PLANT SCIENCE TODAY
Vol 13(1): 1-15
https://doi.org/10.14719/pst.12994

eISSN 2348-1900

RESEARCH ARTICLE

Adaptation of sweet cherry and apple phenology to temperature variability in Moroccan orchards using forcing tests and chill models

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Received: 28 November 2025; Accepted: 01 January 2026; Available online: Version 1.0: 29 January 2026; Version 2.0: 05 February 2026

Cite this article: Hajjioui H, Kodad O, Erami M, Boukhriss H, Charafi J, Outghouliast H, Abba EH, El Yaacoubi A. Adaptation of sweet cherry and apple phenology to temperature variability in Moroccan orchards using forcing tests and chill models. Plant Science Today. 2026; 13(1): 1-15. https://doi.org/10.14719/pst.12994

Abstract

Rising temperatures in the Mediterranean region threaten fruit trees with high chill requirements, such as sweet cherry and apple by reducing winter chill accumulation, altering phenology and increasing production irregularity. Quantifying cultivar chill/heat requirements is therefore essential to identify cultivars adapted to a particular climate. To assess cultivar adaptation potential by determining the endodormancy release dates and their specific agroclimatic requirements, forcing tests were conducted over three consecutive seasons (2020–2023) on ten sweet cherry and two apple cultivars grown at two major fruit-producing regions in Morocco (Azrou and Imouzzer-Kandar). In addition, the impact of temperature variations on flowering and fruit set rates was evaluated. The results revealed major differences in the dynamic endodormancy release and chill/heat requirements among the studied species/cultivars, these requirements ranged between 662–929 Chill Hours (CH), 432–954 Chill Units (CU), 26.7–56.5 Chill Portions (CP) and 8180–10048 Growing Degree Hours (GDH) for sweet cherry and between 986–1025 CH, 1025–1052 CU, 59.3–61.4 CP and 6982–8617 GDH for apple. Based on these responses, sweet cherry cultivars were classified into three groups: i) low-chill cultivars with variable flowering and reproductive performances, ii) high-chill cultivars with late-flowering and high fruit set and iii) cultivars with balanced chill requirements and moderate flowering performances. In apple, Gala outperformed Top Red in reproductive efficiency. Finally, colder site such Azrou promoted flowering but reduced fruit set, whereas milder Imouzzer-Kandar enhanced vegetative growth and fruit set. Our results provided practical decision support for cultivar selection and site-specific orchard planning under ongoing climate warming.

Keywords: apple; chill/heat requirements; endodormancy release; forcing test; sweet cherry; temperature variation

Introduction

Phenology is a crucial indicator of temperature variation, particularly in temperate fruit species such as apple (*Malus domestica* (Suckow) Borkh.) and sweet cherry (*Prunus avium* L.). These species depend on specific thermal requirements to regulate their developmental stages and any shifts in their amounts can have significant agricultural implications (1). Dormancy processes, especially, play a central role in regulating the seasonal growth cycle of temperate fruit trees. According to the classical framework, bud dormancy can be divided into paradormancy, endodormancy and ecodormancy. Endodormancy, which is characterized by reduced growth and increased resistance to frost and desiccation, is controlled by internal bud factors and represents a critical phase of the dormancy cycle (2). The phenology in temperate fruit trees is regulated by the seasonal temperature fluctuation (3). The chill requirements during winter are critical to overcome dormancy and resume growth in spring (4). However, insufficient chilling, which is increasingly occurring under warmer winter conditions, can lead to delayed bud endodormancy release, poor flowering and reduced fruit set, ultimately threatening yields (5).

The Moroccan fruit sector represents a fundamental pillar of the national economy. Among the main fruit crops, sweet cherry and apple species are predominantly grown in temperate microclimates, such as the Middle Atlas and mountain regions, where environmental conditions are especially favorable for their growth. These crops are vital not only for domestic consumption but also for export, with Moroccan apples and sweet cherries gaining recognition for their quality. Global climate change is considered one of the phenomena with the greatest impact on temperate fruit crop production (6). It has been extensively studied and there is now ample evidence that it is having a significant impact on biological systems around the world (7, 8) including changes in the phenophase timing of fruit trees (9). However, the effect of climate change on phenology is very complex, since spring phases are occurring later in some locations (10). Global warming has significant impacts on the phenology of most fruit trees (11). It could reduce chill availability as was reported (10) and therefore hinder the cultivation of high chill species and affect yield such as for sweet cherries and apples. Such species are heavily reliant on winter chilling to provide sufficient chill requirements to overcome the endodormancy release and induce flowering (12). Studies have shown that inadequate chilling can significantly hinder the reproductive success of these species (13–15). Under warming scenarios, earlier flowering and bud endodormancy release have been observed, which may not align with optimal environmental conditions for fruit development, leading to poor fruit quality and reduced yields (16). For temperate fruit crops in regions like Morocco, where chilling conditions are marginal, these disruptions can be even more pronounced (17). Understanding how different cultivars respond to these environmental changes is crucial to developing effective adaptation strategies. However, during the recent decades, apple and sweet cherries growing areas have experienced significant climate shifts, including rising temperatures and consequently decrease in chilling availability. In fact, 30 Chill Portions may be lost up in the regions of North Africa by 2050 under a moderate warming scenario (18).

In this broader regional context, Morocco represents a particularly vulnerable case due to its Mediterranean climate and the marginal nature of winter chilling conditions in several fruit-growing areas. This climate variability presents challenges such as erratic flowering, poor fruit set and reduced yields, threatening both the economic viability of orchards and fruit quality. Moreover, unpredictable weather patterns complicate orchard management, which depends on specific climatic conditions for optimal fruit production. Despite the growing body of research on the impacts of climate change on fruit trees, there is a lack of detailed information on how apple and sweet cherry cultivars in Morocco respond to climate changes, particularly regarding chilling and endodormancy release. While some studies have examined the chill requirements of temperate fruit species globally, localized research is necessary to address Morocco's specific conditions. This knowledge gap highlights the importance of understanding how different cultivars, especially those with high chill requirements will perform under current and future climate scenarios.

Few studies have focused on characterizing the bud dormancy and growth dynamics of temperate fruit species in temperate and mild growing areas, although this is an appropriate framework for anticipating the adaptation of phenology to future warming climate contexts, which could potentially combine decreases in chill and increases in heat. To date, limited data are available for Moroccan apple and sweet cherry cultivars under variable winter chill conditions. Based on field observations and laboratory experiments, this study aimed to assess the adaptability of apple and sweet cherry cultivars to Moroccan climatic conditions by quantifying cultivar-specific chill and heat requirements and determining endodormancy release dates. We further evaluated cultivar differences in flowering and fruit set across contrasting sites to identify more climate-resilient cultivars and provide practical guidance for cultivar selection and site-specific orchard management under ongoing warming.

Materials and Methods

Sites and plant material

Three sites situated in the Fes-Meknes region, Morocco were investigated in this study: two in Azrou (site A situated at 33°27'00.7"N, 5°11'39.7"W with 1406 m above sea level (a.s.l.) and site B located at 33°25'32.6"N, 5°15'23.6"W with 1165 m a.s.l.) and one in Imouzzer-Kandar (site C located at 33°46'09.9"N, 5°01'41.7"W and 1105 m a.s.l.) (Fig. 1). The experiments were carried out during two consecutive seasons 2020–2021 and 2021–2022 for the sites A and B and during 2021–2022 and 2022–2023 for the site C (Fig. 1).

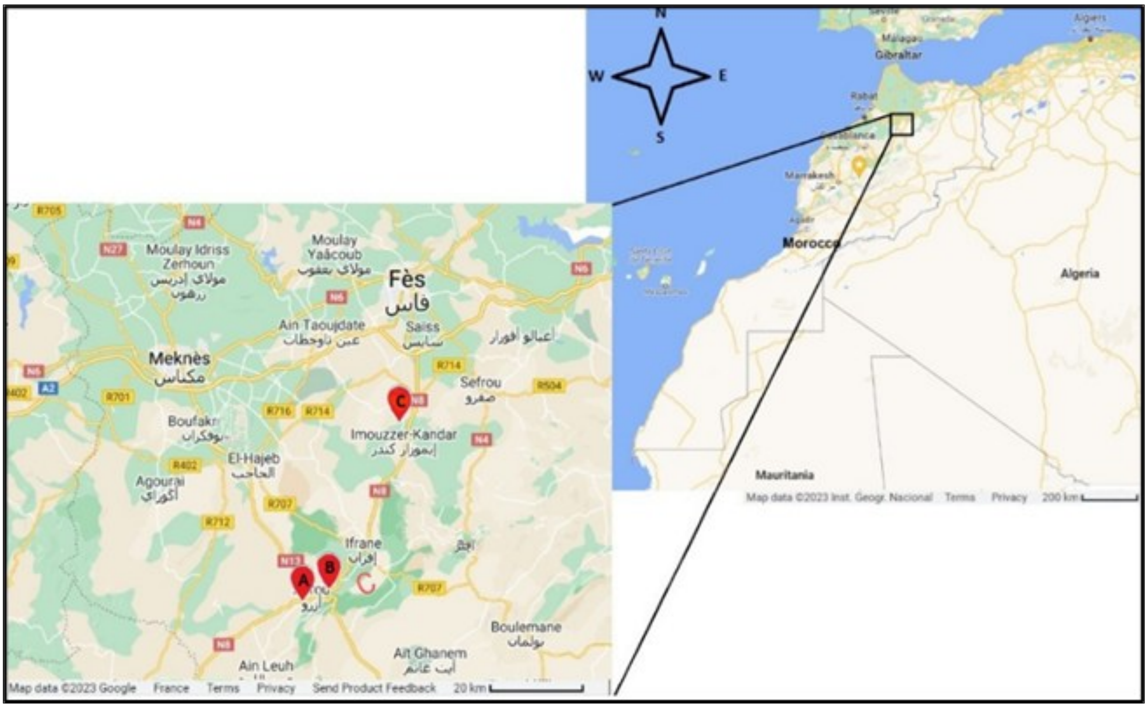

Fig. 1. Geographic localization of the studied sites (A: apple orchard; B and C: sweet cherry orchard).

The study sites were selected to represent contrasting climatic conditions within a Mediterranean context, particularly with respect to winter chill accumulation and seasonal temperature patterns. This climatic gradient provides a relevant framework to evaluate cultivar-specific endodormancy release, phenological development and reproductive performance under conditions representative of both current and projected warming scenarios.

In Azrou, two apple cultivars (Gala and Top Red) were studied at site A. Four sweet cherry cultivars (Bigarreau, Van, Napoleon and Moreau) widely grown in Morocco (19, 20) were investigated at site B and six additional sweet cherry cultivars were evaluated at site C in Imouzzer-Kandar (Lapins, Early Star, Burlat, Big Star, Summit and Kordia). All sweet cherry cultivars were grafted onto Saint-Lucie rootstock in Azrou and onto Maxma 60 rootstock in Imouzzer-Kandar. The trees were planted in loamy-clay soil, irrigated using a drip system and trained according to an open-vase system (Table 1).

Temperature data and phenology monitoring

Temperature data were collected from automatic weather stations of the National Office of Agriculture Advisory (ONCA). For the sites A and B, hourly maximum and minimum temperatures were collected from Azrou weather station located 2 km away from the orchards. For the site C, we used temperature data collected from Ain Chgag weather station located at about 5.5 km away from the sweet cherry orchard. During the three study seasons, shoots were sampled from different sides of the trees, from December to March each year. Flower bud development was assessed regularly. Flowering data were monitored by field observations to register the full flowering date of trees, this phenological stage is achieved when around 50 % of flowers were open (21).

Experimental design

During the three seasons of the study, we used the forcing test on all species and cultivars. Six shoots of 1 year-old of each species/cultivar (with 30–40 cm in length approximately) were sampled periodically (every ten days) from the different sides of trees. The first sample was taken in December and the last one in March of each year. Transferred to laboratory, three of the six collected shoots were immediately used to extract and weight 5 floral buds for each shoot and species/cultivar (5 buds × 3 replications = 15 floral buds in total); the other three shoots were placed in a 5 % sucrose solution in a growth chamber under controlled conditions (at temperature of 24 ± 1 °C and photoperiod of 16 hr and a relative humidity of 70 %). After incubation in the growth chamber for 7 days (after forcing), 5 floral buds for each shoot (5 buds × 3 replications) were similarly extracted and weighed as previously described (before forcing). The B and C phenological stages of the flower buds was also recorded using the methodology proposed by previous researchers (22). The endodormancy release date was established when 30 % of flower buds in forced buds were at Baggiolini's stage B, C and showed a ≥ 30 % increase in fresh bud weight compared with unforced buds. Based on the endodormancy release date, the endodormancy and the ecodormancy phases were determined. The endodormancy phase extending from early October to the endodormancy release date as determined by this forcing-test criterion; while the ecodormancy phase directly followed this period and extended to the observed date of full flowering date observed in field under natural conditions.

Chill and heat requirements

For each species and cultivar, chill requirements for endodormancy release were calculated using three models: 0–7 °C in Chilling Hours (CH), Utah in Chill Unit (CU) and Dynamic in Chill Portion (CP) (23–25). The heat requirements were calculated as the number of Growing Degree Hours (GDHs) with a threshold temperature of 4.5 °C (24). The calculation started from the day following the endodormancy release date determined experimentally by forcing test until the full flowering date (when 50 % of flowers were open) observed in field under natural climate conditions.

Morphological and floral biology parameters

Ten shoots of apple and sweet cherry cultivars were marked from the beginning of flowering to fruit set and used to measure and observe four parameters: length shoot, diameter at the base of the shoot, flowering rate and fruit set rate. Flowering parameters were calculated using the following formulas:

Flowering rate (%) = (Number of buds at full flowering stage × 100)/ Total number of buds

Fruit set rate (%) = (Number of fruit set × 100)/Total number of buds at full flowering stage.

The experimental design included three replications per cultivar per year, considering the limited availability of trees and ensuring adequate representation of phenological variability. Data was analyzed using analysis of variance (ANOVA) to determine the effect of the cultivar and the year on the different studied parameters, using SPSS software. Differences were considered significant at $p \leq 0.05$. The interpretation was combined with ANOVA/ Tukey results and temperature accumulation patterns.

Results

Climatic characteristics of sites

Seasonal temperature patterns

Temperature variation showed differences between the three experimental seasons 2020–2021, 2021–2022 and 2022–2023 (Fig. 2). The temperature highlighted a clear seasonal fluctuation in both Azrou and Imouzzer-Kandar, with decreasing values from October to January followed by a progressive increase toward spring. Azrou tends to have lower minimum temperatures, dropping below 0 °C during winter, while Imouzzer-Kandar showed slightly warmer conditions overall, with higher maximum temperatures particularly during autumn and spring.

Table 1. Studied plant material by site, season and rootstock

Sites	Species	Cultivars	Seasons	Rootstocks
Azrou (Site A)	**Apple**	Gala and Top Red	2020–2021 and 2021–2022	MM106
Azrou (Site B)	**Sweet Cherry**	Bigarreau, Moreau, Napoleon and Van	2020–2021 and 2021–2022	Maxma 60
Imouzzer-Kandar (Site C)	**Sweet Cherry**	Lapins, Early Star, Burlat, Big Star, Summit and Kordia	2021–2022 and 2022–2023	Saint-Lucie

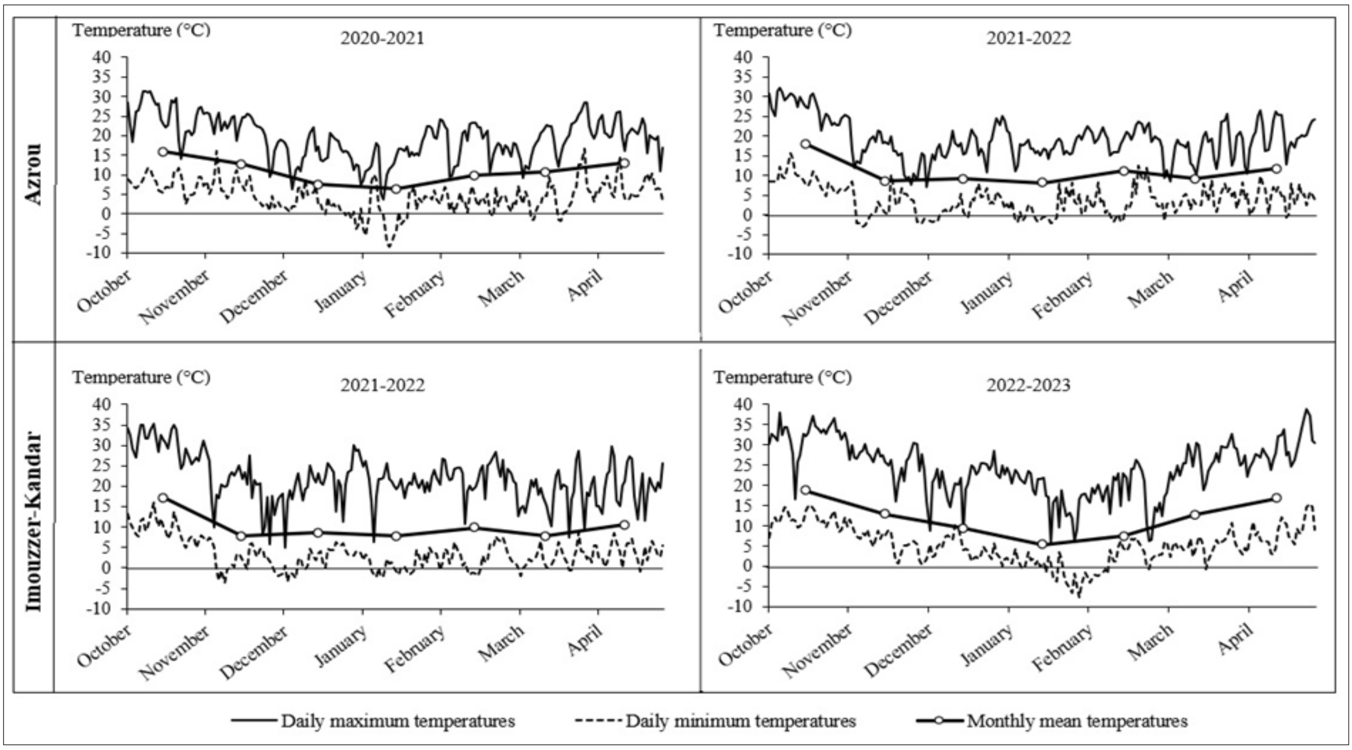

Fig. 2. Daily minimum, maximum and monthly temperature recorded in Azrou and Imouzzer-Kandar during the studied seasons.

Inter-annual variability

Compared to the 2021–2022, 2020–2021 (in Azrou) and 2022–2023 (in Imouzzer-Kandar) seasons were characterized by warmer autumn (October–November), a colder winter (December–February) and warmer spring (March and April) (Fig. 2). In Azrou, the mean daily temperatures during October–November (autumn), December–February (winter) and March–April (spring) were respectively 14.4 ± 3.7 °C, 7.9 ± 3.7 °C and 11.8 ± 3.7 °C in 2020-2021, compared to 13.4 ± 5,6 °C, 9.5 ± 2.9 °C and 10.5 ± 3.3 °C registered during 2021–2022. In Imouzzer-Kandar, these temperatures were respectively 12.6 ± 5.6 °C, 8.7 ± 2.6 °C and 9.1 ± 3.4 °C during 2021–2022, compared with 15.9 ± 3.9 °C, 7. 5 ± 3.2 °C and 14.7 ± 4.1 °C recorded during 2022-2023.

Site-wise comparison

Comparing Azrou and Imouzzer-Kandar during 2021–2022, which is the common season between the studied sites, Azrou was warmer than Imouzzer-Kandar with a mean daily temperatures difference of around 0.7 °C for the first period, 0.8 °C for the second and 1.4 °C for the last one. Considering all three periods, Azrou exhibited higher mean temperatures than Imouzzer, averaging 10.9±4.3 °C compared with 9.9 ± 4.3 °C in Imouzzer. The chill accumulation evolution (from October to March) demonstrated interannual and inter-site variation. In Azrou, chill accumulations according to 0–7 °C, Utah, Dynamic were similar during 2020–2021 and 2021–2022. In Imouzzer -Kandar, chill accumulations were lower than Azrou. They were generally lower in 2022–2023 compared to 2021–2022 (Fig. 2). According to the three chilling models chosen for this study (0–7 °C, Utah and Dynamic), the chill accumulation values recorded during 2021–2022 season were generally higher in Azrou than in Imouzzer-Kandar (Fig. 3). Heat accumulations (GDH) increased steadily from January onwards at both sites, reaching by the end of April about 17210 GDH and 211770 GDH, respectively in Azrou and Imouzzer-Kandar. Values recorded during January–April period were almost similar in Azrou during 2020–2021 and 2021–2022, while they were higher in 2022–2023 in comparison to 2021–2022 season in Imouzzer -Kandar (19226 GDH in versus 21177 GDH in 2022–2023) (Fig. 2).

Flowering and bud endodormancy dynamics

The increase of the fresh weight in forced and unforced flower buds recorded over the three years of the experimentation according to the forcing test is shown in Fig. 4. All dynamics highlighted a general pattern regardless of the site, the cultivar and the year. In each situation, flower bud weights were low during the endodormancy, especially in unforced buds, then they gradually increased until the endodormancy release date determined using forcing test. After this date, the forced flower buds showed considerable weight increase in comparison to unforced ones, exceeding 30 %. For all sweet cherry cultivars tested, the endodormancy release dates occurred later in 2021–2022 than in 2020–2021 (in Azrou) and 2022–2023, except for Lapins, Early Star and Burlat in Imouzzer-Kandar. In Azrou, endodormancy was released between January 4th and January 27th in 2020–2021 and between January 10th and February 21st in 2021–2022. The inter-annual variation in the endodormancy release dates between 2020–2021 and 2021–2022 was lower (6 days) and early (beginning of January) for Bigarreau. However, it was very high (between 25–30 days) and late (late January and beginning of February) for Van, Napoleon and Moreau, emphasizing a high cultivar × year interaction. In Imouzzer-Kandar, it did not change during the two years of experimentation; it happened on January 20th for Lapins and on February 1st for Early Star and Burlat. For the other cultivars, the endodormancy release showed some variation (of 11–12 days) between 2021–2022 and 2022–2023. In average, it was ranged between February 6th (for Big Star and Kordia) and February 16th (for Summit). Comparing sweet cherry cultivars in Azrou, endodormancy release date was earlier for Bigarreau, followed by Van and Napoleon, while it was later for Moreau. However, in Imouzzer-Kandar, it was earlier for Lapins, later for Summit and intermediate for Early Star, Burlat, Big Star and Kordia. Regarding the full flowering dates in Azrou, Moreau and Van cultivars showed earlier flowering in 2020–2021 than in 2021–2022, in comparison to Bigarreau which was late while it was constant for Napoleon. Overall, the full flowering occurred in late March/early April for sweet cherry cultivars in both sites (Table 2). In average, sweet cherries in Azrou flowered earlier than apples, with early

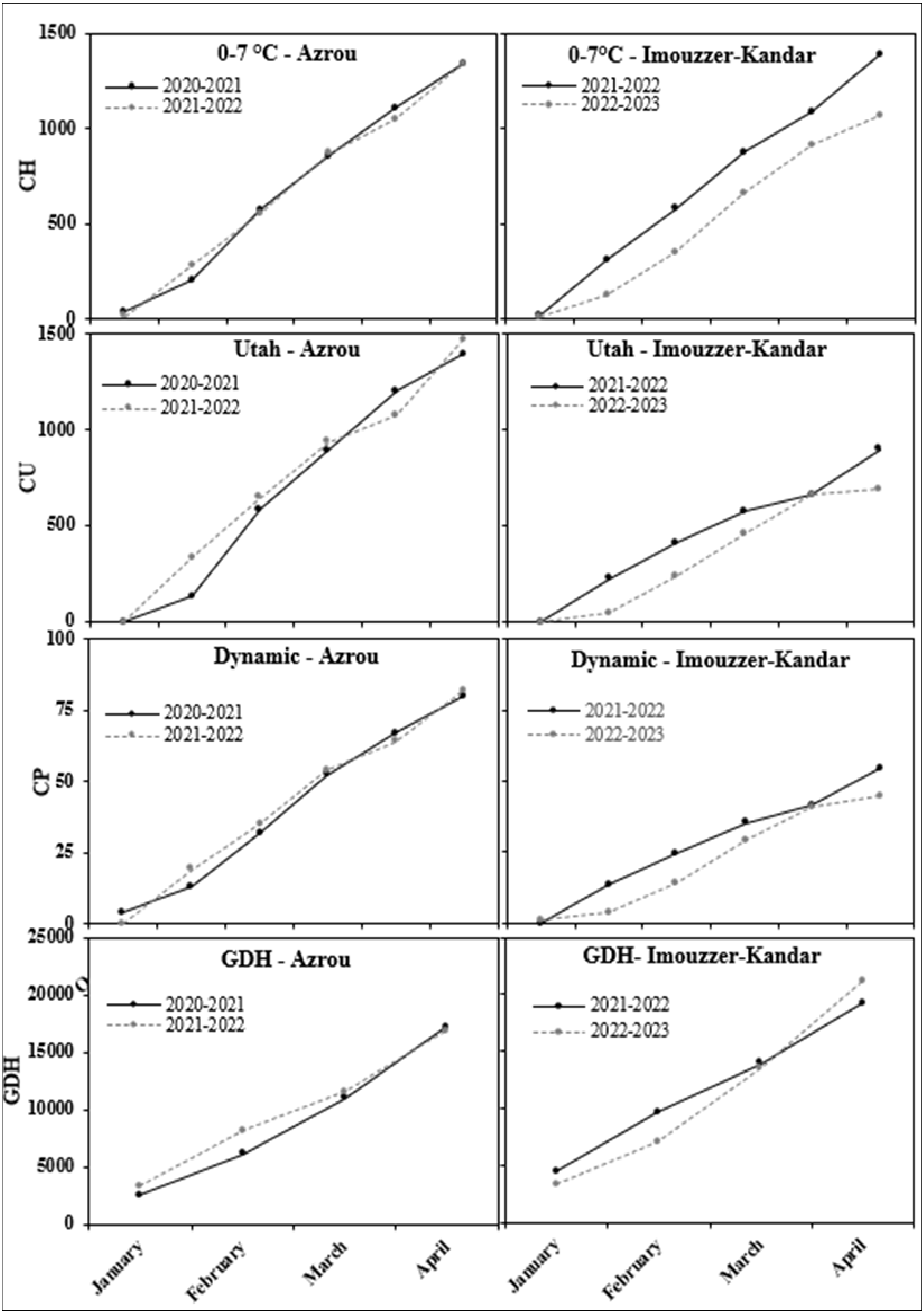

Fig. 3. Chill and heat accumulations recorded in Azrou and Imouzzer-Kandar during the years studied according to 0–7 °C, Utah, Dynamic and GDH models.

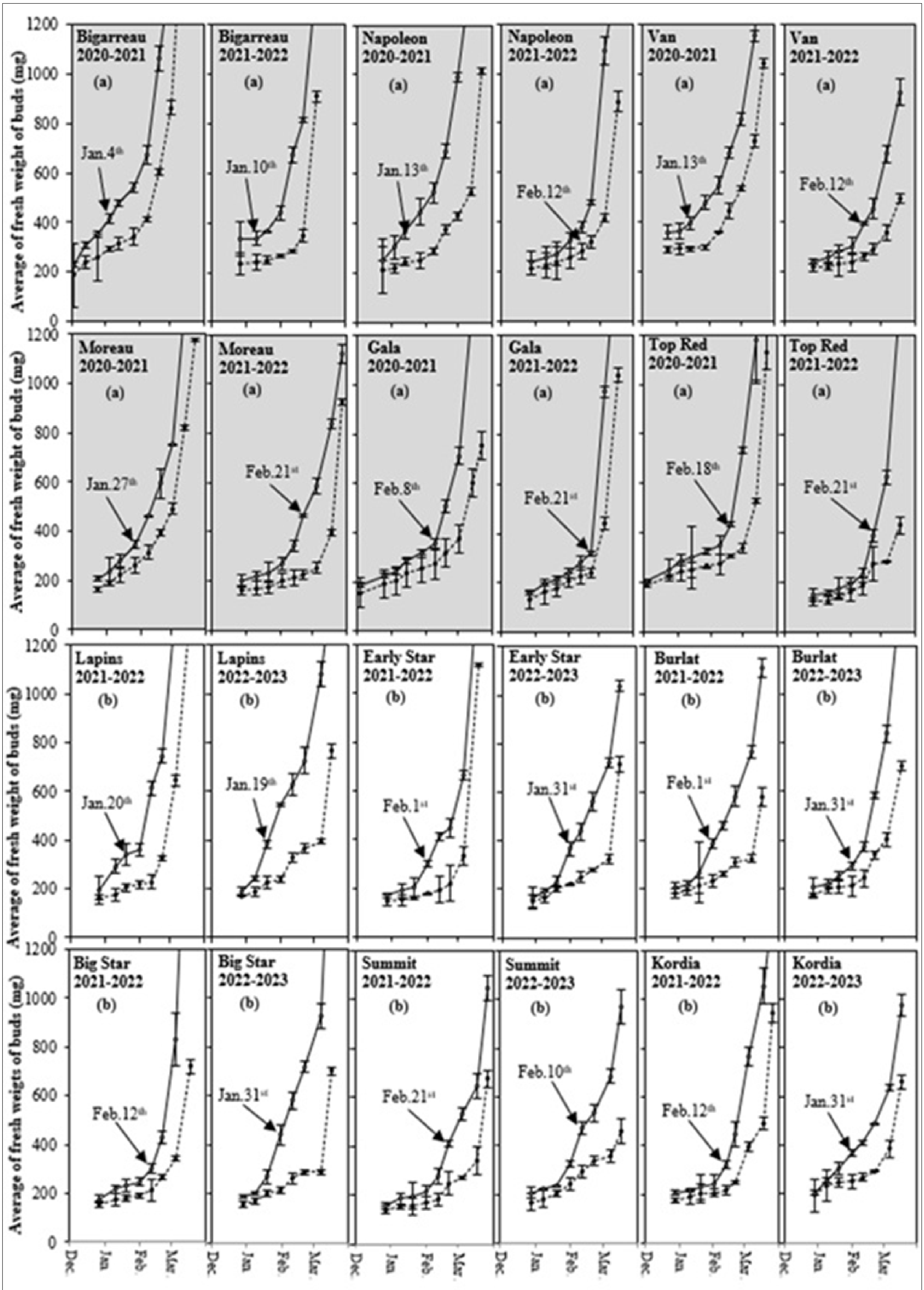

Fig. 4. Average of fresh weight of unforced (discontinued lines) and forced (continued lines) flower buds recorded for apple and sweet cherries in Azrou (a) and Imouzzer-Kandar (b) during the studied seasons. Arrows indicate the date of endodormancy release; bars represent the standard errors.

cultivars such as Bigarreau flowering in late March and later cultivars like Moreau and Van flowering in early April. Regardless of the cultivars, sweet cherries in Imouzzer-Kandar generally flowered earlier than in Azrou. Early cultivars such as Lapins and Burlat flowered around March 22–26th, while later ones like Kordia and Big Star flowered in early April. For apples in Azrou, the endodormancy release occurred earlier in 2020–2021 than in 2021–2022; it happened on February regardless of the seasons and the cultivars. Comparing cultivars, it was earlier for Gala compared with Top Red. The higher chill and heat requirements of apples delayed their flowering, which typically occurred in April (early April for Gala and mid-April for Top Red) (Table 2).

Overall, flower bud fresh weight increased gradually during endodormancy and rose sharply after endodormancy release, particularly in forced buds. Endodormancy release and flowering dates showed marked inter-annual, site and cultivar variability in sweet cherry, with earlier flowering in Imouzzer-Kandar than in Azrou. Apple cultivars exhibited later endodormancy release and flowering compared to sweet cherry due to higher chill and heat requirements.

Table 2. Endodormancy release and full flowering dates, chill and heat requirements of apple and sweet cherry cultivars recorded in Azrou and Imouzzer-Kandar during the studied years. Values between bracket in (1) represent the endodormancy durations while in (2) represents the ecodormancy durations

Species / Cultivar	Season	Chill requirements				Heat requirements	Full flowering date and ecodormancy duration(2)
		Endodormancy release date and duration (1)	0–7 °C (CH)	Utah (CU)	Dynamic (CP)	GDH	
Apple (Azrou)							
	2020/2021	February 8th (131)	937	997	55.8	7997	April 2nd (53)
Gala	2021/2022	February 21st (144)	1034	1052	62.8	5967	April 8th (46)
	Average	**February 15th (138)**	**986**	**1025**	**59.3**	**6982**	**April 5th (50)**
	2020/2021	February 18th (141)	1015	1052	60.0	8968	April 14th (55)
Top Red	2021/2022	February 21st (144)	1034	1052	62.8	8266	April 20th (58)
	Average	February **20th (143)**	**1025**	**1052**	**61.4**	**8617**	**April 17th (57)**
Sweet cherry (Azrou)							
	2020/2021	January 4th (96)	640	635.5	35.7	9004	March 25th (80)
Bigarreau	2021/2022	January 10th (102)	684	757.5	41.5	8921	March 18th (67)
	Average	**January 7th (99)**	**662**	**697**	**38.6**	**8963**	**March 20th (74)**
	2020/2021	January 27th (119)	823	855	50.2	10084	April 5th (68)
Moreau	2021/2022	February 21st (144)	1034	1052	62.8	6277	April 9th (47)
	Average	**February 9st (132)**	**929**	**954**	**56.5**	**8180**	**April 7th (58)**
	2020/2021	January 13th (105)	713	713	41.8	10947	April 3rd (80)
Napoleon	2021/2022	February 12th (135)	981	1024	59.3	6903	April 3rd (50)
	Average	**January 28th (120)**	**847**	**869**	**50.5**	**8925**	**April 3rd (65)**
	2020/2021	January 13th (105)	713	713	41.8	10947	April 3rd (80)
Van	2021/2022	February 12th (135)	981	1,024	59.3	7955	April 9th (56)
	Average	**January 28th (120)**	**847**	**869**	**50.5**	**9451**	**April 6th (68)**
Sweet cherry (Imouzzer-Kandar)							
	2021/2022	January 20th (112)	778	508	32.3	9557	March 20th (59)
Lapins	2022/2023	January 19th (111)	559	356	21.1	9294	March 24th (64)
	Average	**January 20th (112)**	**669**	**432**	**26.7**	**9425**	**March 22th (62)**
	2021/2022	February 1st (124)	887	575	36.1	8241	March 25th (52)
Early Star	2022/2023	January 31st (123)	662	460	29.0	8806	March 25th (53)
	Average	**February 1st (124)**	**775**	**517**	**32.6**	**8524**	**March 25th (53)**
	2021/2022	February 1st (124)	887	575	36.1	8393	March 26th (53)
Burlat	2022/2023	January 31st (123)	662	460	29.0	8806	March 25th (53)
	Average	February **1st (124)**	**775**	**517**	**32.6**	**8600**	**March 26th (53)**
	2021/2022	February 12th (135)	984	628	37.6	7,987	April 4th (51)
Big Star	2022/2023	January 31st (123)	662	460	29.0	10235	March 31st (59)
	Average	**February 6th (129)**	**823**	**544**	**33.3**	**9111**	**April 2nd (55)**
	2021/2022	February 21st (144)	1,061	658	41.1	9363	April 20th (58)
Summit	2022/2023	February 10th (133)	744	522	33.1	10121	April 4th (53)
	Average	**February 16th (139)**	**903**	**590**	**37.1**	**9742**	**April 12th (56)**
	2021/2022	February 12th (135)	984	628	37.6	9398	April 12th (59)
Kordia	2022/2023	January 31st (123)	662	460	29.0	10699	April 2nd (61)
	Average	**February 6th (129)**	**823**	**544**	**33.3**	**10048**	**April 7th (60)**

Chill and heat requirements

For all studied cultivars, we considered October 1st to be the approximate start date of chill accumulation and the beginning of the endodormancy period, which lasts until the endodormancy release date determined using the forcing test. The day after this date, the ecodormancy period begins and lasts until the full flowering dates observed in field (Fig. 3).

In Azrou, sweet cherry cultivars required considerably less chill than apples, ranging in average from 662–929 CH, 697–954 CU and 38.6–56.5 CP (986–1025 CH, 1025–1052 CU and 59.3–61.4 CP for apples). This displayed notable variability among species and cultivars. During the two years of the study, the endodormancy period in sweet cherry was shortest for Bigarreau (average of 99 days) and longest for Moreau (average of 132 days), while Napoleon and Van were intermediate (average of 120 days). Bigarreau recorded the lowest chill requirements, while Moreau recorded higher chill requirements in both seasons. The ecodormancy period was longer in 2020–2021 than in 2021–2022, the average duration of the ecodormancy period was between 58 (for Moreau) and 74 days (for Bigarreau). The highest heat accumulation was recorded for Van with an average of 9451 GDH, while Moreau recorded the lowest heat accumulation with 8180 GDH on average. Despite lower chill requirements than apples, some cherry cultivars required substantial heat to achieve flowering.

Apple cultivars grown in Azrou, such as Gala and Top Red, exhibited high chill requirements. On average, they required about 1025 CH, 1052 CU and approximately 61 CP, with endodormancy release occurring relatively late, around mid- to late February. The shortest endodormancy period (138 days on average) was recorded for Gala, while Top Red recorded the longest (143 days on average). In average, Top Red showed high chill requirements in comparison to Gala. The average duration of the ecodormancy period was between 50 (in Gala) and 57 days (in Top Red) and the highest heat accumulation was recorded for Top Red with an average of 8617 GDH; Gala recorded the lowest heat accumulation with 6982 GDH on average.

In Imouzzer-Knadar, endodormancy was shortest for Lapins (average of 112 days), longest for Summit (average of 139 days) and intermediate for Early Star, Burlat, Big Star and Kordia (from 124 to 129 on average). In terms of the accumulated chill requirements for each cultivar during the studied period, a variation was observed between the years. Sweet cherry cultivars required even less chill, with endodormancy release from mid-January to mid-February. In average, the estimated chill requirements were between 669–903 CH, 432–590 CU and 26.7–37.1 CP. Lapins cultivar recorded the lowest chill requirements, while Summit recorded higher chill requirements in both seasons. For Lapins, Big Star and Kordia cultivars, the ecodormancy period was longer in 2022–2023 than in 2021–2022, in comparison to Summit. Early Star and Burlat had almost the same values during both seasons (52–53 days). The average duration of the ecodormancy period was between 53 (in Early Star and Burlat) and 62 days (in Lapins). The calculated values of heat requirements were between 7987 and 9557 GDH in 2021–2022 and ranged from 8806 to 10699 GDH in 2022–2023. In average, higher heat requirements were recorded by Kordia with 10048 GDH, whereas Early Star recorded the lowest heat requirements with 8524 GDH.

Overall, In Azrou, sweet cherry cultivars had lower chill requirements than apples but showed clear cultivar variability, with Bigarreau requiring the least chill and Moreau the most, while heat requirements remained substantial for some cultivars. Apple cultivars (Gala and Top Red) exhibited consistently higher chill requirements and later endodormancy release (mid-late February) with cultivar differences in both chill and heat. In Imouzzer-Kandar, sweet cherry required even less chill overall, with Lapins showing the lowest chill requirements and Summit the highest and heat requirements varying markedly between cultivars and years.

Morphological and floral biology parameters

Among sweet cherries cultivars grown in Azrou, Napoleon stands out for its balanced performance, with a moderately thick shoot base (8.2 mm), relatively long shoots (33.9 cm), high flowering rate (79 %) and high fruit set rate (48 %) (Table 3). Moreau showed low basal diameters (7.4 mm) and moderate shoot lengths (33.2 cm), with low flowering rates (75 %) and fruit set rate (32 %). Van, despite its good shoot length (34.5 cm) and relatively high flowering rate (78 %) showed the lowest reproductive success, with fruit set rate of 32 %. For apple trees, cultivars showed robust vegetative growth, with Top Red having the thickest shoots (10 mm) and longest shoots (64.2 cm) compared with Gala (9 mm diameter, 51.1 cm shoot length). This latter, however, displayed a higher reproductive performance, with a flowering rate averaging around 68 % and a fruit set rate of about 59 %, compared to Top Red's 64 % flowering and 20 % fruit set. Overall, sweet cherries in Azrou invested less in vegetative growth than apples but generally flowered abundantly.

In Imouzzer-Kandar site, sweet cherries displayed stronger vegetative growth and slightly better reproductive performance than in Azrou. Lapins showed good vegetative vigor and reproductive success, with large shoot diameters (9.5 mm), long shoots (50.8 cm), high flowering (74 %) and fruit set (49 %) rates. Big Star combined good vegetative growth (10.3 mm diameter, 48.9 cm shoots) with balanced reproductive traits (68 % flowering and 44 % fruit set). Early star and Big Star showed low reproductive parameters, 64–68 % of flowering rate and fruit set rate of 45–44 % respectively, despite the relatively high values in shoot diameter (9.6–10.3 mm) and shoot length (38–48 cm). Based on the morphological and reproductive parameters presented in Table 3, the cultivars can be broadly grouped according to defining performance thresholds. Cultivars with balanced vegetative and reproductive performances (e.g., Lapins), cultivars with high vegetative vigor but moderate reproductive efficiency as observed for Big Star and cultivars with lower reproductive performance, vegetative growth and adequate flowering levels (e.g., Moreau). These thresholds provide a practical framework for distinguishing cultivar performance groups and support site-specific cultivar selection.

Considering the effect of the year and the cultivar on the previous vegetative and reproductive measured for sweet cherries grown in Azrou, cultivar effects were highly significant for shoot diameter (p = 0.019), shoot length and fruit set rate (p = 0.000) (Table 4). This reflected the marked variability in vegetative vigor and reproductive efficiency among cultivars such as Napoleon, Van and Bigarreau. The strong cultivar effect on shoot growth suggested that inherent genetic differences largely determine tree architecture. On the other hand, year-to-year variation was significant for both flowering rate and fruit set rate only. These findings underline the

Table 3. Average diameter at the base of shoot, shoot length, rate of flowering and fruit set of the cultivars studied during 2020–2021, 2021–2022 and 2022–2023 in Azrou and Imouzzer-Kandar

Species/Cultivar	Season	Diameter at the base (mm)	Shoot length (cm)	Flowering rate (%)	Fruit set rate (%)
Apple (Azrou)					
	2020/2021	9.3 ± 0.7	55.7 ± 17.9	63 ± 20 %	50 ± 9 %
Gala	2021/2022	9.0 ± 1.7	46.5 ± 14.2	72 ± 21 %	69 ± 24 %
	Average	**9.2**	**51.1**	**68 %**	**59 %**
	2020/2021	10 ± 1.4	65.3 ± 13.6	60 ± 16 %	18 ± 10 %
Top Red	2021/2022	10 ± 1.2	63.1 ± 21	68 ± 20 %	22 ± 8 %
	Average	**10**	**64.2**	**64 %**	**20 %**
Sweet Cherry (Azrou)					
	2020/2021	8.1 ± 1	23.7 ± 3.1	79 ± 13 %	35 ± 11 %
Bigarreau	2021/2022	8.1 ± 1.2	24.0 ± 4	83 ± 15 %	44 ± 15 %
	Average	**8.1**	**23.9**	**81 %**	**39 %**
	2020/2021	7.5 ± 0.6	33.7 ± 7.8	71 ±13 %	28 ± 11 %
Moreau	2021/2022	7.2 ± 0.9	32.7 ± 7.4	79 ± 9 %	37 ± 6 %
	Average	**7.4**	**33.2**	**75 %**	**32 %**
	2020/2021	8.2 ± 1	29.9 ±7.4	76 ± 15 %	39 ± 9 %
Napoleon	2021/2022	8.3 ± 0.8	37.8 ± 5.7	82 ± 18 %	57 ± 9 %
	Average	**8.2**	**33.9**	**79 %**	**48 %**
	2020/2021	7.4 ± 1.3	36.2 ± 7.5	70 ± 15 %	29 ± 9 %
Van	2021/2022	7.7 ± 1.2	32.7 ± 8.1	86 ± 20 %	35 ± 17 %
	Average	**7.5**	**34.5**	**78 %**	**32 %**
Sweet Cherry (Imouzzer-Kandar)					
	2021/2022	9.6 ± 1.2	50.4 ± 7.4	78 ± 11 %	57 ± 19 %
Lapins	2022/2023	9.4 ± 1.2	51.2 ± 11.2	69 ± 12 %	41 ± 25 %
	Average	**9.5**	**50.8**	**74 %**	**49 %**
	2021/2022	9.2 ± 1.4	36.1 ± 6.3	69 ± 19 %	56 ± 11 %
Early Star	2022/2023	10.0 ± 1.8	39.8 ± 11.1	59 ± 22 %	34 ± 15 %
	Average	**9.6**	**38.0**	**64 %**	**45 %**
	2021/2022	7.6 ± 1.1	36.1 ± 8.8	70 ± 12 %	60 ± 12 %
Burlat	2022/2023	8.7 ± 2.3	35.8 ± 8	61 ± 12 %	38 ± 15 %
	Average	**8.2**	**36.0**	**66 %**	**49 %**
	2021/2022	10.3 ± 1.5	48.4 ± 11.5	72 ± 15 %	48 ± 29 %
Big Star	2022/2023	10.3 ± 2	49.4 ± 9.4	65 ± 20 %	39 ± 23 %
	Average	**10.3**	**48.9**	**68 %**	**44 %**
	2021/2022	9.0 ± 1.1	37.9 ± 8.6	72 ± 10 %	54 ± 17 %
Summit	2022/2023	9.1 ± 1.3	38.9 ± 8.5	64 ± 18 %	46 ± 13 %
	Average	**9.1**	**38.4**	**68 %**	**50 %**
	2021/2022	8.3 ± 0.9	43.0 ± 12.1	76 ± 15 %	49 ± 15 %
Kordia	2022/2023	8.0 ± 1.1	42.6 ± 16.3	68 ± 19 %	43 ± 13 %
	Average	**8.1**	**42.8**	**72 %**	**46 %**

Table 4. Signification of the effect of the year and the cultivar on length, diameter at the base, flowering rate and fruit set rate, obtained using the ANOVA test

Species/Site	Diameter at the base (mm)	Shoot length (cm)	Flowering rate (%)	Fruit set rate (%)
Apple				
Cultivar	**0.047**	**0.020**	0.241	**0.000**
Year	0.646	0.295	0.470	**0.005**
Sweet Cherry (Azrou)				
Cultivar	**0.019**	**0.000**	0.691	**0.000**
Year	0.861	0.534	**0.024**	**0.000**
Sweet Cherry (Imouzzer Kandar)				
Cultivar	**0.000**	**0.000**	0.159	0.856
Year	0.297	0.607	**0.016**	**0.000**

sensitivity of reproductive processes in cherries to environmental fluctuations, particularly temperature during floral development and pollination. Thus, while vegetative traits are cultivar-driven, reproductive success in Azrou cherries is strongly affected by annual climatic variation. In apples, cultivar differences significantly influenced shoot diameter (p = 0.047), shoot length (0.020) and fruit set rate (p = 0.000), indicating that genetic variability between Gala and Top Red was decisive for these traits. Gala's higher reproductive efficiency (greater fruit set) can thus be attributed to its genetic predisposition rather than environmental factors. In contrast, year-to-year variation significantly affected fruit set rate but not shoot diameter, shoot length or flowering rate. This suggested that annual climatic conditions mainly influenced the ability of flowers to set fruit rather than vegetative growth. The relatively stable flowering rates across years highlighted the genetic control of floral induction in apples.

In Imouzzer-Kandar, cultivar effects were highly significant for shoot diameter and shoot length (p = 0.000), demonstrating again that genetic differences among cultivars (e.g., Lapins, Big Star and Kordia) strongly governed vegetative vigor in that site. However, year effects were significant for flowering (p = 0.016) and fruit set rates (p = 0.000), while cultivar effects were not significant for these traits. This pattern showed that, in Imouzzer-Kandar, the reproductive traits of sweet cherries were more dependent on inter-annual temperature variations during bud endodormancy and flowering than on genetic differences between cultivars.

Based on the average of chill requirements, endodormancy release dates, flowering dates, flowering rate and fruit set rate measured among sweet cherry cultivars, the results enabled us to identify three distinct groups (Fig. 5). This grouping directly addresses our objectives by synthesizing cultivar chill sensitivity and providing an adaptation-oriented assessment of cultivar suitability under Moroccan conditions. The first group, consisting of the earliest flowering cultivars (Bigarreau and Lapins), is characterized by lower chill requirements, short and early endo-dormancy release. In fact, Bigarreau revealed high flowering rate but low fruit set while Lapins demonstrated moderate flowering rate and high fruit set, suggesting better suitability for warmer or chill-limited conditions where stable fruit set is critical for adaptation. The second group, which included Moreau and Summit cultivars, showed the highest chill requirements, longer and late endo-dormancy release and late flowering date. Both two cultivacultivarsghted an increased fruit set rate, indicating good performance in colder sites but higher vulnerability to winter warming (risk of chilling deficits). Whereas the third group, considered intermediate, consisted of the remaining cultivars (Napoleon, Van, Early Star, Burlat, Big Star and Kordia), which displayed moderate chill requirements and intermediate endodormancy release and mid-season flowering dates. In this last group, Kordia showed the highest flowering rate and fruit set rate, supporting intermediate cultivars as potentially resilient options across variable site × year conditions (Fig. 5).

Discussion

The endodormancy release dates, chill and heat requirements of ten sweet cherry and two apple cultivars were examined in this study. Forcing test experiments were carried out over three seasons in two different Moroccan sites, 2020–2021 (in Azrou only), 2021–2022 (in Azrou and Imouzzer Kandar) and 2022–2023 (in Imouzzer Kandar only). The experiments consisted in monitoring increasing weight of flower buds using forcing tests under controlled climate conditions. Several analyses have provided ample evidence of winter chill importance for endodormancy release in deciduous fruit trees and have also highlighted the need for subsequent heat accumulation to complete bud development (26, 27). In this discussion, we therefore distinguish the role of winter chilling in controlling endodormancy release from the role of spring heat in driving bud development toward flowering. Importantly, our results also highlight pronounced cultivar × site × year interactions, indicating that phenological responses depend jointly on genetic background, local climate and inter-annual temperature variability. These findings provide a basis for developing practical recommendations for cultivar choice and orchard management under current and future climatic conditions.

Our results indicated that Azrou experienced cold winters, which may help fulfill chill requirements more consistently but also increases the risk of late spring frost events affecting sensitive phenological stages. Imouzzer-Kandar, on the other hand, is comparatively milder, but this warmth may reduce chill accumulation in warmer years. The few studies that have been carried out on the chill and heat requirements of apple and sweet cherry in relation to dormancy have been limited to analyses of long-term phenological data using statistical approaches and modeling (1, 28–31).

The period between the endodormancy release dates, determined using the evolution of fresh bud weights corresponds to the transition period between endodormancy and ecodormancy, when important metabolic changes occur in the buds, such as vascular differentiation and changes in carbohydrate content (32). This period as well as the ecodormancy are traditionally determined

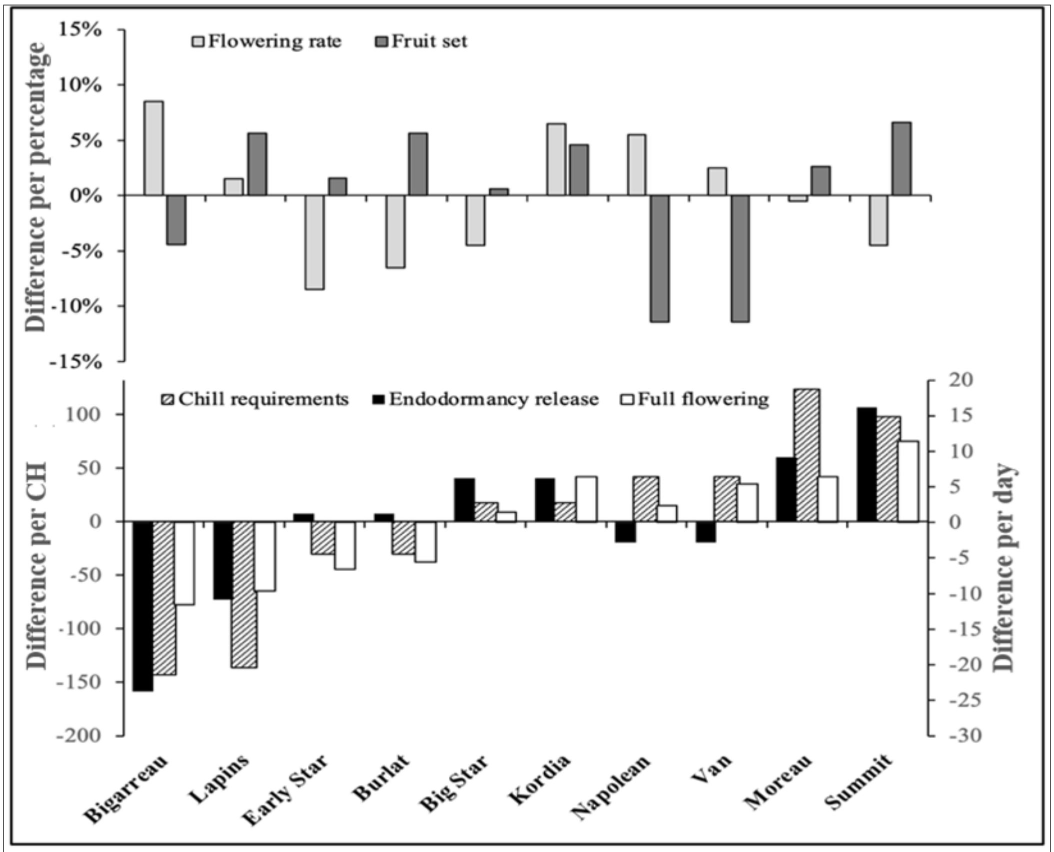

Fig. 5. Classification of sweet cherry cultivars according to the difference in the average of chill requirements (using 0–7 °C model), endodormancy release dates, full flowering dates, flowering rate and fruit set rate.

experimentally, based on shoots collected during the winter after different periods of exposure to low temperature in the field (11). Endodormancy is released when flower buds show an increase in weight (33, 34). We used the same setup on apple and sweet cherry to evaluate phenological behavior of these species in response to temperature variation. Our findings demonstrated that the significant increase in flower bud weight occurred after the accumulation of chill units recorded during the endodormancy phase, inducing bud growth, whereas the accumulated heat units were needed to achieve the flowering period. This latter is crucial for the survival of trees in temperate climates and is regulated by the duration of bud endodormancy (33). Physiologically, cultivars with lower chilling requirements and/or a shallower endodormancy can resume metabolic activity earlier (rehydration, vascular differentiation, carbohydrate mobilization), leading to earlier bud growth and flowering, whereas high-chill cultivars maintain deeper dormancy longer and require more consistent winter cold to synchronize bud break (3, 31).

Forcing tests showed that the first increases in fresh weight could therefore correspond to a period of rehydration of the flower primordia by cell transport and parietal pathways, given that the vascular system is not differentiated at this time. The endodormancy period does not end all at once, there is a gradual transition from endodormancy to ecodormancy that varies between species and cultivars (35). This transition from endodormancy to ecodormancy is strongly linked to the cold and heat of the current season, as reported in previous studies showing the importance of synchronizing chill and heat requirements to determine the phenology of cherry trees and apple (4). This synchronization indicates that insufficient chilling can increase reliance on heat accumulation, whereas sufficient chilling allows a more regular response to spring warming.

In our study, the three years of experimentation showed clear inter-annual difference in the distribution of chill accumulations from October to March, even though total chill accumulation differed only moderately among seasons. In Azrou, the 2020–2021 season was characterized by a colder winter (7.9 °C) compared to 2021–2022 (9.5 °C), resulting in fast sufficient chill accumulation for all studied apple and sweet cherries cultivars and consequently an early endodormancy release. The warm spring (March–April) registered during 2020–2021 (11.8 °C) in comparison to 2021–2022 (10.5 °C) accelerated the heat accumulation, resulting in early flowering time as the endodormancy release was achieved earlier. A similar pattern was observed in Imouzzer-Kandar during 2022–2023, particularly for Big Star, Summit and Kordia, which showed earlier dormancy release and flowering under a combination of colder winter and warmer spring conditions. This explains the important role of months from December to February in achieving chill accumulations in both sites. However, slight difference was also observed regarding the sensitivity of cultivars to temperature in each location. This could be explained by the intensity of temperatures characterizing each site, inducing deeper/ weak dormancy of flower buds. This notion of cold temperature intensity and acclimatization has been reported previously (36). This confirms that the endodormancy release and flowering dates are strongly linked to the year and the synchronization of balanced temperatures recorded in winter and spring, resulting in stimulation of cultivar endodormancy release and enter into the ecodormancy period after adequate chill accumulation. This was observed in both seasons, 2020–2021 for Azrou and 2022–2023 for Imouzzer-Kandar. On the other hand, within Azrou, intra-specific variability among sweet cherry cultivars was evident, consistent with reported genetic variability in chill requirements (4, 37). For example, Bigarreau which had the earliest dormancy release date and short endodormancy period, had the longest duration of ecodormancy, in contrast Moreau which had the latest endodormancy release date (long endodormancy) and the shortest ecodormancy duration. These variations were linked to the ability of cultivars to accumulate enough chill to initiate endodormancy release and the rate of heat accumulation needed to stimulate flowering (33). Such opposite cultivar behaviors across seasons indicate a marked cultivar × year interaction in dormancy dynamics. The synchronization between the phenological stages, particularly endodormancy release and flowering and the subsequent vegetative development plays an important role in determining vigor of temperate fruit tree species and overall, the orchard performance. When this synchronization is disrupted, trees may allocate resources preferentially to either vegetative growth or reproductive development, resulting in a trade-off between shoot growth, flowering intensity and fruit set. From a practical perspective, this highlights the need to select cultivars with dormancy and flowering characteristics that are well adapted to local climatic conditions in order to ensure stable productivity.

In addition, lack of winter chill can induce delayed, irregular or incomplete endodormancy release, affecting directly the endodormancy release, shoot growth and the establishment of the leaf canopy during spring period. When these phenological events are not properly synchronized because of temperature fluctuations from year to year, vegetative performance is often compromised, resulting in decreased shoot elongation, reduced leaf development and an imbalanced function between vegetative and reproductive process (27). Nevertheless, some cultivars behaved very similarly in terms of chill requirements and flowering dates, as is the case for Van and Napoleon (and slightly Moreau) in Azrou and Early Star and Burlat in Imouzzer-Kandar. In fact, phenological synchronization constitute a good trait to promote inter-pollination between cultivars. This observation is consistent with study conducted on sweet cherry who provided a genetic database necessary to assess compatibility among sweet cherry cultivars, thus ensuring effective cross-compatibility between the cultivars Van and Napoleon when their flowering periods overlap (38). In Imouzzer-Kandar, we also found a difference in the dynamics of endodormancy release between some cultivars, which was earlier for Lapins, later for Summit and intermediate for Early Star, Burlat, Big Star and Kordia. This induced a considerable difference in chill requirements between Lapins and Summit, reaching 10.4 CP on average. This value was high than results obtained using the Partial Least Square (PLS) regression for the same cultivars grown in Zaragoza (Northeastern Spain), where it was observed that the chill requirement of Summit is higher than that of Lapins by only 1.2 CP (30). This suggests that one or both cultivars are sensitive to environmental conditions, even if the method used can also influence the result obtained. Given that Lapins and Summit did not show a large difference in chill accumulation between the study seasons (11.2 CP for Lapins compared and 8 CP for Summit), but exhibited a clear difference in the duration of the endodormancy period (11 days for Summit compared to only 1 day for Lapins), it can be inferred that Summit is more sensitive to temperature variations than Lapins. The comparison between sites highlighted a compensatory relationship between chill and heat: in the milder

Imouzzer-Kandar site, sweet cherries accumulate less chill in winter but compensate by requiring relatively more spring heat for flowering. This compensatory behavior supports the concept that chilling and heat requirements jointly shape phenology, but their relative contribution can shift depending on site warmth and year-to-year variability. A similar cultivar-dependent pattern was observed in apple, with Gala showing lower chill and heat requirements than Top Red, consistent with previous findings (33, 34). The heat accumulation was inversely related to chill unit accumulation but not for all sweet cherry cultivars (39).

Regarding flowering in sweet cherry, insufficient chill accumulation in 2020–2021 likely increased the thermal contrast between the end of the chill period and the onset of heat accumulation. This contrast can stress the cultivars, causing them to respond more quickly or intensely to the accumulation of heat, in contrast to season 2021–2022, where the process is more balanced, having benefited from a more regular cold period. This pattern suggests that winter warming may particularly challenge high-chill cultivars (e.g., Moreau, Van, Napoleon) and apple cultivars by increasing the risk of unmet chilling requirements. Conversely, low-chill cultivars such as Bigarreau and Lapins may be better suited to future conditions. In fact, growers in Morocco should match cultivars to local climatic conditions, selecting lower-chill ones for warmer sites or for areas expected to experience winter warming. As winters warm, continuous monitoring of chill and heat accumulation will become crucial for predicting flowering dates and mitigating risks such as late frost damage or irregular flowering. The results highlighted the need for adaptive cultivar choice and management strategies to sustain fruit production in Morocco's mid-altitude regions. The higher chill and heat requirements of apples delay their flowering, which typically occurs during April in Azrou (early April for Gala and mid- to late April for Top Red). This later flowering can provide some protection against early spring frost. Regardless the cultivars, sweet cherries in Imouzzer-Kandar generally flower earlier than in Azrou. Early cultivars such as Lapins, Early Star and Burlat flowered around March 22–26th, while later ones like Kordia and Big Star flowered in early April. This earlier flowering reflected the site's milder winter and faster spring warming. It is challenging to separate cold acclimation from endodormancy, as both processes occur simultaneously and are triggered by the same environmental factors. Thus, the transition from endodormancy to ecodormancy is gradual rather than abrupt and varies among species and cultivars (35).

Our study also aimed to investigate the effect of cultivar and year on vegetative and reproductive parameters such as diameter at the base of shoot, shoot length, rate of flowering and fruit set in both sites, Azrou and Imouzzer-Kandar. However, the vegetative and reproductive traits were evaluated over a limited time window and longer-term monitoring would be needed to confirm whether these cultivar differences remain stable across tree age, management practices and more contrasted climatic years. For all studied cultivars, the diameter of shoot did not show variations within the same cultivar between seasons, given that the difference not exceeding 0.8 mm for each cultivar. Regarding shoot length, the results did not present higher values for one season in favor of the other. Regardless of the species and the site, the results showed a close relationship between chill accumulation and rate of flowering and fruit set, for the same cultivar, a good chill accumulation during endodormancy promotes a higher rate of flowering and fruit set of the cultivar. Apple cultivars exhibit overall stronger vegetative vigor as reflected by greater shoot diameter and length but have lower to moderate reproductive performance, particularly in fruit set. Sweet cherry cultivars showed weaker vegetative growth but generally higher flowering rates. This contrast illustrates a clear reproductive versus vegetative trade-off between species, with apples prioritizing vegetative growth and sweet cherries allocating relatively more resources to reproductive development. For example, in apple, Gala accumulated high chill units during 2021–2022 (62.8 CP) compared to 2020–2021 (55.8 CP), this difference resulted in high flowering rate (72 %) and fruit set rate (69 %) in 2021–2022 than in 2020–2021 (63 % for flowering rate and 50 % for fruit set rate). The same results were observed on sweet cherry in Azrou and Imouzzer-Kanbdar, showing good reproductive performance during the season accumulated more chill units, 2021–2022. Our findings are consistent with (40), showing that inadequate chilling has previously been linked to incomplete flowering and decreased fruit set in apples, while in apricots, mild winters have been associated with altered floral bud development and subsequent low fruit set (5).

These results indicate that flowering is strongly influenced by seasonal climatic conditions and that insufficient winter chilling can disrupt floral primordia development, leading to reduced or absent flowering. This often results in a phenomenon called "poor flowering" (5). Moreover, fruit set serves as a proxy for flower fertility and quality. However, this parameter is strongly influenced by weather conditions prevailing during the flowering stage (41). The differences between the flowering dates of two pollinator cultivars (Gala and Top Red) influenced the fruit set rate, leading to think about other cultivars more compatible with climate change. In fact, Top Red, planted with Gala as pollinator, did not have a compatible flowering time, leading to a fruit set rate of no more than 20 % on average. Pollination and the availability of compatible pollen must be considered in orchard management systems to increase fruit set and improve both the quality and storability of apples (42). Comparing apples to sweet cherry, the flowering rate appeared more stable in apples (not significantly affected by either factor) but is sensitive to year-to-year variation in cherries, reflecting their higher susceptibility to environmental stress during floral induction and flowering. The significant effect of the season on the flowering rate and the fruit set rate observed on sweet cherry (but not on apple) could be explained by the higher temperature sensitivity of sweet cherry flower initiation and fruit set to annual fluctuations, especially chill and heat availability during the season effecting endodormancy release and flowering (43). A partial fulfillment of chill requirements due to a mild winter combined with a delayed heat accumulation is by a cold spring could result in irregular and asynchronous endodormancy release and flowering in sweet cherries, leading to a lower flowering rate and reduced pollination efficiency (44). In addition, sweet cherries generally flower earlier than apples, often in late winter or early spring when climatic conditions are less stable. This makes sweet cherry flowers more vulnerable to late spring frosts, which can damage floral organs and reduce fruit set (45). Moreover, sweet cherry is often self-incompatible, relying heavily on cross-pollination and synchronized flowering of compatible cultivars. Seasonal variations that disrupt flowering synchrony or pollinator activity (e.g., due to cold, wind or rain during bloom) can significantly reduce fruit set. Apple cultivars, while often also requiring cross-pollination, tend to be less sensitive to brief unfavorable weather conditions because of their longer flowering period (28). Physiologically, apple floral buds tend to be harder than sweet cherry buds during dormancy and early spring, tolerating wider ranges of temperature fluctuation. Long-term phenological studies in Western Europe have shown that apple exhibits more stable flowering dynamics under warm conditions, whereas sweet cherry remains highly sensitive to thermal variability, particularly in continental climates (46). Furthermore, projections indicated that apple could maintain stable flowering under future warming scenarios due to its relatively lower chilling requirements, reflecting a greater physiological tolerance to climatic change (47). On the other hand, apple cultivars exhibit overall stronger vegetative vigor as reflected by greater shoot diameter and length but have lower to moderate reproductive performance, particularly in fruit set. Sweet cherry cultivars showed weaker vegetative growth but generally higher flowering rates. Higher temperatures during flowering accelerated pollen tube growth but simultaneously reduced the number of tubes developing along the style (48). Site effects were also evident, Azrou's colder climate favors abundant flowering in sweet cherries but can limit fruit set, possibly due to spring frost or reduced pollinator activity, while Imouzzer-Kandar's milder climate supports higher fruit set and better shoot development. These observations underscore the importance of matching cultivar requirements with local climatic conditions to optimize both vegetative vigor and reproductive success. Comparing the two species, apples have stronger vegetative vigor (thicker and longer shoots) but often suffer from lower reproductive efficiency, as seen particularly in Top Red. This demonstrates the genetic variability between Gala and Top Red which is decisive for these traits. Gala's higher reproductive efficiency (greater fruit set) can thus be attributed to its genetic predisposition rather than environmental factors, as recent work has shown that flowering regularity and fruit set in apple are strongly genotype-dependent (49). In contrast, year-to-year variation significantly affected fruit set rate but not shoot diameter, shoot length or flowering rate. This suggests that annual climatic conditions mainly influenced the ability of flowers to set fruit rather than vegetative growth. This pattern is consistent with previous study who showed that tree flowering and fruit set exhibited significant interannual variability (33). The relatively stable flowering rates across years highlighted the genetic control of floral induction in apples and sweet cherries as demonstrated earlier (50).

Sweet cherries have less vegetative growth but generally higher flowering rates, indicating better floral induction. However, their fruit set is more variable and sensitive to site and cultivar choice. The site effect is also clear: the warmer Imouzzer-Kandar site enhanced shoot growth and stabilized fruit set in sweet cherries, while the colder Azrou site promotes higher flowering rates but may limit reproductive success due to harsher spring conditions. Overall, Gala (apple) is more productive than Top Red due to higher reproductive performance despite lower vegetative vigor. Napoleon (Azrou) and Lapins (Imouzzer-Kandar) are among the most promising sweet cherry cultivars, offering good vegetative and reproductive balance. Site effect significantly influenced cherry performance: Imouzzer-Kandar favors vegetative vigor and fruit set, while Azrou supports high flowering but lower fruit set. Consequently, cultivar selection based on both vegetative vigor and reproductive success is crucial for optimizing yields under current and changing climatic conditions. In Imouzzer-Kandar, cultivar effects were highly significant for shoot diameter and shoot length, demonstrating again that genetic differences among cultivars (e.g., Lapins, Big Star, Kordia) strongly govern vegetative vigor in that site. However, year effects were significant for flowering and fruit set rates, while cultivar effects were not significant for these traits. This pattern showed that, in Imouzzer-Kandar, the reproductive traits of sweet cherries are more dependent on inter-annual temperature variations during bud endodormancy and ecodormancy than on genetic differences between cultivars.

Finally, based on the average of chill requirements, endodormancy release dates, flowering dates, flowering rate and fruit set rate measured among sweet cherry cultivars, three cultivar groups were identified: i) Early-flowering cultivars with low chill requirements and variable flowering and fruit set rate, especially represented by Bigarreau and Lapins, ii) Late-flowering cultivars with higher chill requirements and high reproductive performance, mainly represented by Moreau and Summit cultivars and iii) intermediate cultivars with balanced chill and moderate flowering performance. This classification highlights the role of chill accumulation and dormancy release in flowering phenology and fruit set. Moreover, group 1 cultivars may be better adapted to mild winters but can remain vulnerable to spring frost and unstable fruit set. In contrast, group 2 cultivars appear more suitable for colder areas, showing higher reproductive stability, though they might be unsuitable for mild winters due to insufficient chilling This grouping provides a practical basis for cultivar selection and site-specific orchard planning under ongoing climate warming.

Beyond the present findings, future research should integrate chill-heat phenological models with climate projections to simulate cultivar-specific responses to warming, including flowering shifts and chilling deficits, thereby supporting cultivar selection and adaptation strategies under climate change.

Conclusion

Based on field monitoring and experimental forcing tests conducted over three contrasting seasons (2021–2022, 2022–2023 and 2023–2024). Our study clarified how interannual temperature variability affects endodormancy release, flowering timing, chill and heat requirements and reproductive performance of ten sweet cherry and two apple cultivars grown under contrasting mid-altitude Moroccan environments. In fact, we highlighted that the endodormancy date release and the subsequent phenological development were mainly affected by the interaction between cultivar-specific requirements and seasonal temperature variation. Our finding clearly revealed that chill accumulation during December–February was the most driver of endodormancy release, while spring heat influenced ecodormancy fulfillment and flowering achievement. Seasons characterized by cold winters and warm early springs induced earlier endodormancy release and flowering in both species. In addition, intra-specific variability was showed among sweet cherry cultivars in Azrou and Imouzzer-Kandar, with clear clustering between early, intermediate and late cultivars in terms of chill needs, flowering dates and fruit set. Marked intra-specific variability was observed among sweet cherry cultivars, leading to three performance groups: low-chill early cultivars, intermediate cultivars and high-chill late cultivars. This grouping reflected a genotypic difference affecting responsiveness to chill and heat accumulation. Apples were more stable in terms of flowering behavior across years, whereas sweet cherries cultivars exhibited high sensitivity to interannual temperature variations, especially in reproductive parameters. In terms of sensitivity, our study demonstrated that lack of chill induced incomplete flower bud emergence, resulting in lower rate of flowering and fruit set.

From an applied perspective, cultivar performance differed clearly between sites, with colder winters favored high flowering rates but increased the risk of reduced fruit set, while milder conditions promoted vegetative growth and more stable fruit set. These contrasting responses illustrate a general trade-off between vegetative vigor and reproductive stability, modulated by site climate rather than by individual cultivar performance alone. These findings underlined the value of matching cultivar requirements with local temperature regimes, highlighting the importance of climate-adaptive cultivar selection in Morocco's mid-altitude orchards, as warming winters could compromise high-chill cultivars. Continuous monitoring of chill and heat accumulation will be urgent need for predicting phenological behavior and ensuring stable yields under ongoing climate change. Finally, the detailed data the phenological dataset presented in this study provides practical guidance for growers and breeders to optimize cultivar choice, reduce frost-related risks in low-chill cultivars and mitigate insufficient chilling in high-chill cultivars. Nevertheless, further studies are necessary to better understand the physiological, biochemical and histological mechanisms involved and to anticipate the phenology and adaptation of temperate fruit trees to the current context of global warming.

Acknowledgements

This research was financially supported by the PRIMA Programme through the AdaMedOr project (2020–2023), with funding in Morocco provided by the Ministère de l'Enseignement Supérieur et de la Recherche Scientifique et de l'Innovation / Direction de la Recherche Scientifique et de l'Innovation (MESRSI/DRSI).

Authors' contributions

Conceptualization was carried out by HH, AEY and OK. Methodology was developed by HH, AEY, ME, JC, HO, HB and OK. Formal analysis and investigation were performed by HH, JC, ELHA and HO. Writing of the original draft, as well as review and editing of the manuscript, were undertaken by all authors. All authors contributed to visualization. Funding acquisition and supervision were provided by AE and OK. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical issues: None

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