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Model-based analysis of chill accumulation in European hazelnut catkins highlights site-specific climatic sensitivity across Italian locations

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ABSTRACT

Rising global demand for hazelnuts requires improved tools to support cultivar adaptation without compromising quality. This study evaluated male flowering phenology and chilling accumulation over three years in four European hazelnut cultivars and one wild type accession grown in two contrasting environments: Viterbo (central Italy, sub-coastal temperate climate) and Chieri (northern Italy, sub-continental temperate climate). Pollen dispersal was monitored, and chilling accumulation was calculated from November 1st to dormancy release using chilling hours (CH, 0–7 °C), Utah (chilling units, CU), and Dynamic (chilling portions, CP) models. Results revealed clear genotype-specific differences in flowering timing and duration. Early-flowering cultivars reached anthesis two to four weeks earlier in Viterbo than in Chieri, reflecting adaptation to local mesoclimatic conditions. Chilling accumulation differed significantly between sites, with consistently lower values in the warmer environment. Among models, CH showed the most stable and consistent response to environmental differences and best agreement with observed phenology, while CU provided comparable but slightly less robust estimates. CP captured the influence of temperature fluctuations and warm spells, but showed less consistency in cross-site comparisons. These findings highlight the strong interaction between genotype and environment in hazelnut phenology and emphasize the importance of selecting appropriate chilling models to support cultivar choice and orchard management under variable climatic conditions.

1. Introduction

European hazelnut (*Corylus avellana* L.) is one of the most economically relevant nut crops in temperate regions, particularly in the Mediterranean basin, where orchard productivity and yield stability depend strongly on winter temperature regimes (Luedeling et al., 2011). Historically, Turkey, Italy, and Spain dominated global production (FAO, 2024), but new producers, such as Chile, are emerging, providing stable income and supporting rural communities (Mohr Fuchslocher and Navarro Gaete, 2023). In Italy, hazelnut production is concentrated mainly in a few specialized regions with favorable pedoclimatic conditions. The primary producing areas are Piedmont in northern Italy, and Latium and Campania in central and southern Italy, which together concentrate the majority of Italian hazelnut orchards (Nera et al., 2020). These regions differ substantially in climate: northern Italy is generally characterized by a temperate humid climate with with hot summers and cool winters (Köppen–Geiger Cfa), whereas central and southern Italy are mostly defined by Mediterranean climates with hot, dry summers and mild, wetter winters (Köppen–Geiger Csa). This gradient of climatic conditions within Italy mirrors the broader range of environments in which hazelnut is cultivated worldwide. In general, European hazelnut exhibits a broad pedoclimatic adaptability, being successfully cultivated from Mediterranean to temperate regions across Europe and America. Its phenological and reproductive responses vary according to local climates, as shown by cultivar trials under different winter regimes in southern Poland (Piskornik et al., 2001), in Ukraine (Slyusarchuk and Ryabokon, 2001), and in New Jersey, USA (Hlubik et al., 2023). The species grows well on well-drained, fertile soils with adequate moisture, showing optimal performance on neutral to slightly acidic soils rich in organic matter (Pacchiarelli et al., 2022).

Temperate nut trees require chilling accumulation during winter to overcome seasonal dormancy (Di Lena et al., 2022; Hlubik et al., 2023).

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During this period, physiological activity is reduced and vegetative growth is suspended (Solovchenko et al., 2022). Like other temperate nut species, European hazelnut requires a period of endodormancy followed by ecodormancy (Faust et al., 1997), both of which must be satisfied to ensure regular flowering and stable yield (Jha et al., 2021). Therefore, determining chilling requirements is essential for predicting dormancy release and classifying cultivars into early-, mid-, or late-flowering groups, particularly for synchronizing pollen shed and female receptivity in monoecious systems.

Chilling requirements for European hazelnut have been estimated on limited number of studies using different modelling approaches, mainly based on empirical chilling models. Available values for Mediterranean and European hazelnut cultivars, including several widely studied Italian cultivars, as well as some wild accessions, generally fall within broad ranges depending on genotype, location and methodological approach, differences in phenological definitions, experimental conditions, and modelling frameworks. However, these estimates are not directly comparable across studies due to differences in chilling models and associated methodological approaches.

Several models have been developed to estimate winter chill accumulation in temperate perennial species, including the Chilling Hours, Utah, and Dynamic models. The Chilling Hours model quantifies exposure to temperatures within a fixed range (0–7.2 °C) assumed to be effective for dormancy release (Bennet, 1949; Weinberger, 1950). The Utah model assigns differential weights to temperature ranges and includes negative contributions at high temperatures, reflecting the inhibitory effect of warm spells (Richardson *et al.*, 1974; Gilreath and Buchanan, 1981). These two empirical approaches are widely used but assume relatively fixed temperature responses, which may limit their applicability under fluctuating winter conditions. To address this limitation, the Dynamic Model was developed (Fishman et al., 1987a, 1987b), introducing a mechanistic two-step process in which chilling accumulation proceeds through a reversible intermediate stage before irreversible formation of Chill Portions (CP). This formulation allows a more realistic representation of dormancy progression under fluctuating temperature regimes.

Despite the availability of several chilling models, their application in hazelnut research remains fragmented and inconsistent and most studies on the species have traditionally relied on single-model approaches, predominantly based on the Chilling Hours or Utah models (Mehlenbacher, 1991; Rovira et al., 2014; Jha et al., 2021). At the same time, chill accumulation modelling has evolved through the development of region-specific adaptations for other cropping systems, such as the Positive Utah model (Linsley-Noakes et al., 1995) and the North Carolina model (Shaltout and Unrath, 1983). Although the Dynamic Model has been widely applied in deciduous fruit species such as *Prunus armeniaca* (Egea et al., 2021), *Pistacia vera* (Zhang and Taylor, 2011), *Prunus amygdalus*, and *Prunus avium* (Caspersen et al., 2026), its use in European hazelnut remains comparatively limited. Only a small number of studies have explicitly investigated chilling requirements in Corylus avellana using Dynamic Model-based or standardized comparative approaches, with Hlubik et al. (2023) representing one of the few recent examples.

However, a more fundamental gap remains: chilling requirements of the same hazelnut cultivars have rarely been evaluated across contrasting pedoclimatic environments within a unified methodological framework. Consequently, the consistency and transferability of cultivar-specific chilling requirements across geographic regions remain poorly understood, despite their relevance for genotype × environment interactions in perennial crop phenology.

In the genus *Corylus* L., chilling requirements are influenced by genetic factors, including the "non-dormant" allele. Heterozygous genotypes carrying this allele exhibit lower chilling requirements compared to homozygous dormant genotypes (Thompson et al., 1985). Many commercially important cultivars from the Mediterranean basin (Turkish Black Sea coast, Italy, and Spain) carry this allele in heterozygous form (Mehlenbacher, 1991), including the Italian varieties examined in this study. Several Italian hazelnut cultivars have been widely introduced and evaluated in different production regions outside Italy, highlighting their international relevance. Cultivars such as 'Tonda di Giffoni', 'Tonda Gentile Romana', and 'Nocchione' have been evaluated under the pedoclimatic conditions of northern Spain (Rovira et al., 2014), while 'Tonda Gentile delle Langhe' and 'Mortarella' have also been studied in Türkiye (Ozturk et al., 2025). In addition, 'Tonda di Giffoni' is currently among the principal cultivars adopted in Chilean hazelnut production systems (Ellena et al., 2014). This broad geographic distribution makes Italian hazelnut cultivars suitable candidates for evaluating the stability of chilling requirements across contrasting environments.

The implications of climate change on winter chill in European hazelnut have been recently investigated (Jha et al., 2021; An et al., 2020; Ahmadov, 2024). However, no prior research has evaluated the consistency of chilling requirements for the same species and cultivars across different production areas with distinct pedoclimatic conditions. The aim of this study was therefore to assess the stability of chilling requirements in European hazelnut male inflorescences across contrasting environments, using three chilling models as complementary tools to evaluate the robustness of phenological responses and the potential plasticity of chilling accumulation under different climatic conditions.

2. Materials and methods

2.1. Plant material and experimental sites

The investigation was conducted on four European hazelnut cultivars of Italian origin and well-known for their high commercial interest, covering a wide range of male flowering periods: the early flowering cultivar Tonda Gentile *sin.* 'Tonda Gentile delle Langhe' (TG), the mid-flowering cultivars Nocchione (N) and Tonda di Giffoni (TdG), and the mid-late flowering cultivar Tonda Gentile Romana (TGR), in association with late flowering wild type accessions (WT). All the shrubs were selected from two independent varietal fields located in north and central Italy (Table 1). In both sites, plants were trained according to the multi-stem bush system and planted at a spacing of 5 × 4 m. The shrubs in both orchards, ranging in age from 12 to 24 years, had reached full reproductive maturity, ensuring comparable phenological behavior between sites (Salardi-Jost et al., 2025). Cultivars were arranged in rows, each consisting of at least ten plants per genotype. Daily field observations were conducted on each genotype from December 1st to March 1st during the 2021–22, 2022–23, and 2023–24 growing seasons. During each assessment, the entire canopy of each shrub was examined to monitor male flowering phenology.

The two collection orchards are characterised by distinctive pedological characteristics. The Chieri area is identified with poor skeleton, a predominantly silty-clayey soil with a sub-alkaline reaction and medium exchange capacity. The organic matter content detected according to the Soil Map of the Piedmont Region corresponds to 1.28% (Geoportale Regione Piemonte, 2025).

On the contrary, the collection orchard of Viterbo province is located around the volcanic region of Vico Lake, characterized by a sandy clay loam texture (66% sand, 27% clay) with reworked tuff and debris

Table 1
Regional location and coordinates of the two European hazelnut cultivar fields.

Area	Region	Field name	Coordinates
Chieri (Torino province)	Piedmont	Tetti Grondana	latitude 45°02'29'' N, longitude 7°50'08'' E, altitude 327 m s.l.
Caprarola (Viterbo province)	Latium	Le Cese	latitude 42°20'00'' N, longitude 12°11'00'' E, altitude 570 m s.l.

deposits (ArpaLazio, 2012). The concentrations of exchangeable calcium, magnesium, and potassium were measured at 771, 273, and 172 mg kg^{-1} , respectively, indicating a well-balanced cationic profile. Soil organic matter content was 2.3%, while the soil assimilable phosphorous was low (13 mg kg^{-1}). Soil pH is slightly acidic, with an average value of 6.1 (Pacchiarelli et al., 2024).

2.2. Meteorological and phenological data

Meteorological data were collected from experimental hazelnut (*Corylus avellana* L.) orchards located in Chieri (Piedmont) and Viterbo province (Latium), which are representative of two distinct agro-climatic environments in northern and central Italy, both highly suitable to hazelnut cultivation, due to their favorable pedoclimatic conditions. According to the Köppen–Geiger climate classification, the Chieri site falls within the Cfa zone (humid temperate climate), characterized by cold, humid winters with minimum temperatures that can frequently fall below 0 °C and by the recurring fog events, especially in the late autumn and winter months. Spring and autumn are mild, while summers tend to be hot and humid, with average maximum temperatures often exceeding 30 °C in July and August (https://servizi.regione.piemonte.it/catalogo/banca-dati-agrometeorologica-ram). In contrast, the site of Viterbo province is characterized by a Csa (hot-summer Mediterranean) climate, marked by milder winters and distinctly drier summers. The warmest and driest months are June, July and August, during which average daily maximum temperatures exceed 30 °C. During the coldest period (January-February), average minimum temperatures drop to about 2–3 °C, although extreme temperatures below freezing are slightly uncommon. The territory is mainly mesaxeric, with precipitation concentrated in autumn and, to a lesser extent, in the spring months (ArpaLazio, 2019). The site represents a typical Mediterranean environment, widely recognized as one of the most suitable areas in Italy for European hazelnut (*Corylus avellana* L.) cultivation.

Hourly and daily temperatures were obtained from *in situ* meteorological stations: a HOBO® Data Logger (U23 series) was used at the Tetti Grondana field in Chieri and a TerraSence AS100Plus at the Le Cese field in Viterbo. Phenological observations were conducted once a week from December 1st to March 1st during the 2021–22, 2022–23, 2023–24 seasons.

2.3. Chilling accumulation models

Chill accumulation during the plant winter rest was calculated for cultivar male inflorescences using three hourly temperature-based models: the chilling hours model, the Utah model and the Dynamic model. The chilling hours model (CH), one of the earliest and most widely used approaches, considers all hourly temperatures between 0 and + 7 °C excluding freezing temperatures (Weinberger, 1950). This method was previously validated in European hazelnut cultivars by Mehlenbacher (1991). The number of chilling hours was calculated as follows:

$$CH\,t = \sum_{i=1}^{t} T, \text{with } T = \begin{cases} 0\ ^\circ C < T < 7\ ^\circ C & : 1 \\ else & : 0 \end{cases}$$

The Utah model (Richardson *et al.*, 1974) attributes different chilling efficiencies to specific temperature ranges, including a negative contribution for temperatures above or equal to + 18 °C. The number of Chilling Units (CU) was calculated as follows:

$$CU\,t = \sum_{i=1}^{t} T_U, \quad with\ T_U = \begin{cases} T \le 1.4\ ^\circ C & : 0 \\ 1.5\ ^\circ C \le T \le 2.4^\circ C & : 0.5 \\ 2.5\ ^\circ C \le T \le 9.1\ ^\circ C & : 1 \\ 9.2\ ^\circ C \le T \le 12.4\ ^\circ C & : 0.5 \\ 12.5\ ^\circ C \le T \le 15.9\ ^\circ C & : 1 \\ 16\ ^\circ C \le T \le 18\ ^\circ C & : -0.5 \\ T > 18\ ^\circ C & : -1 \end{cases}$$

The Dynamic Model (Fishman et al., 1987a; 1987b; Erez et al., 1988) provides an alternative conceptual framework in which chill accumulation is considered a two-step process. In this model, chill portions (CP) are formed through intermediate products that can be reversibly influenced by warm temperatures before becoming irreversibly accumulated. By accounting for the reversible effects of warm spells, this temperature-driven dynamic provides a more robust estimate of chill accumulation under increasingly erratic winter temperature patterns associated with climate change.

The temperature dependence of the reaction rates is described by Arrhenius-type functions:

$$k_1 = A_1 e^{-E_1/T}$$

$$k_2 = A_2 e^{-E_2/T}$$

where k_1 and k_2 are the rate constants for formation and degradation of the precursor, respectively, A_i are the pre-exponential factors, E_i the activation energies, and T the absolute temperature. The dynamics of the precursor (x) are described by:

$$\frac{dx}{dt} = k_1 - k_2 x$$

For a constant temperature interval, the solution of the differential equation is:

$$x(t) = x_s - (x_s - x_0)e^{-k_2 t}$$

where x_0 is the initial amount of precursor, t is time (typically 1 h intervals), and $x_s = \frac{k_1}{k_2}$ represents the steady-state value. When the concentration of the intermediate product reaches a threshold value of unity ($x = 1$), one CP is irreversibly formed, and the system is reset for the next accumulation cycle. Chilling requirement was therefore expressed as:

$$CP_t = \sum_{i=1}^{t} CP_i, \text{ with } CP_i \in \{0, 1\}$$

where $CP_i = 1$ when one CP is completed during hour i, and $CP_i = 0$ otherwise.

This formulation allows the model to account for both promotive and inhibitory effects of fluctuating temperatures, incorporating the reversible impact of warm periods on chilling accumulation. Consequently, the Dynamic Model provides a robust estimation of chill accumulation under variable winter temperature regimes.

In all cases, hourly temperature were recorded from November 1st, according to the first seasonal time in accumulating chilling units in the explored temperate areas, until the date when 50% of male catkins were visibly elongated and approaching flowering (equivalent to BBCH 59–60), as reported by Luedeling *et al.*, (2009), Črepinšek et al., (2012) and Di Lena et al., (2022). The models were used to quantify chill accumulation up to this phenological stage.

Various other hourly time-based models, such as the Positive Utah Model (Linsley-Noakes and Allan, 1994) and the Positive Chill Units (Linsley-Noakes et al., 1995), originally developed for warmer climate conditions, were not considered in this study because they do not include the negative influence of high temperatures.

2.4. Data and statistical analysis

Statistical analyses were performed using Microsoft Excel (version 16.0, Microsoft Corporation, USA) with the Analysis ToolPak add-in for advanced statistical functions. Statistical differences between fields were assessed using Student's *t*-test ($P \le 0.05$). The R^2 and linear regression functions were used to determine the most suitable model for chilling accumulation over a 3-year period. A simple regression approach based on analysis of variance (two-way ANOVA) was set up for

each collection field to evaluate which of the chilling models better met the descriptive criteria for a significant correlation between field factors (environment) and observation times (year), and their interactions.

Fig. 2 was generated in R (version 4.4.2) using standard packages for data manipulation and visualization.

The Chilling Hours and Utah models were implemented in Microsoft Excel based on their original formulations (Weinberger, 1950; Arlo Richardson et al., 1974), while the Dynamic Model was computed in R using the chillR package (package chillR, function Dynamic_Model).

Chill accumulation was based on hourly mean air temperatures starting from November 1st of each season (Luedeling et al., 2009a; 2009b), corresponding to the onset of winter chill accumulation in temperate environments.

3. Results

3.1. Phenological traits and climatic characteristics

The male flowering times recorded over three years for each cultivar are shown in Fig. 1. In the Viterbo area, the early-flowering cultivar TG showed higher inter-annual variability, with a marked delay of approximately 3–4 weeks in the 2023–24 season compared to previous years. An early pollen dispersal was also observed for N and TdG, which also showed a more concentrated release, mainly between late December and January, with relatively stable trends over the years. The late-flowering cultivar TGR and the wild-type accession (WT) consistently released pollen in late January to early February. Overall, in the Chieri site, pollen dispersal occurred predominantly between January and February, with generally lower inter-annual variability. Here, TdG showed the most stable phenological behavior, while other cultivars exhibited moderate variability. Differences in duration and timing of pollen shedding were observed across cultivars and years in both environments (Fig. 1).

Fig. 2 displays the monthly temperature distributions for the Chieri and Viterbo areas during the winter months (November to February) over three consecutive years: 2021–22, 2022–23, and 2023–24. In general, Chieri experienced colder conditions than Viterbo across all observed winters, with temperatures typically ranging from −4 °C to + 8 °C, particularly in January and February. These months were characterized by more stable yet consistently colder weather patterns. In contrast, Viterbo exhibited a generally warmer and more variable thermal profile, with frequent temperatures between + 8 °C and + 16 °C, and occasional peaks above + 20 °C. Sub-zero temperatures were rare, particularly from January onwards, while increased synoptic variability was observed during transitional months such as November and February. The 2021–22 winter season was the coldest among the three for both locations. The following year, 2022–23, was characterized by high thermal variability, particularly in Viterbo, where temperature distributions assumed a bimodal trend. The last flowering season, 2023–24, was comparatively milder, although Chieri consistently recorded lower temperatures compared to Viterbo.

During the pre-flowering period (November–December), Viterbo invariably exhibited higher temperatures than Chieri. Across all three years, November temperatures in Viterbo were predominantly distributed between + 8 °C and + 16 °C, occasionally exceeding + 18 °C. In contrast, Chieri showed a narrower range, mostly between + 4 °C and + 12 °C, with only a few instances above + 14 °C. In December, temperatures in Viterbo typically ranged from + 6 °C to + 14 °C, occasionally reaching higher values, while Chieri was characterized by lower and more concentrated distributions between 0 °C and + 10 °C, with sub-zero temperatures occurring each year. Across all years, Viterbo showed broader, sometimes bimodal, patterns, in contrast to Chieri's narrower and more symmetrical profiles.

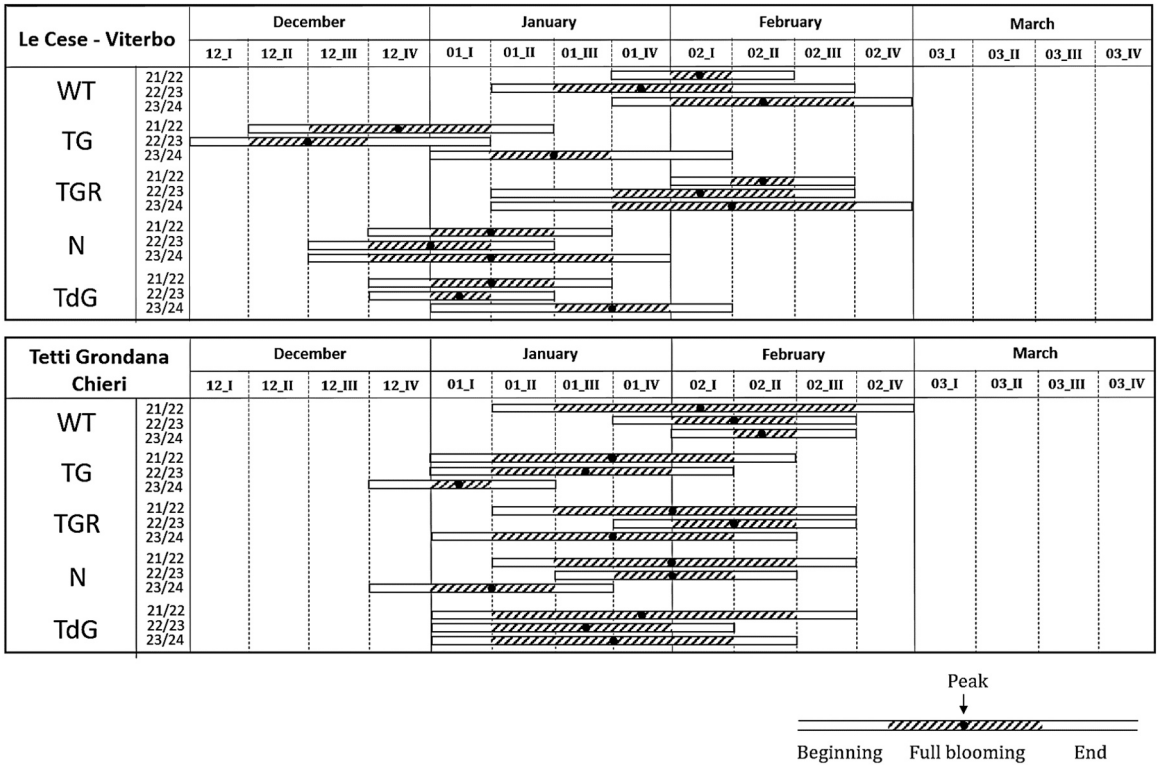

Fig. 1. Comparison of the phenograms of male hazelnut flowers belonging to the two collection fields of Le Cese (Viterbo) and Tetti Grondana (Chieri), relating to the cultivars Tonda Gentile sin 'Tonda Gentile delle Langhe' (TG), Tonda Gentile Romana (TGR), Nocchione (N) and Tonda di Giffoni (TdG) in association with a wild type accession (WT), during the flowering seasons 2021–22, 2022–23 and 2023–24. 'Beginning' indicates the time when a few catkins begin to shed pollen (about 5–10% elongated catkins). The dotted lines (full blooming) indicate when peak pollen shedding is reached (about 50% of the catkins are shedding pollen) and 'End' indicates the latter part of flowering when few catkins are still shedding pollen (last 5–10% of elongated catkins).

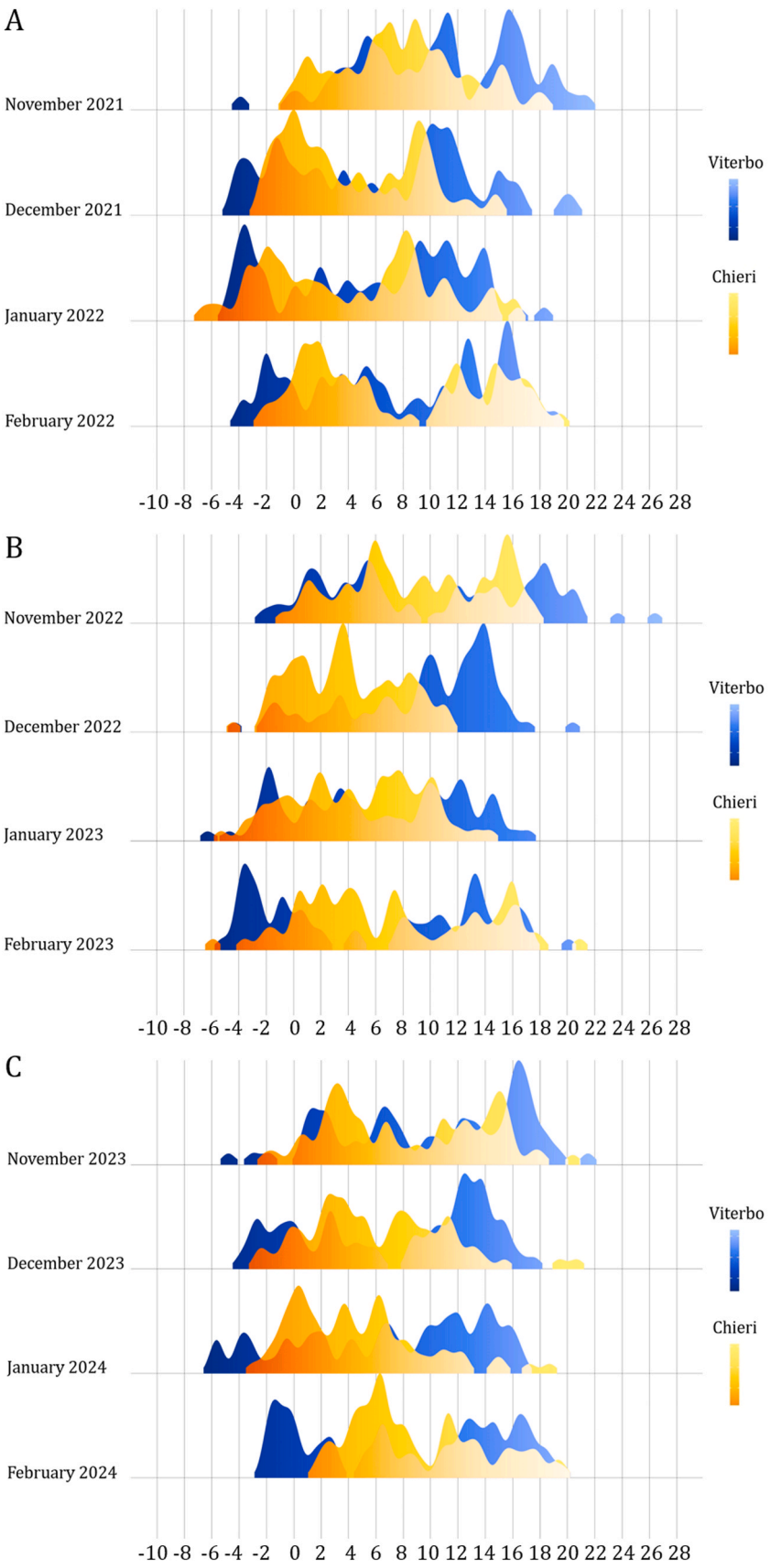

Fig. 2. Monthly temperature distributions in Viterbo and Chieri across the (A) 2021–22, (B) 2022–23, and (C) 2023–24 winter seasons from November to February. Each ridge represents the daily temperature distribution for a given month, with Viterbo (light blue to dark blue) and Chieri (yellow to orange) indicating the frequency and range of recorded temperatures.

3.2. Chill accumulation in catkins across environments and genotypes

Chill accumulation was analysed following three complementary levels: (i) absolute accumulation across models and environments, (ii) stability across years and sites, and (iii) consistency among chilling models.

Chill accumulation calculated using the chilling hours (CH), Utah (CU), and Dynamic (CP) models from November 1st during the winter periods 2021–22, 2022–23 and 2023–24, is summarized in Table 2 and Figs. 3–5. The chill accumulation calculated using the chilling hours model ranged from 200 to 315 in Chieri and from 64 to 140 in Viterbo across the three seasons. The chill accumulation showed different values compared to those reported by Mehlenbacher (1991). Although the observations on flowering times were consistent, a clear increase in cumulative chilling hours was observed in both areas, especially in Chieri. Chill accumulation differed significantly between fields ($P < 0$, 001), with Chieri showing consistently higher values than Viterbo, as illustrated in Fig. 3. This characteristic involved both commercial genotypes and the WT accession. The coefficient of variation (CV) calculated for each genotype indicated a greater variability in the Viterbo field, as TGR, TG, TdG and N cultivars showed a CV of 26.7, 22.9, 17.9% and 17.5% respectively (Table 2).

Catkin chilling accumulation was also estimated using the Utah model. The results highlighted a significantly ($P < 0.001$) lower chilling demand in plants grown in the Viterbo area, with the exception of TGR that during the first flowering year (2021–22) equaled the requirement of the same cultivar grown in the Chieri area (Fig. 4). Cumulative chilling unit (cCU) values ranged from approximately 1046.5–1414.5 in Chieri and from 605.5 to 1235.5 in Viterbo across cultivars and seasons (Table 2). The variability of cCU estimates was moderate to high, with coefficients of variation (CV%) ranging from 10.4% to 26.1% in Chieri and from 19.7% to 26.7% in Viterbo. The results reported in Table 2 further support these findings, showing lower cCU values in Viterbo compared to Chieri across all cultivars and seasons. Genotypic differences were also observed, with late-flowering accessions generally accumulating higher CU values than early- and mid-flowering cultivars.

Chill accumulation, expressed as cumulated chilling portions (cCP), is reported in Fig. 5. The results show marked differences between environments for all cultivars and seasons. In general, cCP values exhibited a variable pattern between sites, with no consistent trend across all cultivars, although late-flowering genotypes (TGR and WT) tended to reach higher CP values in Viterbo in some seasons. These trends are generally consistent with the cCP values reported in Table 2, which also showed a variable pattern between environments, ranging from 44.7 to 60.4 in Chieri and from 30.5 to 62.5 in Viterbo. The variability estimates was generally moderate, with coefficients of variation ranging from 8.5% to 18.5% in Chieri and from 11.3% to 15.6% in Viterbo. Cultivar-specific differences were observed, with Nocchione and Tonda Gentile showing lower mean CP values in Viterbo over the three-year period.

Across all chilling models (CH, CU, and CP), chill accumulation values were consistently higher in Chieri than in Viterbo across cultivars and seasons (Figs. 3–5; Table 2). Significant differences between environments were detected in most cultivar–year combinations ($P < 0.05$ to $P < 0.001$). Differences among cultivars were observed across all models, with higher values in late-flowering genotypes compared with early- and mid-flowering cultivars.

3.3. Stability and environmental sensitivity of chilling models

The stability of chilling accumulation models across environments and years was evaluated using coefficient of variation (CV) and two-way ANOVA (Tables 2 and 3). The CV analysis indicated that CH and CU exhibited moderate variability across years, whereas CP showed lower variability in Chieri and higher variability in Viterbo, reflecting site-dependent sensitivity in the Dynamic model.

All models showed significant environmental effects on chill accumulation. In particular, CH showed a highly significant effect of environment ($F = 131.8$, $P < 0.001$), whereas neither the effect of year ($F = 1.86$, $P =$ n.s.,) nor the environment × year interaction were significant. Similarly, cumulated chilling units were significantly affected by environment ($F = 29.14$, $P < 0.001$), with no significant effects of year or the interaction between factors. For cumulated chilling portions, the effect of environment was significant but of lower magnitude ($F = 3.68$, $P < 0.05$), while neither year nor the environment × year interaction showed statistically significant effects.

Table 2
Male inflorescence (catkin) chilling accumulation of European hazelnut cultivars and one wild-type accession. Comparison among cumulative chilling hours (cCH), cumulative chilling units (cCU), and cumulative chilling portions (cCP) recorded over three years, together with their annual averages and coefficients of variation (CV %) for the studied accessions. Chilling accumulation was calculated starting from November 1st of each year.

Cultivars	Synonyms	Mehlenbacher (1991)		Three years of cumulated chilling hours				Three years of cumulated chilling units				Three years of cumulated chilling portions			
		Estimated chilling hours requirements	Date of first observation	Chieri	CV (%)	Viterbo	CV (%)	Chieri	CV (%)	Viterbo	CV (%)	Chieri	CV (%)	Viterbo	CV (%)
Wild Type	-	-	-	315	18.5	140	6.1	1414.5	8.5	1207	15.6	60.4	11.3	62.5	12.1
Tonda Gentile	Tonda Gentile delle Langhe Tonda Gentile Trilobata	< 100	4 December	200	13.5	64	22.9	1046.5	13.3	605.5	19.7	44.7	9.6	30.5	29.9
Tonda Gentile Romana	-	100–170	8 January	272	26.1	131	26.7	1295	10.4	1235.5	26.6	55	9.5	61	21.1
Nocchione	Montebello Mansa Comune Nostrale Racinante Maria del Gesù	170–240	1 January	236	22.2	95	17.5	1176.5	20.6	679	22.7	50.3	18.4	33.8	14.9
Tonda di Giffoni	-	170–240	8 January	205	9.6	100	17.9	1135.5	5.2	939.5	29.8	48	3.5	47	25.5

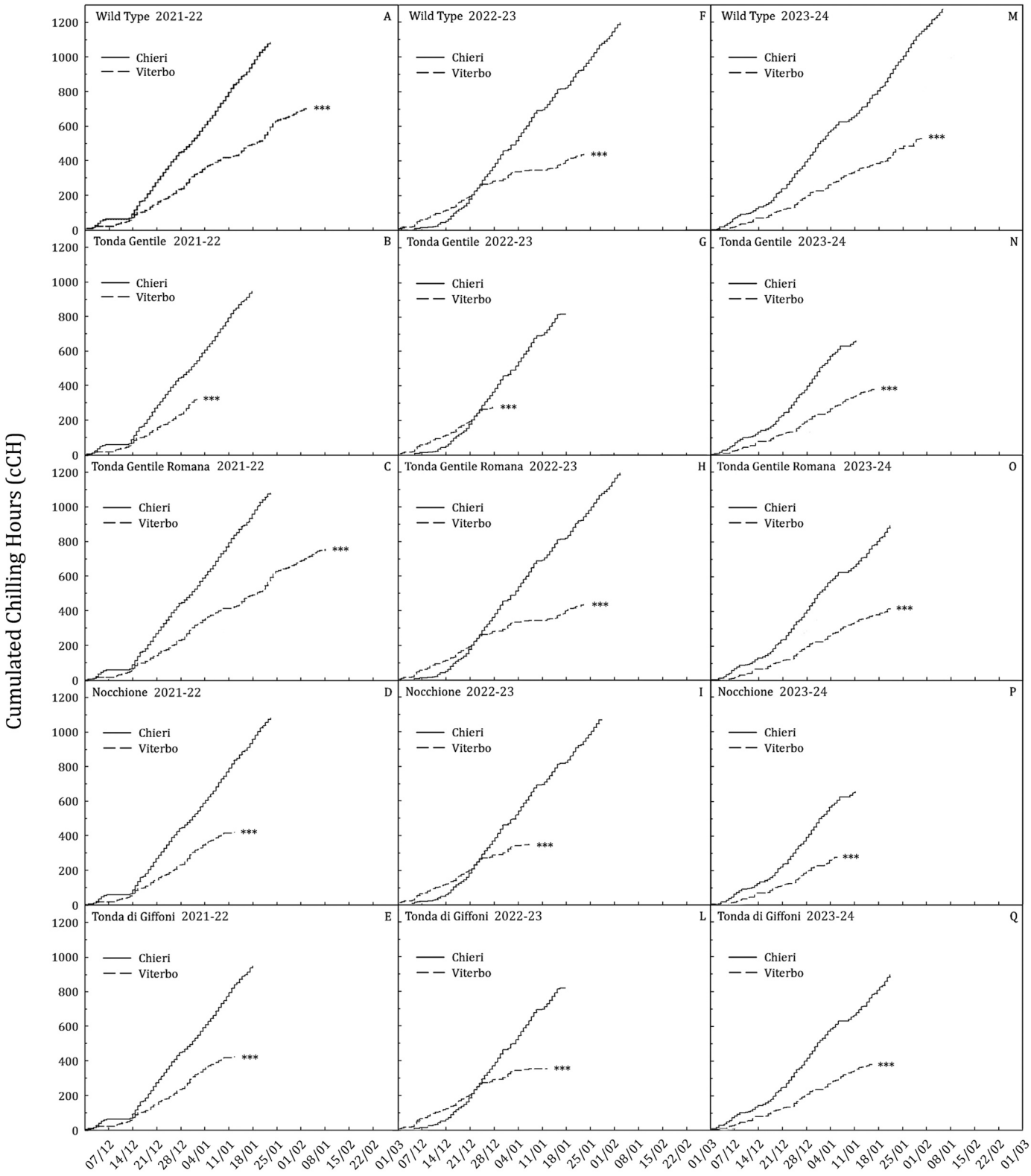

Fig. 3. Trend of male inflorescence cumulated chilling hours between 0 and + 7 °C at the first observation in the field in which 50% of the catkins were elongated and dormancy was considered concluded, in the hazelnut collection fields of Chieri and Viterbo relating to the wild type accession (A, F, M), and the cultivars Tonda Gentile sin 'Tonda Gentile delle Langhe' (B, G, N), Tonda Gentile Romana (C, H, O), Nocchione (D, I, P) and Tonda di Giffoni (E, L, Q), during the seasons 2021–22 (A, B, C, D, E), 2022–23 (F, G, H, I, L) and 2023–24 (M, N, O, P, Q). Asterisks indicate statistical significance between Chieri and Viterbo cultivars with *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$ according to Student's T-test.

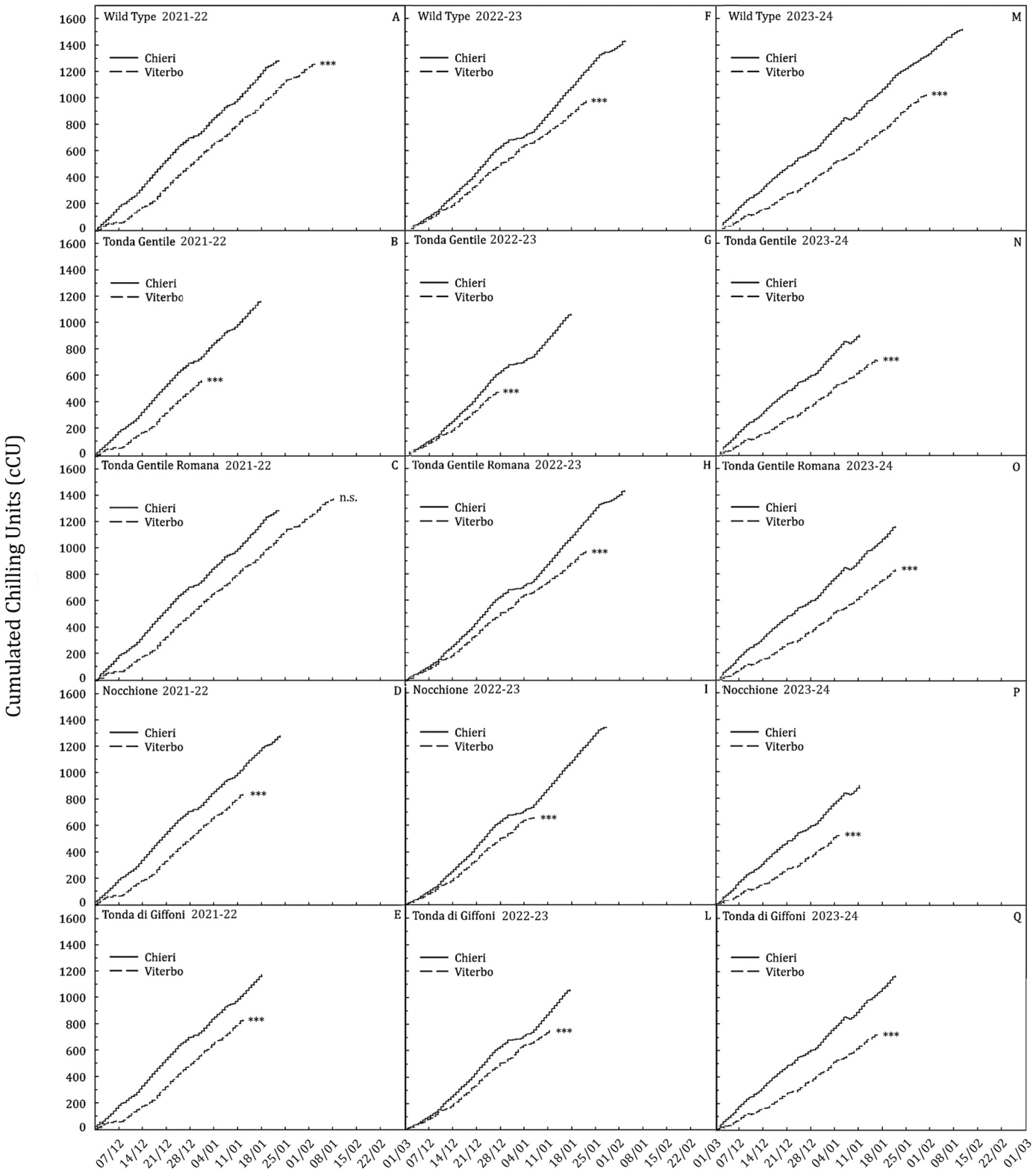

Fig. 4. Trend of male inflorescence cumulated chilling units at the first observation in the field in which 50% of the catkins were elongated and dormancy was considered concluded, in the hazelnut collection fields of Chieri and Viterbo relating to the wild type accession (A, F, M), and the cultivars Tonda Gentile sin 'Tonda Gentile delle Langhe' (B, G, N), Tonda Gentile Romana (C, H, O), Nocchione (D, I, P) and Tonda di Giffoni (E, L, Q), during the seasons 2021–22 (A, B, C, D, E), 2022–23 (F, G, H, I, L) and 2023–24 (M, N, O, P, Q). Asterisks indicate statistical significance between Chieri and Viterbo cultivars with *P < 0.05; **P < 0.01; ***P < 0.001 according to Student's T-test.

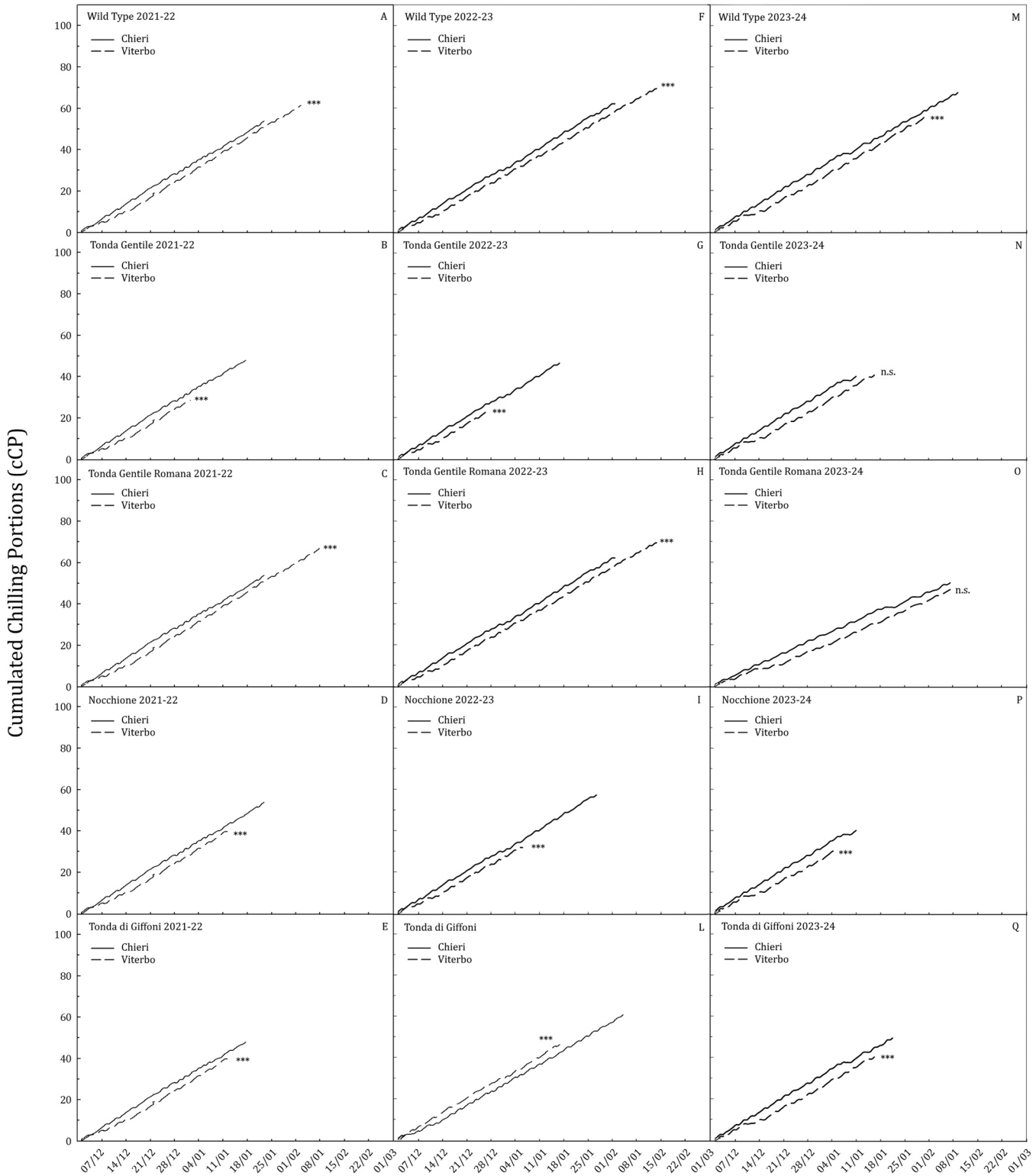

Fig. 5. Trend of male inflorescence cumulated chilling portions at the first observation in the field in which 50% of the catkins were elongated and dormancy was considered concluded, in the hazelnut collection fields of Chieri and Viterbo relating to the wild type accession (A, F, M), and the cultivars Tonda Gentile sin 'Tonda Gentile delle Langhe' (B, G, N), Tonda Gentile Romana (C, H, O), Nocchione (D, I, P) and Tonda di Giffoni (E, L, Q), during the seasons 2021–22 (A, B, C, D, E), 2022–23 (F, G, H, I, L) and 2023–24 (M, N, O, P, Q). Asterisks indicate statistical significance between Chieri and Viterbo cultivars with *P < 0.05; **P < 0.01; ***P < 0.001 according to Student's T-test.

3.4. Structural consistency and divergence among chilling models

Relationships between chilling models are shown in Fig. 6. Statistical analysis indicated strong linear relationships (P < 0.0001) between chilling hours and Utah models in both Viterbo and Chieri, with coefficients of determination (R^2) ranging from 0.96 to 0.99 in Viterbo and consistently equal to 0.99 in Chieri across the three seasons. Similar strong linear relationships were observed among the other model

Table 3
Significance by two-way ANOVA test on commercially interesting European hazelnut cultivars and a wild type accession of environment (E) and year of collection (Y), as well as the interaction environment × year of collection (E × Y) on cumulate chilling hours, chilling units and chilling portions (*P < 0.05; **P < 0.01; ***P < 0.001). n.s. means not significant.

	Environment (E)	F	Year (Y)	F	ExY
cumulate chilling hours	***	131.8	n.s.	1.86	n.s
cumulate chilling units	***	29.14	n.s.	2.7	n.s.
cumulate chilling portions	*	3.68	n.s	0.59	n.s.

comparisons: CU vs. CP and CP vs. CH relationships showed consistently high R^2 (0.99) across all cases, with all regressions being statistically significant ($P < 0.0001$).

Despite the consistently high coefficients of determination observed across all model comparisons, relevant differences emerged in the regression parameters between sites. In particular, CU vs. CP relationships showed highly consistent slopes between Viterbo (0.048–0.053) and Chieri (0.043–0.045), with uniformly high R^2 values (0.99) across all cases (Fig. 6 C, D). In contrast, CH vs. CU relationships exhibited clear site-dependent differences, with markedly lower slopes in Viterbo (0.557–0.564) compared to Chieri (0.925–0.961) (Fig. 6 A, B). A similar pattern was observed for CP vs. CH relationships, which, despite high coefficients of determination, showed substantial variation in slope between sites and years (Viterbo: 7.41–8.70; Chieri: 21.26–21.91) (Supplementary Tables 1 and 2).

4. Discussion

Phenological analyses conducted over a three-year period highlighted characteristic male flowering trends for each observed cultivar, both in terms of timing and duration of pollen dispersal, despite some seasonal fluctuations. Notably, differences in male flowering time were observed for certain accessions when comparing the two orchards. This was particularly evident for the early-flowering cultivars TG, N, and TdG, grown in the Viterbo area, which flowered two to four weeks earlier than the same cultivars cultivated in Chieri (Fig. 1), showing a reduced environmental plasticity for male blooming. Earlier male flowering in Viterbo, relative to other growing areas, had been previously reported (Brandoli et al., 2024, 2025a). These differences could be attributed to specific local pedo-climatic conditions of the experimental sites. Indeed, the onset and duration of male and female flowering are parameters strongly influenced by both the intrinsic genetic traits of each genotype (e.g., earliness or lateness of the cultivar) and, more importantly, by local environmental factors (Menzel et al., 2006). Light and temperature are the primary environmental cues regulating plant growth and development (Adams and Langton, 2005). Floral induction, in particular, is highly sensitive to environmental stimuli and is regulated by both photoperiod and thermoperiod, which activate distinct physiological pathways governed by circadian clock genes (Gould et al., 2006; Song et al., 2018). In the Viterbo orchard, an earlier onset of male flowering was recorded for early-flowering cultivars compared to those in Chieri, likely due to more frequent temperatures exceeding + 12 °C in the months preceding male anthesis (Fig. 2). These warmer conditions may have accelerated flowering, as previously suggested by Luedeling and Brown (2011) and Vitasse et al., (2018). Similar advancements in flowering time have been reported in *Malus domestica* Borkh. (Chitu and Paltineanu, 2020) and *Olea ferruginea* (Khan et al., 2023), with observed shifts of 7.3 days over the past 50 years and 15–21 days over the past century, respectively, as a result of climate change. These findings align with those of Črepinšek et al. (2009), who reported that the timing of phenological stages in fruit trees is primarily temperature-dependent. Similarly, a marked difference in catkin chilling accumulation was observed between cultivars in the two orchards (Fig. 3). This pattern was consistently supported by the two-way ANOVA, which revealed a highly significant effect of environment on all chilling accumulation indices, while no significant effect of year or environment × year interaction was detected (Table 3). These results suggest that, within the studied period, differences between sites were more pronounced than interannual variability. Among the chilling models evaluated, all approaches consistently detected significant differences in winter chill accumulation between the two study sites, as confirmed by ANOVA results. However, the magnitude of the environmental effect differed among models, with higher F-values observed for the chilling hours (CH) and Utah chilling units (CU) compared to the dynamic model (CP), indicating a stronger separation between environments in cumulative approaches. This pattern reflects differences in model formulation and scaling rather than differences in model performance per se. While CH and CU consistently reflected a clear separation between the two sites, with higher chilling accumulation in the colder environment of Chieri compared to Viterbo, the dynamic model (CP) showed a less uniform response. In particular, CP values did not follow a consistent directional pattern across cultivars, with some genotypes exhibiting higher chilling portions in Viterbo and others in Chieri. This non-monotonic behaviour suggests that CP is less driven by the overall magnitude of winter chilling and more influenced by the temporal distribution of temperatures, including the occurrence and timing of warm spells within the season. Consistently, coefficients of variation indicated that variability patterns differed among models and environments, with generally higher CV values observed in Viterbo, particularly for CU and CP, reflecting a greater sensitivity of these approaches to warmer and more fluctuating winter conditions. In contrast, CH showed comparatively more stable variability patterns across sites and cultivars.

Cultivars grown in the warmer environment of Viterbo generally exhibited lower chilling accumulation than those cultivated in Chieri, particularly when estimated using the cumulative CH and CU approaches. This pattern suggests that local site conditions strongly shape the chilling behavior of each cultivar, a phenomenon also reported for *Prunus avium* L. in southern Spain (Alburquerque et al., 2008), where chilling requirements were found to vary with orchard altitude, likely reflecting associated differences in temperature regimes. Similar observations have been made for *Prunus dulcis* Mill. cultivars grown in Australia and Spain (Egea et al., 2003), as well as for *Prunus persica* (L.) Batsch in the Republic of Korea, where shifts in flowering phenology and chilling requirements have been linked to long-term increases in temperature (Kwon et al., 2020). Overall, differences among study sites are better described in terms of local climatic conditions and site-specific environmental characteristics rather than strictly pedological effects. These physiological differences in temperature response may reflect cultivar-specific adaptations to contrasting climatic conditions rather than fixed ecotypic differentiation. While climate is the primary driver of agricultural productivity, affecting both yield and fruit quality (Ghosh and Mandal, 2023), flowering results from a fine-tuned interaction between genetic factors, local pedoclimatic conditions and agronomic practices. Among these, genetic plays a fundamental role in determining key phenological traits. In particular, several QTLs have been reported to control complex traits such as dormancy release and flowering (Valentini et al., 2021; Baytar et al., 2024). Each genotype carries a specific combination of alleles at these loci, resulting in a unique genetic background that determines its classification in early, mid or late flowering group. However, the high number of QTLs involved, together with the complexity of their regulation, may also contribute to differences in phenological responses under contrasting environmental conditions (Črepinšek et al., 2012). Overall, the observed variation in chilling accumulation and flowering phenology across sites appears to be primarily associated with differences in local temperature regimes and seasonal thermal patterns.

The comparison among chilling models highlighted that chill accumulation estimates varied according to both environmental conditions and model structure (Table 2). Comparisons with chilling requirements

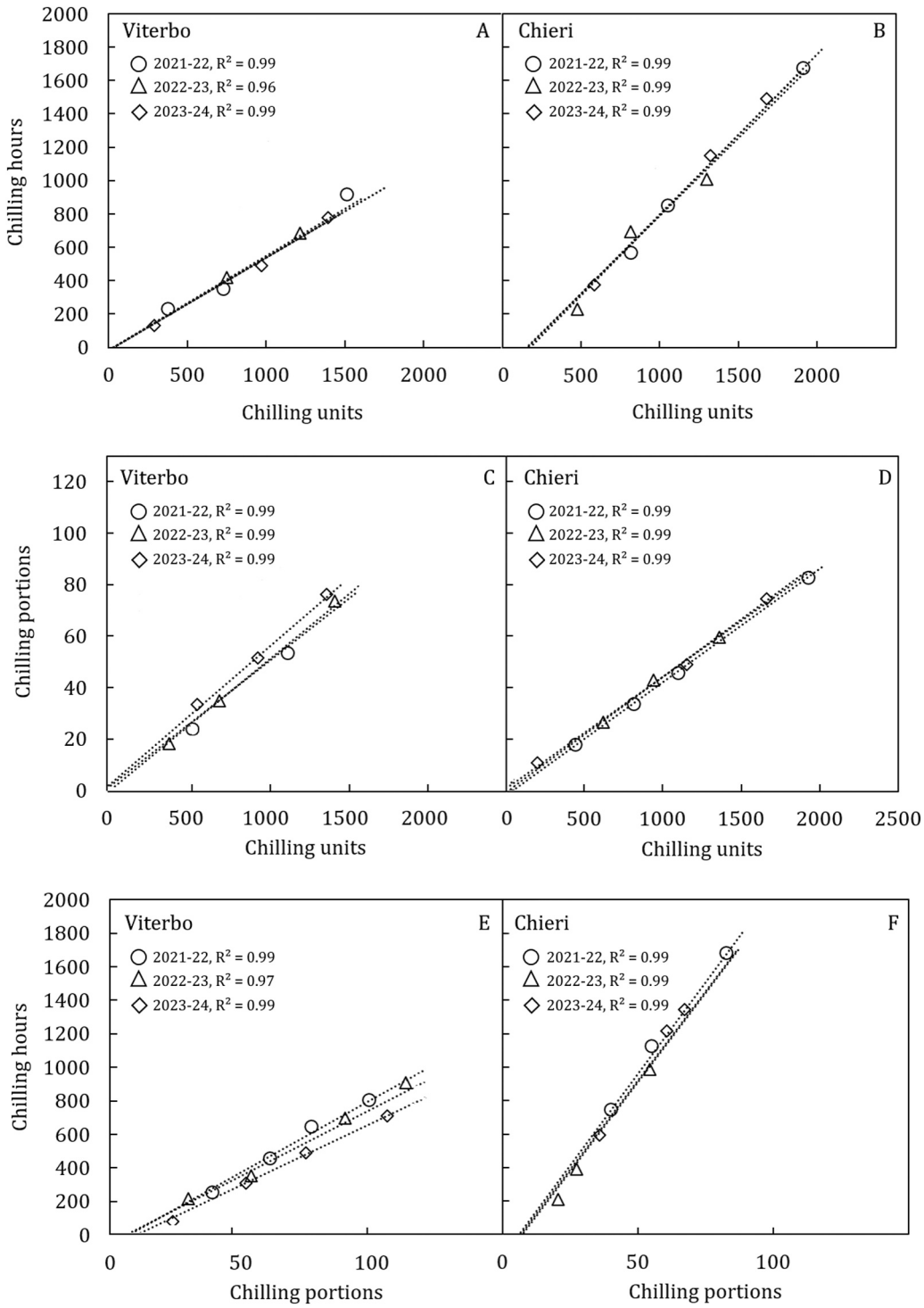

Fig. 6. Correlation between chilling units (UT model), chilling hours (CH model below +7 °C) and chilling portions (dynamic model) in Viterbo (A, C, E) and Chieri (B, D, F) over three seasons (2021–2022, 2022–2023, 2023–2024). Correlations were calculated on seasonal totals of male inflorescences, pooling data from four Italian hazelnut cultivars and one wild type accession.

previously reported for hazelnut cultivars grown in Oregon by Mehlenbacher (1991) further suggest that chilling accumulation is strongly influenced by local climatic conditions and by the specific approach used to quantify winter chill. In particular, cumulative chilling hours (cCH) ranged from approximately 200–315 in Chieri and from 64 to 140 in Viterbo across cultivars and seasons, consistently showing higher values in the colder site. A similar pattern was observed for cCU, which ranged from approximately 1046.5–1414.5 in Chieri and from 605.5 to 1235.5 in Viterbo, also reflecting the lower winter temperatures recorded in the northern site. These differences likely reflect the longer persistence of temperatures within the effective chilling range at the Chieri site (Fig. 2), where winter temperatures remained low for more extended periods during the season. Under these conditions, cumulative models such as CH and CU progressively increased chill accumulation throughout winter, resulting in a clearer separation between the two environments. Once chilling requirements are fulfilled, catkins enter

ecodormancy and remain quiescent until sufficient heat accumulation promotes flowering. Consequently, prolonged exposure to low winter temperatures may continue to contribute to cumulative chilling estimates even after dormancy release processes have largely progressed physiologically.

In contrast, the Dynamic Model revealed a less uniform response across cultivars and environments. Chill portion values ranged from approximately 44.7–60.4 in Chieri and from 30.5 to 62.5 in Viterbo, indicating a weaker and less consistent separation between sites compared with cumulative models. In certain years and for some cultivars, CP values were similar to, or even higher in Viterbo than in Chieri, despite the overall warmer winter conditions of the central Italian site. This pattern likely reflects the greater sensitivity of the Dynamic Model to the temporal distribution of temperatures and to the occurrence of warm spells during winter. Unlike cumulative approaches, CP accumulation is not driven exclusively by the total amount of cold exposure, but also by the sequence and fluctuation of temperatures throughout the season. As a consequence, winters characterized by alternating cold and mild periods may produce chilling dynamics that differ substantially from those described by CH and CU models. Overall, these findings indicate that winter chill accumulation is influenced not only by the overall intensity of winter cold, but also by the seasonal thermal structure, which is differently captured by cumulative and dynamic chilling models.

Rather than identifying a single optimal model, the results highlight that different chilling models capture complementary aspects of winter chill dynamics across contrasting environments. These differences do not indicate variability in the intrinsic genetic chilling requirement of each cultivar, but rather reflect the context-dependent nature of chilling requirement estimation, which is influenced by both the environmental conditions under which dormancy release occurs and the modelling framework used to quantify chill accumulation

5. Conclusions

The results of this study highlight the primary role of environmental conditions in shaping chill accumulation and male flowering dynamics in European hazelnut. The two-way ANOVA consistently showed that the environment significantly affected all chilling indices, while year and environment × year interaction were not significant, indicating stable site-dependent effects across seasons.

Among the evaluated models, cumulative Chilling Hours (CH) and Utah Chilling Units (CU) consistently captured clear differences between sites, reflecting the overall climatic contrast between the two environments. In contrast, the Dynamic Model (CP) captured additional variability associated with temperature fluctuations and warm spells, providing complementary information on the temporal structure of winter temperatures.

Importantly, the results indicate that chilling accumulation values associated with flowering can vary substantially between contrasting environments and modelling approaches, even for the same cultivars when compared with previously reported reference values. This does not imply changes in intrinsic genetic chilling requirements, but rather reflects a plastic phenological response to environmental conditions, in which the expression of dormancy release and flowering is modulated by local climatic regimes and seasonal thermal dynamics.

Overall, the results demonstrate that chilling accumulation is not solely determined by the total amount of winter cold, but is also influenced by the temporal distribution of temperatures, which is differently represented by cumulative and dynamic models. These findings suggest that chilling responses should be interpreted as context-dependent expressions shaped by local climatic conditions and seasonal thermal patterns rather than as fixed cultivar-specific thresholds. These insights may have implications for cultivar selection and orchard management under conditions of increasing climatic variability and ongoing expansion of hazelnut cultivation into new environments.

CRediT authorship contribution statement

Claudio Brandoli: Conceptualization, formal analysis, investigation, writing—original draft preparation, writing—review and editing, visualization, supervision. **Elisabetta Sgarbi:** writing—review and editing, project administration, funding acquisition. **Giovanni Caccialupi:** writing—review and editing, visualization. **Claudio Todeschini:** writing—review and editing. **Valerio Cristofori:** Conceptualization, writing—original draft preparation, writing—review and editing, supervision, funding acquisition.

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Declaration of Competing Interest

This work was financially supported by Ferrero Trading Lux S.A. Author Claudio Todeschini is an employee of Ferrero Trading Lux S.A. The remaining authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128218.

Data Availability

Data will be made available on request.

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