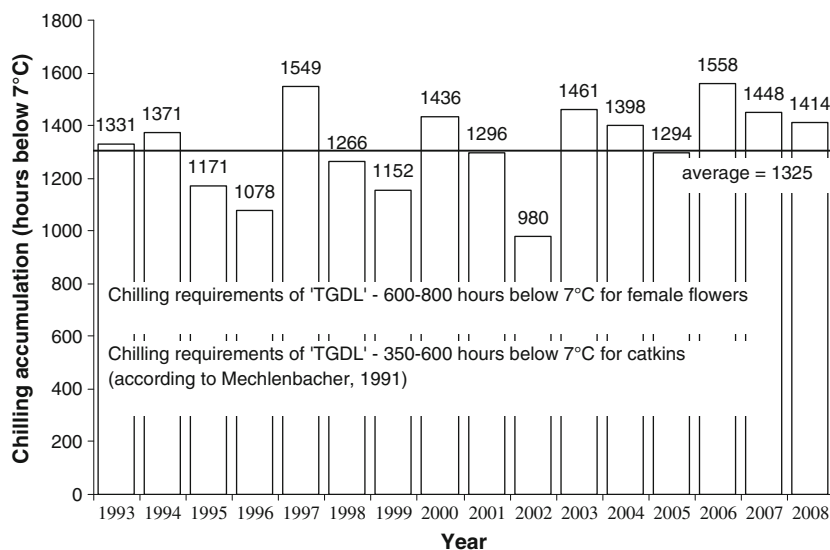
Fig. 3 Chilling accumulation ('0–7°C Model') in Maribor between 1 November and 28 February during the period from 1993/1994 to 2008/2009

Table 4 Growing degree-day (GDD) requirement for the beginning of flowering of hazelnut in Maribor for two periods (P1:1969–1979, P2:1994–2007), with a summary of MANOVA (Roy test), significancevalues are indicated fore greater GDDs. *SE* Standard error, *CV* coefficient of variation, *Tbase*=2°C

Cultivar	Period	Female flowers			Male flowers		
		GDD	SE	CV(%)	GDD	SE	CV(%)
‘Daviana’	P1	50.8	3.6	23.7	35.2	2.3	21.3
	P2	57.0	3.0	19.6	45.9	2.2	18.2
‘Gunslebert’	P1	36.4	1.6	14.6	29.9	1.6	18.4
	P2	45.0	1.6	12.9	46.6	2.4	19.2
‘Istrska’	P1	25.3	1.3	16.5	30.1	1.4	15.3
	P2	34.4	1.6	17.1	40.4	1.8	16.6
‘Bollwiller’	P1	34.8	2.4	23.0	30.5	2.1	22.9
	P2	53.2**	3.0	21.3	62.0	3.4	20.8
‘TGDL’	P1	12.7	0.5	13.4	10.9	0.5	16.5
	P2	26.8**	1.1	15.2	27.7***	1.1	15.5
MANOVA (Roy test)	Df	Test stat	Approx F	Num Df	Den Df	Pr(>F)	
Cultivar	4	71.026	377.02	4	4	0.0005729***	
Period	1	6.611	9.91	2	3	0.000479***	

** $P<0.01$, *** $P<0.001$

male flowers was with ‘TGDL’, 19.3°C, and the highest with ‘Bollwiller’, 46.2°C. The coefficients of variation were between 15.3% and 22.9%.

Discussion

Thermal conditions during the 1969–2007 period

According to the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change, global surface temperature increased by $0.74\pm0.18^\circ\text{C}$ over the period 1906–2005 (IPCC 2007) but the rate of warming over the last half of that period was almost double that for the period as a whole. Temperature changes varied over the globe, land regions have warmed faster than the oceans and Europe has warmed slightly more than the global average (IPCC 2007). Geographically, particularly significant warming has been observed in the past 50 years over the Iberian Peninsula, in central and north-eastern Europe, and in mountainous regions. An observed warming of $0.49^\circ\text{C}/\text{decade}$ confirmed earlier research results for Slovenia (Črepinšek et al. 2009; Kajfež-Bogataj 2001). In addition, the aforementioned rate of warming is in accordance with a linear temperature trend of 0.05°C per year derived from historical weather data from 1975 to 2007 for Austria (Strauss et al. 2010) and other European countries (Menzel et al. 2006). During the period P2, all years except one (1996) were warmer than the long-term average. The temperatures from December to April are important for

the timing of hazelnut flowering and leafing in Slovenian climatic conditions (Solar and Štampar 1997). Significant temperature changes occurred during these months, i.e. average temperatures from December to April were higher in P2 compared to P1, which is in accordance with previous reports on increasing air temperature over Slovenia (Črepinšek et al. 2009; Kajfež-Bogataj 2001) and national warming patterns across 19 European countries (Menzel et al. 2006). Chmielewski (2003) reported an increase of mean air temperature between February and April of 1.6°C between 1961 and 2000, leading to earlier tree flowering by 8 days in Germany.

Timing of phenological phases

In our study, the earliest leafing cultivar ‘TGDL’ and the latest ‘Gunslebert’ differed by 17 days in P1 and by only 9 days in P2. This is in agreement with Chmielewski (2003) and Črepinšek et al. (2009), who reported that the timing of spring phenological phases in temperate zones is driven mainly by temperature. The beginning of flowering and the flowering duration are influenced by the earliness (lateness) of the cultivar and, crucially, by the weather conditions of the current year and previous winter months (Menzel et al. 2006).

It can be seen from average data, calculated for a long-term period, that flowering patterns can be consistent over the two observed periods, e.g. in ‘Daviana’ and ‘Istrska’. Phenological patterns may also transit from protogyny to homogamy (‘TGDL’) or even from protoandry to weak

protogyny ('Gunslebert' and 'Bollwiller'). On the contrary, all the cultivars preserved their blooming pattern when individual dates were recorded in individual years. We conclude that different climatic conditions from year to year led to a change in dichogamy type for the studied cultivars. This is consistent with the results of Turcu et al. (2001) who reported for Oltenia, Romania, a change in the type of dichogamy for 'Hall's Giant (Bollwiller)', 'Romavel' and 'Du Chilly' hazelnut cultivars. Bastias and Grau (2005) concluded that, for some commercial hazelnut cultivars in Chile, the dichogamy phenomenon was not totally dependent on the genotype but also on local climatic conditions. Piskornik et al. (2001) showed in their study, in the climatic conditions of southern Poland, that some hazelnut genotypes were protandrous after long and severe winters, homogamous after short but cold winters, and protogynous when winters were short and relatively mild. In our case, mild winters could also be the reason for changed dichogamy during P2 for 'Gunslebert' and 'Bollwiller'.

The range of year-to-year variability was greater in flowering dates than for leafing. As explained by Schleip et al. (2009), early phenophases are more adaptable to lower, even below zero temperatures; they are less frost-sensitive and a small temperature variation triggers a quick response in phenological events. Later phenophases, such as leafing in the case of hazelnut, react more cautiously towards higher spring temperatures to avoid the last spring frosts. Furthermore, dependency of the degree of homogamy on both genotype and environmental conditions was proved by Bastias and Grau (2005) and Turcu et al. (2001) when prospecting different hazelnut cultivars in Chile and Romania. In the early spring, periods with low temperatures often occurred after the beginning of flowering, and phenological development was slowed or even stopped, with the restart depending on temperature. The ability of hazelnut plants to extend the flowering time to the onset of more favourable weather conditions improves the possibilities of growing hazelnut commercially even in areas with low winter temperatures. Turcu et al. (2001) found that the stigmas of early blooming hazelnut cultivars were receptive for a longer time, sometimes 60–80 days, when there were large variations in temperature. In our research, 'TGDL', as the earliest flowering cultivar, also showed the largest variation range regarding the length of the flowering period, with extremes of less than 1 week, such as in 2007 with $T_{\text{jan-feb}}$ above 5°C, up to 70 days as in 1974 with $T_{\text{jan-feb}}$ below 3°C. In other cultivars, the flowering duration did not exceed 60 days; it depended on average temperatures and variations in temperature. Comparison among the months from December to April showed that February, when the average flowering peaks of male and female flowers appeared in all of the investigated cultivars, was the

most variable month regarding mean air temperatures. This could explain why earlier hazelnut cultivars showed greater differences in the times of phenological events and their duration than later ones, as also reported by Kluza-Wieloch and Szewczak (2006) and Turcu et al. (2001).

With the most recent warming trends over the Northern Hemisphere, the advancement of spring phenological events has been confirmed in many parts of Europe (Kramer 1994; Scheifinger et al. 2003; Schleip et al. 2008), including Slovenia (Črepinšek et al. 2009). Most of the observed phenophases displayed a tendency towards earlier appearance in P2, although the majority of these trends were not statistically significant. Among the reasons for non-significant results might be the shortness of the time series and high year-to-year variability of both phenological and temperature time series, including also extremely high/low values. Such short time series might be influenced significantly by single-year data or short-term phenological changes. The leafing time series shows much less fluctuation than flowering phenophases. Among the reasons for that could be a larger January and February temperature range compared to the March temperature range, since flowering is correlated better to February and leafing to March temperatures. There was a tendency for flowering to be earlier in P2 but significant changes can be obtained only from a longer series. In some other studies for Slovenia, flowering of wild growing hazelnut *Coryllus avellana* L. was found to be significantly earlier in recent decades (Črepinšek 2005; Črepinšek et al. 2006) but the phenological data set was much longer (1955–2007) than for the cultivated plants in our trial.

The findings obtained by our analysis agree with the results of Menzel et al. (2006), who found a clear signal across Europe of changing spring and summer phenology, with 78% of leaf unfolding and flowering records advancing. Leafing and the end of flowering for male and female flowers in our study showed a shift to earlier dates in all cases. The same was noted for the duration of flowering for male and female flowers, in which the difference between P1 and P2 was clearest because of enhanced developmental processes during higher temperatures. The tendency towards earlier phenological dates could be explained by changes in the courses of air temperatures over subsequent years (Fig. 1) but the trends of the phenological time series do not necessary follow at the same rate as the trends of the temperature time series (Scheifinger et al. 2003). In addition to air temperatures, soil temperatures have also increased significantly over recent decades in Slovenia and the water cycle is altering (Bergant et al. 2002), which could also have an influence on phenological changes. Unfortunately, these meteorological data were unavailable for the Maribor location when we were attempting to improve our investigation.

Correlations of phenological phases with temperature

This study found that the effect of increasing air temperature was expressed as earlier starting dates of single phenophases, confirming the findings of Chmielewski (2003), who recognised the thermal conditions as the main determinant of spring plant phenological development in mid-latitudes in deciduous trees and shrubs. Our findings are also comparable with the results of correlation analysis between *Corylus* spp. phenological dates and mean temperatures in the UK (Emberlin et al. 2007), where the highest correlation coefficient (0.74) was calculated between mean temperatures in December and the start of pollen shedding. Menzel et al. (2006) reported that most spring phenological phases correlated significantly with mean monthly temperatures of the month of onset and the two preceding months. A phenomenon observed in our investigation was that both male and female flowers responded more strongly to increased air temperature than leafing, as was explained in a study by Scheffinger et al. (2003). He stated that early phenophases are more adapted to below zero temperatures and therefore follow temperature variability more closely. The important question in phenological studies is whether plant phenological dates shift at lower or higher rates toward earlier/ later occurrence than other plant development related events such as spring late frosts, plant diseases, outbreaks of pests or invasive species. Scheffinger et al. (2003) found that spring frost events have been advancing faster than phenological phases during the last 50 years in Central Europe, so the risk of late frost damage should have been lower recently compared to previous years. In hazelnut production, plant protection will depend also on the extent to which hazelnut phenology shifts in parallel with pest and disease phenology.

Corylus pollen grains cause severe allergies and often mark the start of seasonal allergies; hazelnut flowering may begin as early as January or February in Slovenia (Črepinšek et al. 2006). Previous studies in Europe have shown that pollen seasons for many allergenic taxa have tended to become earlier by about 5–10 days/decade over the last 30 years, and that this pattern has been linked to warmer winters and springs in recent years (Menzel et al. 2006). Earlier flowering of hazelnut means that the allergy season begins earlier and, because *Corylus* pollen has allergens that cross-react with those of other trees such as *Betula* or *Alnus*, it has a priming effect, and an allergic reaction in susceptible individuals may occur at a lower pollen concentrations later in the season (Emberlin et al. 2007). On the other hand, the shorter hazelnut flowering duration because of high temperatures, as noticed in P2, means less time of exposure to pollen, which may result in decreased predisposal to allergenic pollen.

Because of the different temperature responses of hazelnut cultivars (Piskornik et al. 2001), and also of male and female flowers of the same cultivar, such as 2.3 days for 1°C with 'TGDL' as shown by our research, greater temperature changes in the future could lead to decreased synchrony between the maturation of male and female flowers and increasing incompatibility among cultivars in terms of pollination. The phenomenon of cross-compatibility in hazelnuts has great economic importance (Turcu et al. 2001) and could have an even greater future impact.

Chilling accumulation in field conditions during the period 1993–2009

The length of the period within the 0–7°C range has been about 100 days over recent decades in Maribor (ARSO 2010), which means that autumn and winter chilling is not a limiting parameter in hazelnut production in regard to this location and current climatic conditions. Since a body of scientific evidence suggests that global climate warming (IPCC 2007) and minimum daily temperatures over the last 50 years have increased at a greater rate than maximum daily temperatures (Kajfež-Bogataj 2001), the amount of winter chilling available at some locations might be strongly affected in the near future (Luedeling et al. 2009b). Chilling accumulation up until 15 January was sufficient for breaking flower bud dormancy in all the discussed cultivars in relation to chilling requirements (Mehlenbacher 1991; Germain and Sarraquigne 2004). In accordance with the results shown in Table 3, the chilling requirements for leafing were also sufficient by the end of February.

Chilling accumulation for the period 1993–2009 demonstrates that if growers had planted a hazelnut cultivar with a chilling requirement of 800 h, e.g. 'TGDL', prior to 1993 in Maribor, they would not have experienced insufficient chilling during this period. In most parts of Slovenia, periods with low temperatures can normally be expected to be long enough to break dormancy, unless the climate changes. Part of Slovenia has a warm, Mediterranean climate, with a mean temperature of winter months above 5°C (ARSO 2010), where additional warming could impact on fruit and nut production in the future, in terms of chilling accumulation, as already predicted for some other agricultural areas with a warm climate (Luedeling et al. 2009b). Baldocchi and Wong (2008) found that the annual accumulation of winter chilling is diminishing across the fruit and nut growing regions of California, with observed trends in winter chilling ranging between 50 and 260 CH per decade. Chilling models projected declining winter chilling in California from 1950–2099 (Luedeling et al. 2009a) and, consequently, the need to develop agricultural

adaptation measures in terms of low-chilling varieties and dormancy-breaking chemicals. In recent years, we have experienced some very mild winters in Slovenia, which altered usual phenological patterns. This could be even more frequent in the future, as predicted by climate scenarios for Slovenia for the twenty-first century (Bergant et al. 2002; Kajfež-Bogataj and Bergant 2005). However, it is possible that the predicted warmer winters in the future may also alter the chilling accumulation pattern, so this will be a field that will need constant study in the future.

Heat requirements for the beginning of flowering

Post-rest weather conditions strongly influence the flowering times of male and female inflorescences of hazelnut. Endodormancy is usually followed by an ecodormancy period, the length of which varies considerably from year to year. According to Mehlenbacher (1991), catkins and female inflorescences have different post-rest heat requirements. However, in our analysis, there was no significant difference between the heat requirements of male and female flowers. Heat requirements for particular plants vary considerably with the method used, which makes it difficult to compare results from various studies. Vučetić et al. (2008) found a base temperature of 5°C for calculating heat requirements for the start of the *Corylus* spp. pollen season in north-western Croatia. For climatic conditions in the UK, Emberlin et al. (2007) determined 4°C, while for Romania and for western Norway, a base temperature of 0°C and as low as −2°C was reported by Turcu et al. (2001) and Wielgolaski (1999), respectively. The average GDD above 0°C for the flowering of several hazelnut cultivars in Romania was 127°C, ranging from 102°C for ‘TGDL’ to 150°C for ‘Romavel’ (Turcu et al. 2001). However, over north-western Croatia, the required GDD above 5°C was from 15°C to 20°C (Vučetić et al. 2008). The parameters for GDD calculations obtained by different methods have statistical significances that can differ from real physiological base temperatures or starting dates. These data may indicate the climatic demands of hazelnut cultivars in different climatic regions that are important for agricultural practice.

Current modelling studies widely assume that the thermal time accumulation of crops remains constant under various climatic conditions (Chmielewski 2003; Galan et al. 2005). However, some studies have indicated that the thermal time accumulation for the entire growing season is not constant, and positive time trends in GDD have been found, reducing the predictability of climate change effects on agriculture. A study by Zhang et al. (2008) revealed an increase in thermal time accumulation at the Thongua station (China) during the period 1985–2005; this increase was statistically significant at a rate

around 9.4 degree-days (°Cd) per year over the entire time period. Comparison between periods P1 and P2 in our research indicated that increased amounts of GDD are required for the beginning of flowering for male and female flowers in hazelnut. In all cases, the GDD was greater in P2 than in P1 (Table 4). Although analysis of the data gives results that are not statistically significant for the most part in relation to phenophases, a general trend toward greater GDD can be seen, and the patterns of change for all cultivars were quite similar. Among the reasons for non-stationary thermal time accumulation could be the method of GDD calculation. We used a uniform base temperature (2°C) and starting date (1 January) to calculate thermal time for P1 and P2, as this resulted in the lowest SD of GDD. In perennial plants, the physiologically best starting dates are generally difficult to determine. Wielgolaski (1999) concluded in his study that the starting dates for growth and development can vary greatly between cultivars or ecotypes within a plant species and due to genetic variations even between individuals; starting dates can also be influenced by the age of trees, latitude or photoperiod. Basic temperature also varies with several factors in terms of plant and environment, such as the age of woody plants or development stage, soil characteristics, water conditions or day length (Wielgolaski 1999). Another possible reason for the change in GDD during P2 could be acclimatisation—the process of an individual organism adjusting to change in its environment, allowing it to survive changes in temperature, water and food availability and other stresses. Organisms adjust their morphological, behavioural, physical and/or biochemical traits in response to the environmental changes with which they are faced. Evolutionary temperature acclimatisation ensures that photosynthesis and respiration are adjusted to the average temperature climate in the habitat of the plant species (Larcher 1995). Gunderson et al. (2010) investigated photosynthetic sensitivity to temperature and the potential for acclimation in relation to the climatic provenance of five species of deciduous trees. Adjustment of thermal optima was confirmed in all species, suggesting that photosynthetic responses should not be modelled using static temperature functions but should incorporate an adjustment to account for acclimatisation. Longer time series data extended to other agricultural and wild plants would be helpful in tracking possible acclimatisation and future changes in thermal time accumulation in our case. Understanding the relationships between plant development and environmental factors, especially the temperatures in our climate, is fundamental for appropriate cultivar choices, as well as for crop management, in which the timing of agricultural practices are dependent on phenological phases.

Conclusions

Our study is the first attempt to quantify the correlation between hazelnut phenology and air temperatures in Slovenia. It also provides unique information about phenological adaptation of hazelnut to increasing air temperature over an extended period. The above results demonstrate that increased air temperature during recent years is already significantly influencing hazelnut spring phenological events, with implications for hazelnut production and public health. Detailed knowledge of the relationship between flowering time and temperatures is important for predicting the start of the pollen season in view of the increased prevalence of allergies to airborne pollen. The results of our correlation and regression analysis might be useful for predictive models of the start, duration and end of the hazelnut pollen season in Slovenia. This is especially useful for patients that have to take medicine several days before the hazelnut begin to bloom to achieve the maximum effect of medical treatment. To identify the impact of earlier leafing and flowering on final yields, other phenological phases, such as ripening, maturity and senescence, should be analysed. Another important question is whether there have also been significant changes in the phenology of hazelnut pests and disease occurrence, which might lead to increased plant vulnerability during its development. However, observed phenological shifts already provide important help in decision-making for growers in terms of fertilising, irrigating or crop protection planning, while taking into account agrometeorological forecasts. The effect of environmental temperature in relation to flowering time and the degree of dichogamy varied depending on the cultivar, which should be taken into consideration when selecting a set of pollinisers for productive cultivars. It may be essential to choose completely new combinations of ‘main cultivar + pollinisers’ compared to those planted lately in commercial orchards. Since climate changes are global, it is expected that such readjustments will be necessary in all areas in which hazelnut is grown commercially. Moreover, a weak trend of delaying autumn phenophases, such as leaf fall, was proved (Menzel et al. 2006) and an extension of the growing season can be expected due to climate warming. Such new circumstances may provide an opportunity to plant hazelnut in new areas and replace some crops as an alternative but economically interesting fruit species.

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References

- ARSO (2010) Climate data archive for the period 1969–2009. The Environmental Agency of the Republic of Slovenia. <http://meteo.arso.gov.si/met/sl/app/webmet/>. Accessed 12 January 2010
- Baldocchi D, Wong S (2008) Accumulated winter chill is decreasing in the fruit growing regions of California. *Clim Chang* 87:153–166. doi:10.1007/s10584-007-9367-8
- Baldwin B (2004) The potential for hazelnut production in Australia. *Australas Farm Bus Manag J* 1:84–92
- Bastias R, Grau P (2005) Floral phenology of commercial cultivars and Chilean pollinizers of hazelnut (*Corylus avellana* L.) in Chile. *Acta Hort* 686:151–155
- Bergant K, Kajfež-Bogataj L, Črepinšek Z (2002) Statistical down-scaling of general-circulation-model- simulated average monthly air temperature to the beginning of flowering of the dandelion (*Taraxacum officinale*) in Slovenia. *Int J Biometeorol* 46:22–32. doi:10.1007/s00484-001-0114-y
- Chmielewski FM (2003) Phenology and agriculture. In: Schwartz MD (ed) *Phenology: an integrative environmental science. Series: tasks for vegetation science*. Kluwer, Dordrecht, pp 505–522
- Chuine I, Cour P, Rousseau DD (1998) Fitting models predicting dates of flowering of temperate-zone trees using simulated annealing. *Plant Cell Environ* 21:455–466. doi:10.1046/j.1365-3040.1998.00299.x
- Črepinšek Z (2005) Spring phenological events in Slovenia related to air temperatures. *Arbor Phoenol* 48:9–18
- Črepinšek Z, Kajfež-Bogataj L, Bergant K (2006) Modelling of weather variability effect on fitophenology. *Ecol Model* 194:256–265. doi:10.1016/j.ecolmodel.2005.10.020
- Črepinšek Z, Solar M, Štampar F, Solar A (2009) Shifts in walnut (*Juglans regia* L.) phenology due to increasing temperatures in Slovenia. *J Hort Sci Biotechnol* 84:59–64
- Emberlin J, Smith M, Close R, Adams-Groom B (2007) Changes in the pollen season of the early flowering trees *Alnus* spp. and *Corylus* spp. in Worcester, United Kingdom, 1996–2005. *Int J Biometeorol* 51:181–191. doi:10.1007/s00484-006-0059-2
- Encyclopaedia Britannica (2010) Encyclopaedia Britannica Online. <http://www.britannica.com/EBchecked/topic/479601/protandry>. Accessed 4 December 2010
- Galan C, Garcia-Mozo H, Vázquez L, Ruiz L, Diaz dela Guardia C, Trigo MM (2005) Heat requirement for the onset of the *Olea europaea* L. pollen season in several sites in Andalusia and the effect of the expected future climate change. *Int J Biometeorol* 49:184–188. doi:10.1007/s00484-004-0223-5
- Germain E (1994) The reproduction of hazelnut (*Corylus avellana* L.): a review. *Acta Hort* 351:195–209
- Germain E, Sarraquigne JP (2004) *Le Noisetier*. Centre Technique Interprofessionnel des Fruits et Legumes, Paris
- Gunderson CA, O'Hara KH, Campion CM, Walker AV, Edwards NT (2010) Thermal plasticity of photosynthesis: the role of acclimation in forest responses to a warming climate. *Global Change Biol* 16:2272–2286. doi:10.1111/j.1365-2486.2009.02090.x
- IPCC (2007) *Climate Change 2007—Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Reisinger A (ed) IPCC, Geneva, Switzerland
- IPGRI (2008) *Descriptors for Hazelnut (Corylus avellana L.)*. Biodiversity International. CIHEAM, FAO, Roma
- Jato V, Rodríguez-Rajo FJ, Méndez J, Aira MJ (2002) Phenological behaviour of *Quercus* in Ourense (NW Spain) and its relationship with the atmospheric pollen season. *Int J Biometeorol* 46:176–184. doi:10.1007/s00484-006-0059-2
- Kajfež-Bogataj L (2001) Changes in the minimum and maximum temperatures in Slovenia over the last 50 years. *Research*

- Reports, University of Ljubljana, Biotechnical Faculty 77:299–307
- Kajfež-Bogataj L, Bergant K (2005) What might the climate of Slovenia look like in this century? *Ujma*, Ljubljana 19:218–223
- Kluza-Wieloch M, Szewczak J (2006) Flowering phenology of selected wind pollinated allergenic deciduous tree species. *Acta Agrobot* 59:309–316
- Kramer K (1994) A modelling analysis of the effects of climatic warming on the probability of spring frost damage to tree species in the Netherlands and Germany. *Plant Cell Environ* 17:367–377. doi:10.1111/j.1365-3040.1994.tb00305.x
- Larcher W (1995) *Physiological plant ecology*, 3rd edn. Springer, New York
- Larcher W (2003) *Physiological Plant Ecology*. Springer, Berlin
- Lieth H (ed) (1974) *Phenology and seasonality modelling*. Ecological studies 8, Springer, New York
- Luedeling E, Zhang M, Luedeling V, Girvetz EH (2009a) Validation of winter chill models using historic records of walnut phenology. *Agr Forest Meteorol* 149:1854–1864. doi:10.1016/j.agrformet.2009.06.013
- Luedeling E, Zhang M, McGranahan G, Leslie C (2009b) Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central valley. *Agr Ecosyst Environ* 133:123–131. doi:10.1016/j.agee.2009.04.016
- Manzo P, Tamponi G (1982) *Monografia di cultivar di nocciuolo*. Istituto Sperimentale per la Frutticoltura Roma, Rome
- Mehlenbacher SA (1991) Chilling requirements of hazelnut cultivars. *Sci Hortic* 47:271–282. doi:10.1016/0304-4238(91)90010-V
- Menzel A, Sparks T, Estrella N et al (2006) European phenological response to climate change matches the warming pattern. *Global Change Biol* 12:1969–1976. doi:10.1111/j.1365-2486.2006.01193.x
- Migliavacca M, Cremonese E, Colombo R, Busetto L, Galvagno M, Ganis L, Meroni M, Pari E, Rossini M, Siniscalco C, Morra di Cella U (2008) European larch phenology in the Alps: can we grasp the role of ecological factors by combining field observations and inverse modelling? *Int J Biometeorol* 52:587–605. doi:10.1007/s00484-008-0152-9
- Piskornik Z, Wyzgolik GM, Piskornik M (2001) Flowering of hazelnuts cultivars from different regions under the climatic conditions of Southern Poland. *Acta Hortic* 556:529–535
- Ruiz D, Campoy JA, Egea J (2007) Chilling and heat requirement of apricot cultivars for flowering. *Environ Exp Bot* 61:254–263. doi:10.1016/j.envexpbot.2007.06.008
- Scheifinger H, Menzel A, Koch E, Peter C (2003) Trends in spring time frost events and phenological dates in Central Europe. *Theor Appl Climatol* 74:41–51. doi:10.1007/s00704-002-0704-6
- Schleip C, Rutishauser T, Luterbacher J, Menzel A (2008) Time series modeling and central European temperature impact assessment of phenological records over the last 250 years. *J Geophys Res* 113: G04026. doi:10.1029/2007JG000646
- Schleip C, Rais A, Menzel A (2009) Bayesian analysis of temperature sensitivity of plant phenology in Germany. *Agric For Meteorol* 149:1699–1708. doi:10.1016/j.agrformet.2009.05.014
- Solar A, Štampar F (1997) First experiences with some foreign hazelnut cultivars (*Corylus avellana* L.) in Slovenia. *Acta Hortic* 445:83–89
- Solar A, Štampar F (2009) Performance of Hazelnut Cultivars from Oregon in Northeastern Slovenia. *Hortic Technol* 19:653–659
- Strauss F, Formayer H, Asamer V, Schmid E (2010) Climate change data for Austria and the period 2008–2040 with 1 day and km² resolution. No 482010, Working Papers, University of Natural Resources and Applied Life Sciences, Vienna, <http://econpapers.repec.org/RePEc:sed:wpaper:482010>. Accessed 13 April 2011
- Turcu E, Turcu I, Botu M (2001) Flowering of hazelnuts cultivars in Oltenia, Romania. *Acta Hortic* 556:365–370
- Vučetić V, Vučetić M, Lončar Ž (2008) History and present observations in Croatian plant phenology. In: Nekovar J (ed) *The History and Current Status of Plant Phenology in Europe*, Vammalan Kirjapaino Oy, Brussels, COST 725, pp 44–50
- Weinberger JH (1950) Chilling requirements of peach varieties. *Proc Am Soc Hortic Sci* 56:122–128
- Wielgolaski FE (1999) Starting dates and basic temperatures in phenological observations of plants. *Int J Biometeorol* 42:158–168. doi:10.1007/s004840050100
- Wilkinson J (2005) *Nut growers's guide: the complete handbook for producers and hobbyists*. Landlinks, Collingwood
- Zhang T, Zhu J, Yang X (2008) Non-stationary thermal time accumulation reduces the predictability of climate change effects on agriculture. *Agric For Meteorol* 148:1412–1418. doi:10.1016/j.agrformet.2008.04.007