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Climatic Characterization and Phenology of Local Peach Genotypes in the Udzungwa Uplands of Tanzania

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The phenology of two local peach genotypes was studied to verify whether peaches can be produced in the Tanzanian uplands. Observations were conducted on trees of one early- and one late-ripening peach genotype in 2010 and 2011. Temperature trends were reconstructed and three chilling estimation models were tested. The two peach genotypes differed for timing of flower and leaf bud-break. Common symptoms of insufficient chilling (presence of numerous stages at a specific date and about 20% of undeveloped flower buds) were observed in the late genotype. Both Utah and Dynamic models indicated low chilling accumulation, lower than the Mean Temperature model in most cases. This is inconsistent with the actual phenology, suggesting that (1) both models show some limitations under our conditions, (2) the two genotypes partly adapted to the local climate, and (3) mechanisms other than chilling (seasonal rainfall fluctuations) play a role in rest control.

KEYWORDS   bud-break, chilling requirement, chilling estimation models, dormancy, Prunus persica

INTRODUCTION

Certain regions of the tropical belt are not suitable for cultivation of tropical and subtropical fruits due mainly to elevation and orography like in the

Udzungwa uplands in Tanzania. In those areas, and especially in remote villages, the availability of fresh fruit may become scarce even during peak production of tropical fruit. In those cases, and particularly when tropical and temperate fruit productions do not overlap, cultivation of temperate species may play a key role in the attempt to supply adequate amounts of nutrients and vitamins to local people.

Cultivation of temperate fruit crops in tropical and subtropical areas has been studied in many contexts, with a special focus on the inadequate satisfaction of chilling requirements (Erez, 2000). However, growing temperate fruit species in the tropics has been successful (Edwards, 1990), especially at high-altitude sites, such as in the Ethiopian mountain areas (Ashebir et al., 2010), but also at low altitudes, such as in tropical Zimbabwe (Jackson and Bepete, 1995), with the support of specifically developed cultural techniques aimed at the management of temperate fruit tree species dormancy and chilling requirements. Such a large amount of studies and technologies developed for temperate crops facilitates the establishment of specialized and intensive orchards in new suitable areas.

Introduction in Tanzania of a limited number of peach (*Prunus persica* [L.] Batsch.) trees, belonging to some European genotypes, can be dated back to the beginning of the 20th century, mostly by German settlers and aimed at satisfying their own local needs in periods where native tropical fruits were not available (Epenhuijsen, 1976). Some offspring of those peach genotypes are currently partially adapted to local climatic conditions and still being seed-propagated by local people, mainly in the Udzungwa uplands, with scarce and sporadic cropping. Despite the evident problems due to absolute lack of cultural practices and low chill disorders, the adaptation of those trees to local climatic conditions suggests good possibilities for commercial peach production in the area.

As stated before, a major limiting factor for growing peaches and nectarines in tropical countries is the inadequate amount of chilling. Many physiological disorders result from insufficient chilling at winter, and some of them have been described. The most indicative symptoms are delayed foliation, reduced fruit set and buttoning, reduced fruit quality (Byrne and Bacon, 1992), bud break spread over a long period of time and unevenly throughout the canopy (Couvillon, 1995).

Cold temperatures needed to overcome dormancy are commonly quantified by several methods in terms of units or amount of time within a certain range. Chilling units (CU) accumulation is critical in peach to allow for bud breaking and development (Byrne and Bacon, 1992). The dormancy stage allows buds to be tolerant to temperatures much below freezing. Once an adequate amount of chilling is accumulated, buds begin their growth according to temperature increases (Byrne and Bacon, 1992).

Methods to estimate chilling accumulation do not follow a standard model for all climatic regions. Most people agree, however, that temperatures

below freezing or above 15.5°C are not effective for chilling accumulation (Byrne and Bacon, 1992). There are many models to estimate chilling accumulation, each defining a different concept of chilling unit (or portion). The two most widely used models are the number of hours below 7.2°C or "chilling hours" model (Weinberger, 1950) and the Utah model (Richardson et al., 1974).

The first model is simple and defines a chilling unit as one hour below or 7.2°C. The Utah model is more complex because it introduces the concept of relative chilling effectiveness and negative chilling accumulation (or chilling negation) (Richardson et al., 1974). These two models require hourly temperatures to be recorded (or estimated) for calculation and since they were developed in regions where high chill-requirement peach cultivars are grown, their usefulness under medium and low chill-accumulation conditions has been limited. Specifically, the Utah model performed well under temperate conditions but failed to predict the end of dormancy under subtropical conditions (Linsley-Noakes and Allan, 1994; Erez, 2000).

Another approach is the Mean Temperature model based on the relationship between the mean monthly temperature of the coldest month and total chill accumulation (Sharpe et al., 1990; Weinberger, 1956). The model uses either the temperature of the coldest month or the one of the two coldest months in winter to estimate chill accumulation and has given better results than the standard Utah model in those areas with low chill accumulation (Byrne and Bacon, 1992).

More recently, the Dynamic model has proven to give the best estimates of chilling accumulation in warm-temperate and sub-tropical climates (Fishman et al., 1987; Erez et al., 1988; Pèrez et al., 2008). This model considers also the effect of high temperatures, supposing that chilling is accumulated in the buds of deciduous fruits in an irreversible manner once a critical concentration of a hypothetical intermediary compound is reached, depending on the intensity and duration of the temperature (Fishman et al., 1987).

Recently, the non-profit organization, TULIME onlus, which operates in this region since 2001 for rural development and international cooperation purposes, has started working on the project "Vitamine per Pomerini" to explore the possibility of establishing a fruit district for cultivation of temperate fruits and with the general aim to improve the nutritional value of the local diet. The objective of this study was to describe and interpret the phenology of two locally-adapted peach genotypes in relation to the local climate in the Pomerini village, Tanzania. Ultimately, the study will give more insight on the real possibility to cultivate and produce peaches and will help choose the most appropriate genotypes to be utilized for cultivation under Tanzanian upland climate.

MATERIALS AND METHODS

Direct observations on local peach genotypes were carried out at Pomerini village (08° 05′ 60″ S and 35° 46′ 00″ E and 1897 m a.s.l.), in the Udzungwa uplands near Iringa (central Tanzania). Peach trees utilized for the experiment are home-grown by villagers of Pomerini; they are only harvested for local family needs and there is no attempt of providing cultural cares. Those peach trees are chance seedlings deriving from unknown old varieties imported by German settlers (Epenhuijsen, 1976). All trees were in the adult stage, but age was variable and difficult to estimate.

Field observations were carried out in Sept. 2010 and at the end of July–beginning of Aug. 2011. Nine trees were randomly selected, five of which were showing an early bud-break and flowering (early genotype), while the other four trees showed delayed bud-break (late genotype). Five shoots per tree were selected and labeled for subsequent phenological observations (flower and leaf buds). To define the phenological stages of the two genotypes, each labeled shoot was photographed against a white background with a Casio EX-Z350 digital camera (Casio Europe GmbH, Norderstedt, Germany). In 2011, direct bud observations and counts were carried out on the same shoots.

Flower bud developmental stages were interpreted from digital images in 2010 and directly on the trees in 2011 according to the Baggiolini phenological scale (Baggiolini, 1952). A number was attributed to each stage classified by the scale to translate categorical data into numerical values. A similar protocol was used for leaf buds attributing in this case progressive numbers to modified and expanded BBCH (Meier et al., 1994) stages, in order to consider shoot elongation throughout the fifth node (Table 1). Numerical values obtained for flower and leaf buds were used to construct box-plots showing bud stage advancement over time for each genotype. Subsequently, numerical stages were converted into Principal Growth Stages of the BBCH scale (Meier et al., 1994), and the converted data were used to study the frequency of various stages at each date and stage transitions.

On 10 Aug. 2010, a Davis wireless Vantage Pro 2 (Davis Instruments Corp., Hayward, CA, USA) weather station was installed in the village and local climate data were recorded. Historical series (2001–11) of climatic data at the nearest FAO weather station were also retrieved from Tutiempo Network (n.d.).

The recent portion of these data set (2010–11) was used to establish a relationship between mean (T_{med}), maximum (T_{max}), and minimum (T_{min}) temperatures of Iringa and Pomerini. Specifically, Pomerini maximum temperatures ($T_{\text{max}P}$) were estimated through the following linear function: $T_{\text{max}P} = -4.427 + (0.944 \times T_{\text{max}Ir})$, $R^2 = 0.620$. On the other hand, a logarithmic function was used to get minimum temperatures: $T_{\text{min}P} = -14.97 + 10.03 \times \ln |T_{\text{min}Ir}|$, $R^2 = 0.477$. Finally, Pomerini mean temperatures (T_{medP}) and Iringa mean temperatures (T_{medIr}) were related by a quadratic function:

TABLE 1 Phenological Stages and Corresponding Numerical Values According to Baggiolini and BBCH Scales for Flower and Leaf Buds

Flower buds	Baggiolini[z]	BBCH[y]	Leaf buds	Numerical[z]	BBCH[y]
Dormant bud	0	0	Dormant bud	0	0
Bud swelling	1	5	Beginning of bud swelling	1	
Visible calyx	2		End of leaf bud swelling (separated scales showing green tips)	2	1
Pink stage	3		First leaves separating	3	
Beginning of flowering	4	6	First leaves fully expanded	4	
Full flowering	5		Shoot elongation—1st node	5	3
Petal fall	6		Shoot elongation—2nd node	6	
Fruit set	7	7	Shoot elongation—3rd node	7	
Fruit enlargement	8		Shoot elongation—4th node	8	
Fully ripen fruit	9	8	Shoot elongation—5th node	9	

[z]Numerical values used to represent phenological advancement over time.
[y]Categories used to represent stage frequency at each sampling date.

$T_{medP} = -22.161 + (2.71 \times T_{medIr}) - (0.043 \times T_{medIr}^2)$, $R^2 = 0.711$. These regression models were then used to reconstruct a complete historical series (2001–11) of temperatures for Pomerini. Reconstructed values of T_{max} and T_{min} were adopted to generate hourly temperature data according to the Linvill method (Linvill, 1990).

Three chilling estimation models were tested to obtain a first indication on climatic potential for peach growing in the area. The reconstructed hourly temperatures (2001–11) were used to estimate CU by the Utah model (Richardson et al., 1974). A second model, which uses mean temperatures (°C) of the coldest 30 days (T_{cold}, 15 June–15 July) and is suitable for low-chill subtropical peaches (Sherman and Rodriguez-Alcazar, 1987), was tested. In the model, $CU = -1174 + 27{,}585/T_{cold} + [-75{,}466/(T_{cold})^2]$ (Okie, 1998). Finally, hourly temperatures were also used to calculate chilling portions (CP) by the Dynamic model (Fishman et al., 1987).

Between the end of January and the first half of Feb. 2011, fruits were harvested, counted, and a subsample of 20 fruits was weighed and photographed. Average fruit weight and shape index (length/width) were calculated for both the early and the late genotypes.

Systat (Systat Software Inc., Chicago, IL, USA) procedures were used to perform basic data analysis and obtain box plots. Sigmaplot (Systat Software Inc.) was used to perform regression analysis and plot graphs.

RESULTS AND DISCUSSION

Tree Phenology

As visually observed, the two peach genotypes were different for timing of bud-break and bud development in both years and for both flower and
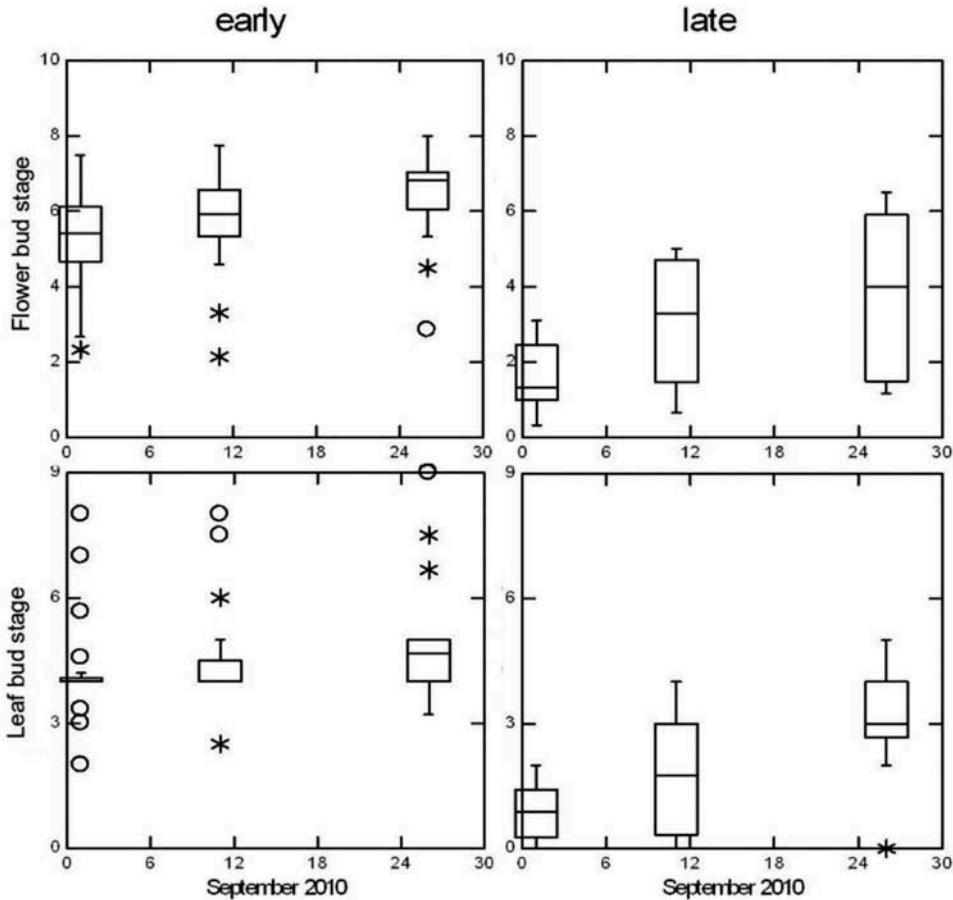
FIGURE 1 Advancement of flower and leaf bud stage (see Table 1) in 2010 for trees of the early and late peach genotypes grown in Pomerini. In the box plot, asterisks mark outside values (>1.5 interquartile range) and empty circles mark far outside values (>3 interquartile range).

leaf buds. In this work, we only report data from 2010 because the results are compatible and analogous to those of 2011. In particular, in Sept. 2010, median flower stage of the early genotype ranged from about 5 to 7, while median flower stage of the late genotype ranged from about 1 to 4 (Fig. 1). In the same year, leaf buds ranged from 4 to 5 in the early genotype and from 1 to 3 in the late genotype (Fig. 1).

It is important to notice that in both of the observation periods (more advanced in 2010 and right after bud-break in 2011), flower buds developed generally earlier than leaf buds. This is not consistent with a situation of insufficient chilling since apical leaf buds commonly tend to have lower chilling requirement and break earlier. In our case, however, this is due to the fact that all leaf buds (apical and lateral) were counted and monitored

together, and the resulting stage was strongly affected by a relatively high number of delayed lateral buds.

In 2010, distribution of phenological stages grouped by BBCH categories show an earlier development of flower and leaf buds in the early-ripening than in the late-ripening genotype (Fig. 2). In addition, in the late-ripening genotype a significant percentage of buds remained dormant (Fig. 2A). This suggests that in the late genotype about 20% of flower buds may never develop into fruits, a common symptom of insufficient chilling. A similar behavior is not apparent in the early-ripening genotype, probably due to lower chilling requirement. On 11 Sept. 2010 and 26 Sept. 2010, the late genotype exhibited a relatively uniform distribution among stages, whereas the early genotype showed a clear dominance of the more advanced stages 6 and 7 (Fig. 2A). In leaf buds, on the contrary, grouping numerical stages into three BBCH main categories masked the differences between the two genotypes in terms of variability (Fig. 2B). This is merely due to the fact that few BBCH categories group several different numerical stages together, especially BBCH 0 including leaf stages 0, 1, and 2. Similar results were observed for leaf bud distribution of 2011 (data not shown).

For each genotype, type of bud and BBCH stage changes over time in bud percentage were described by regression analysis. Flower bud percentage at BBCH stage 0 remained constant over time in both genotypes (data not shown), but at different levels as seen previously (Fig. 2A). The percentage of flower buds at BBCH stage 5 followed a decreasing logarithmic trend for both early and late genotypes (Fig. 3A). The decrease shown in the late genotype was more marked than in the early genotype due to the fact that few buds were still at BBCH 5 and many had already progressed to more advanced stages in the early compared to the late genotype. Time changes of buds at BBCH stage 6 followed different trends in the two genotypes: in the early genotype the percentage increased until 11 Sept. and then decreased following a quadratic trend; in the late genotype, percentages increased according to a saturation model (Fig. 3B). Flower bud percentage at BBCH stage 7 increased in both genotypes but according to different exponential functions (Fig. 3C). The increase in the early genotype was in fact much more marked than in the late genotype, showing once again the drastic difference in timing of bud development between the two genotypes (Fig. 3C).

On the other hand, leaf bud percentage at BBCH stage 0 (from dormancy to the end of leaf bud swelling) showed significant changes over time. In particular, leaf bud percentage decreased in a different way in the two genotypes: the early genotype followed a polynomial inverse trend, while the late genotype decreased linearly (Fig. 4A). The non-linear trend found for the early genotype shows that by 8 Sept. all open buds had progressed to the following stages and only about 1% of total leaf buds remained dormant and will probably drop. Moreover, percentage of buds at BBCH stage 1 increased
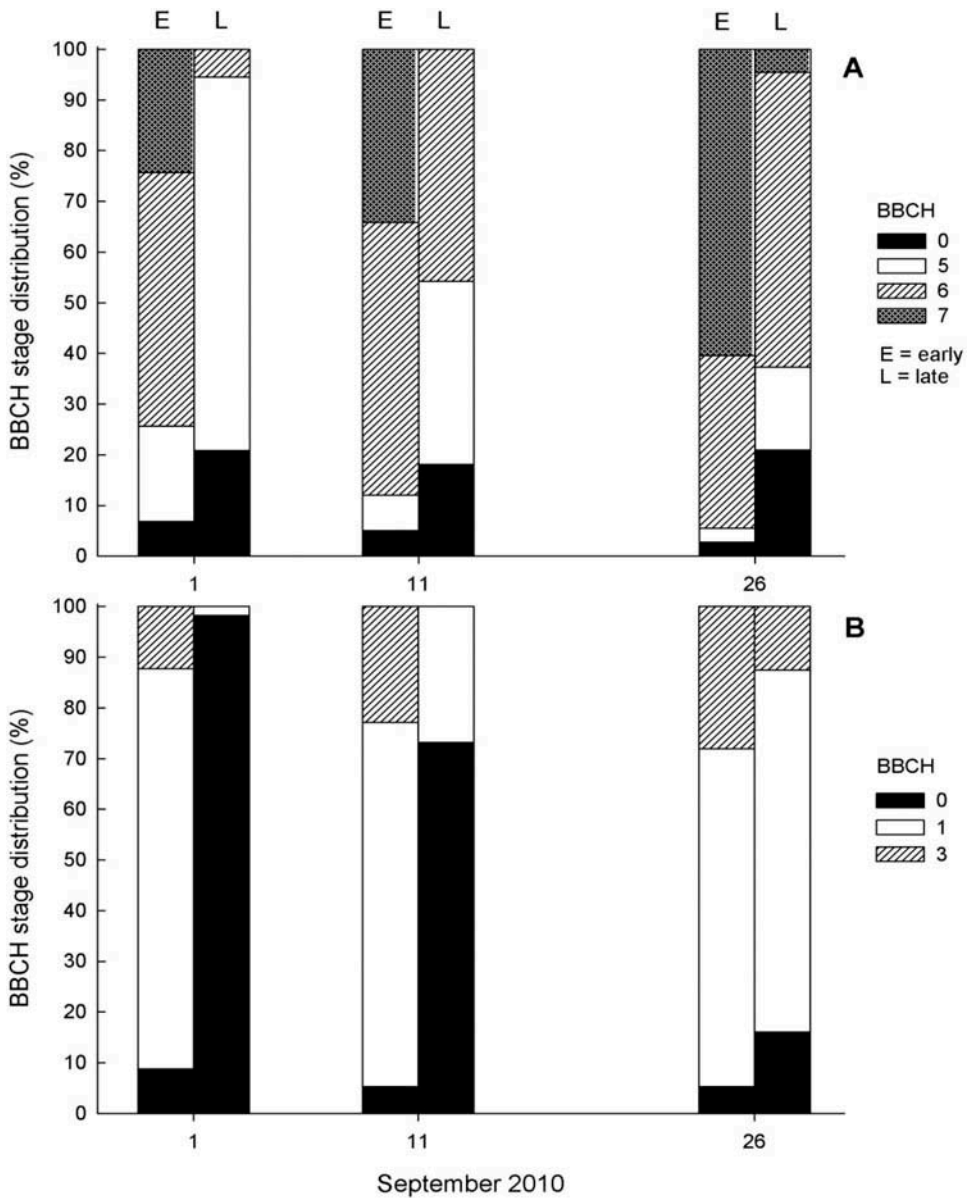
FIGURE 2 Percentage of various BBCH stages at each 2010 sampling date for flower (A) and leaf (B) buds of the early and late peach genotypes grown in Pomerini.

linearly only in the late genotype (Fig. 4B). No apparent change in percentage of buds at BBCH stage 1 occurred in the early genotype, meaning that concurrently an equal number of buds entered and exited this stage. Finally, percentage of leaf buds at BBCH stage 3 increased according to different functions in the two genotypes: in the early genotype it increased linearly,
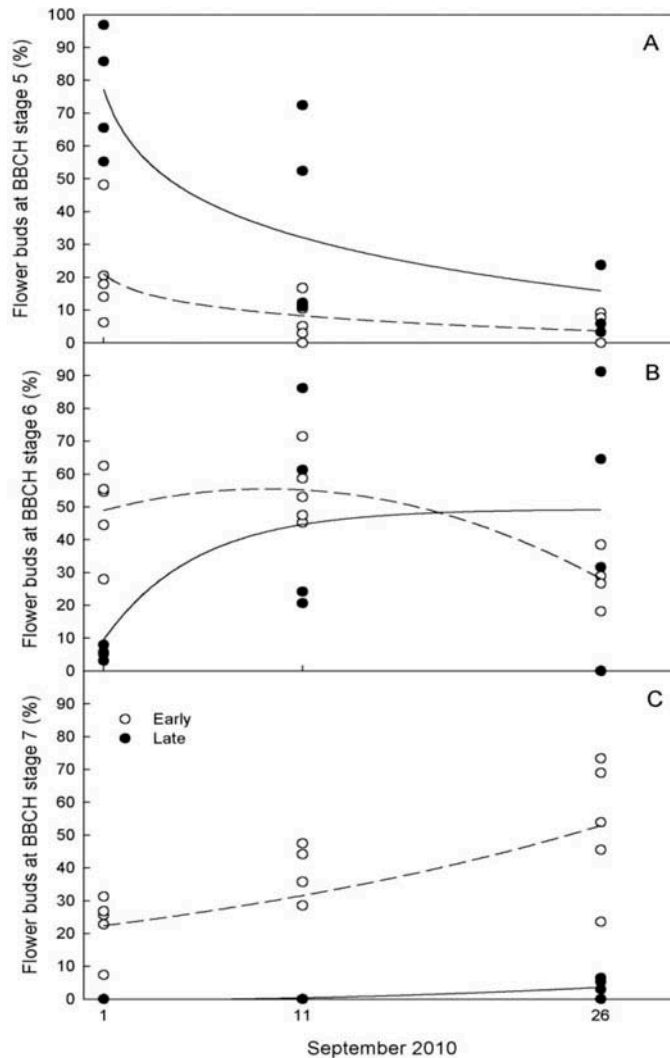
FIGURE 3 Changes in the percentage of flower buds at each BBCH stage during the days of Sept. 2010 (DoS) in the early and late peach genotypes grown in Pomerini. For the early genotype (dashed lines), %BBCH5 = $21.0 - 5.3$ Ln($|$DoS$|$), $R^2 = 0.389$, $P = 0.013$; %BBCH6 = $47.3 + 1.8$ DoS $- 0.1$ DoS^2, $R^2 = 0.560$, $P = 0.011$; %BBCH7 = 21.6 exp(3.4 DoS), $R^2 = 0.421$, $P = 0.009$. For the late genotype (solid lines), %BBCH5 = $77.2 - 18.8$ Ln($|$DoS$|$), $R^2 = 0.633$, $P = 0.003$; %BBCH6 = 49.3 ($100 - 80.7^{\mathrm{DoS}}$), $R^2 = 0.370$, $P = 0.036$; %BBCH7 = $-0.3 + 0.006$ DoS^2, $R^2 = 0.579$, $P = 0.004$.

while in the late genotype it followed an exponential trend (Fig. 4C). In the late genotype, the exponential function shows that shoots started elongating around 15 Sept., while the linear function suggests that shoot elongation in the early genotype started around 22 Aug.
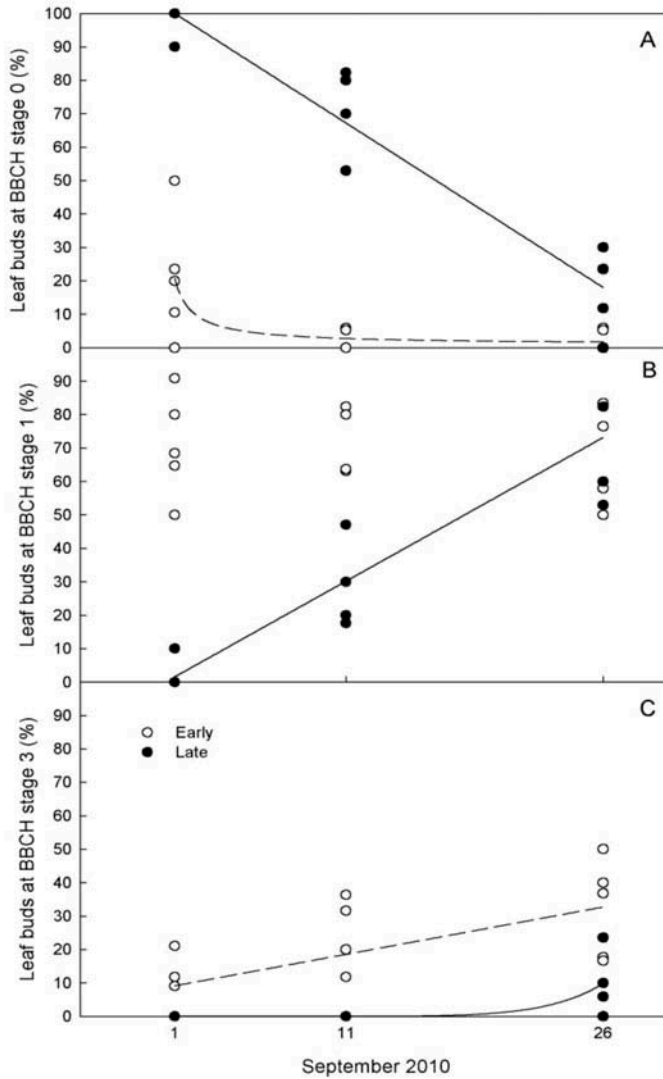
FIGURE 4 Changes in the percentage of leaf buds at each BBCH stage during the days of Sept. 2010 (DoS) in the early and late peach genotypes grown in Pomerini. For the early genotype (dashed lines), %BBCH0 = 1.0 + (19.8/DoS), $R^2 = 0.438$, $P = 0.007$; %BBCH3 = 8.2 + 0.9 DoS, $R^2 = 0.408$, $P = 0.010$. For the late genotype (solid lines), %BBCH0 = 103.3 − 3.3 DoS, $R^2 = 0.917$, $P < 0.001$; ArcSen$\sqrt{}$%BBCH1 = 6.7 + 4.1 DoS, $R^2 = 0.805$, $P < 0.001$; %BBCH3 = (2.53×10^{-11}) DoS$^{819.1}$, $R^2 = 0.463$, $P = 0.015$.

Climate and Chilling Accumulation

Before installing the weather station at Pomerini (Aug. 2010), there were no historical data available. Data obtained from Pomerini station (2011) were used to plot the Walter and Lieth's climatogram (1960), which shows that
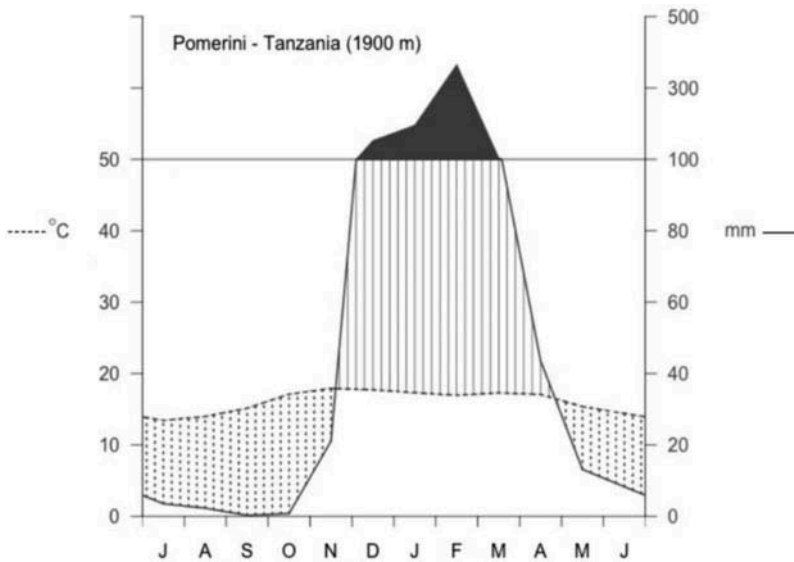
FIGURE 5 Climatogram of Walter and Lieth for the experimental site in Pomerini (08° 05′ 60″ S and 35° 46′ 00″ E and 1897 m a.s.l.), in the Udzungwa uplands near Iringa (central Tanzania).

the dry part of the year (May to November) corresponds to the cooler months while most of the precipitations occur from November to April (Fig. 5). In addition, temperature trends indicate very contained yearly fluctuations (Fig. 5) and, therefore, no clear seasonality, typical of tropical areas. Nevertheless, July appears to be the coldest month of the year (Fig. 5). Considering that no direct observation of the entrance into dormancy was made and that the beginning of bud-break for the early genotype was recorded toward the end of July (2011), the most useful days for chilling accumulation should occur between 15 June and 15 July. Reconstructed temperature daily trend exhibited a peak at about 3:00 PM, a minimum around 7:00 AM and was skewed to the left (Fig. 6). Temperature excursion for typical winter days reached about 9.5°C.

    Chilling units estimated by the Utah model indicated a relatively low chilling accumulation (Table 2). According to this model only hours at the optimal temperature of 6°C yield a full chilling unit, whereas chilling negation starts at temperatures above 14.1°C (Fig. 7A). The distribution of the number of hours across temperatures during the period June–July 2011 at Pomerini shows that a significant portion of hours above 14.1°C occurred (Fig. 7B). This generated a strong chilling-negation effect, yielding only about 23% net chilling accumulation and explains the relatively low amount of CU reported in this study. This is inconsistent with the observed phenological behavior and confirms that the Utah model is not suitable for simulating dormancy evolution of temperate fruits in tropical climates (Guardian and Biggs, 1964;
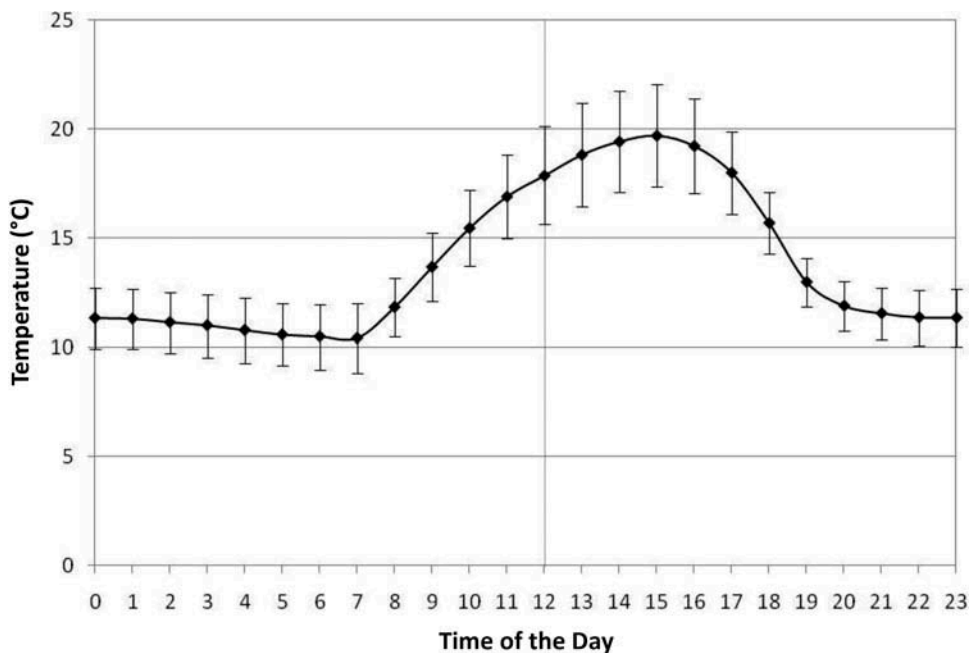
FIGURE 6 Daily temperature changes recorded in Pomerini during June–July 2011. Error bars indicate standard deviations of the means.

TABLE 2 Chilling Units Accumulation According to the Utah and the Mean Temperature Models from 2001 to 2011 at Pomerini. Statistics Indicate the Probability That a Certain Level of Yearly Chilling Accumulation Occurs under the Climate of the Region

Year	Utah[z]	Mean temperature[z]	Dynamic[y]
2001	105	303	2.02
2002	36	322	3.02
2003	118	318	3.02
2004	36	367	4.01
2005	—	—	—
2006	143	367	6.05
2007	91	472	6.04
2008	83	456	11.05
2009	131	410	4.03
2010	116	518	4.03
2011	121	462	5.05
Median	110.6	388.6	4.03
75th Percentile	85.2	333.4	3.27

[z]Chilling units (CU).
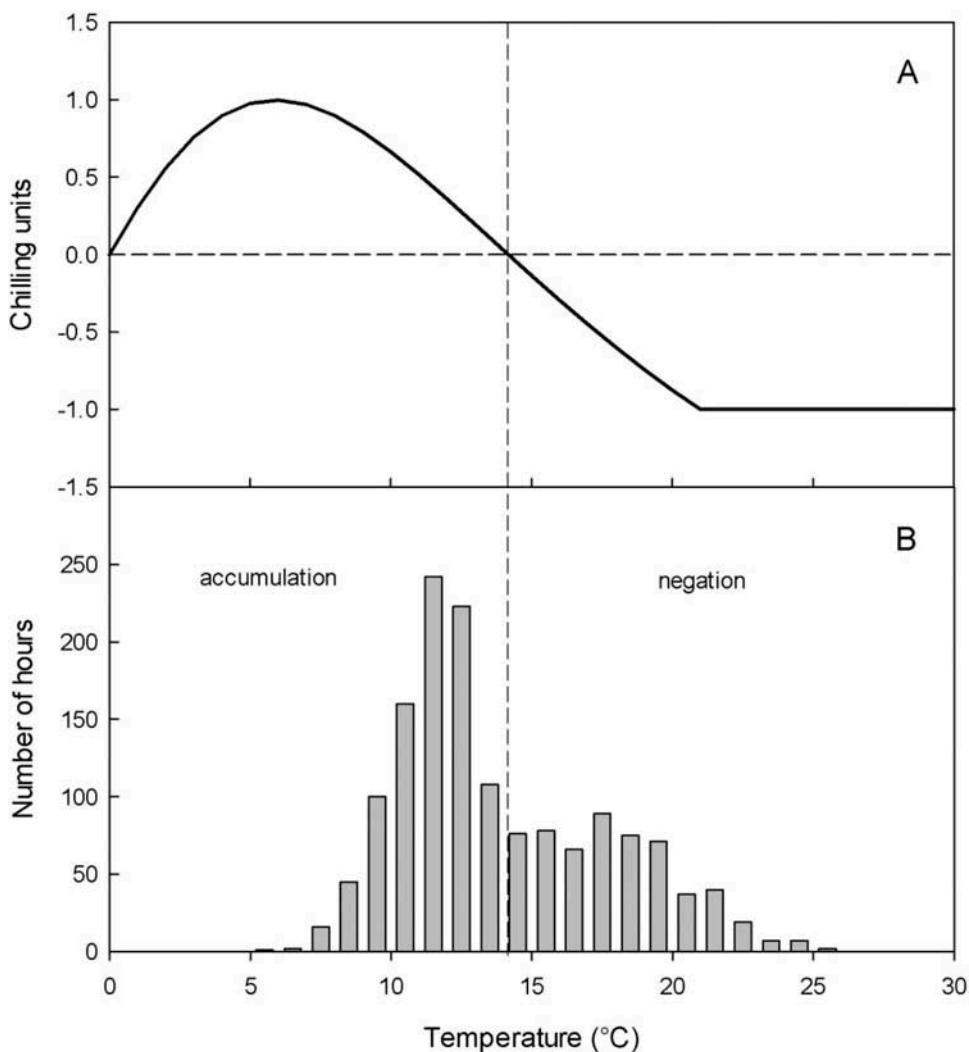[y]Chilling portions (CP). 1 CP ≈ 20 CU.

FIGURE 7 Relative chilling effectiveness (expressed in chilling units) of hourly temperatures according to the Utah model (A) and distribution of the number of hours across temperatures (B) during the period June–July 2011 in Pomerini. The vertical dashed line indicates transition from chilling accumulation to chilling negation.

Pèrez et al., 2008; Sharpe, 1969; Rouse and Sherman, 2003; Sharpe et al., 1990).

On the other hand, the Mean Temperature model (considering the period 15 June–15 July as the coldest month) seemed to estimate higher chilling unit accumulation than the Utah model (Table 2). Similar findings in favor of this model were reported for peach by Rouse and Sherman (2003). Besides some expected variation from year to year, in 75% of cases chilling accumulation estimated by the Utah model is expected to be about $\frac{1}{4}$ of

TABLE 3 Number of Fruits per Tree, Average Fruit Weight and Shape Index (Length/Width) in Peach Trees of the Early and Late Genotypes Grown at Pomerini (Means ± Standard Errors)

	N. fruits	Fruit weight (g)	Shape index
Early	97 ± 13	52.5 ± 5.12	1.06 ± 0.016
Late	172 ± 48	98.0 ± 8.15	1.04 ± 0.011
P^z	0.132	0.001	0.304

[z]*P* value from analysis of variance.

chilling accumulation by the Mean Temperature model. Even though CUs estimated by the Mean Temperature model suggest a greater chilling accumulation, no suggestion on the mechanisms of controlling dormancy utilized by plants is provided.

Chilling estimation by the Dynamic model yielded also a relatively low amount of CP, which was not associated to CU obtained with the other two models (Table 2). Despite this last model taking into account daily temperature fluctuations, our results do not seem to reflect any expected chilling satisfaction by peach trees. Although, several studies conducted in various climatic regions (Alburquerque et al., 2008; Allan et al., 1995, 1997; Erez, 2000; Erez et al., 1990; Fishman et al., 1987; Gardner and Bertling, 2005; Luedeling et al., 2009; Perez et al., 2008; Ruiz et al., 2006, 2007) have found the Dynamic model to be superior or equivalent to all others and especially accurate for warmer climates (Luedeling and Brown, 2011), peach phenology was not explained by any chill-accumulation model, including the Dynamic model, under the tropical climate of Reunion Island (Balandier et al., 1993).

Fruiting (Yield)

Production of the trees in trial was recorded between January and February, when fruits are commonly harvested by local people. Number of fruits per tree did not differ between the two genotypes due to great variability from tree to tree (Table 3). The observed variability is in the most part due to strong differences in tree size (data not recorded). Average fruit weight was significantly greater in the late than in the early genotype, whereas fruit shape was similar in both genotypes (Table 3). In all cases, fruit length was greater than width indicating a certain tendency of fruits to form pronounced tips.

CONCLUSIONS

Considering that the local genotypes come from old peach varieties imported by European settlers at the beginning of the 1900s and that no known or selected low-chill variety was available at that time, we can assume an initial chilling requirement for the two genotypes ranging from 600 to 900 CU

(Rieger, 2006). Chilling estimates with the tested models were not compatible with such requirements and some phenological and productive disorders (especially in the late genotype) confirm this fact. It is expected, however, that since local peach orchards during the last century have been customarily established by seed propagation, offspring of the original genotypes may have undergone selection (both unconscious and/or methodical) by local farmers, leading to a population of genotypes with moderate to low chilling requirements; this would explain the productivity of local genotypes. On the other hand, the lack of agreement between dormancy models and actual peach phenology in this study may reside in the assumption that chilling requirements are under genetic control. While this assumption holds true under temperate climates, cultural and environmental factors, such as the alternation of dry and humid seasons (Borchert, 1999), have been shown to affect dormancy and chilling requirements of temperate fruit trees in the tropics. On this basis, rest-avoidance techniques based on artificial or natural defoliation in response to water deficits are commonly adopted to reduce chilling requirements of temperate fruit species growing in tropical and subtropical climates (Jackson and Bepete, 1995; Lloyd and Firth, 1990).

Whatever the mechanism, this study shows that insufficient chilling is a major limiting factor in peach adaptation to growing in the Udzungwa uplands in Tanzania. To further develop peach growing in the area, research should aim to both the selection, or the introduction, of low chill cultivars and the development of rest avoidance techniques for reducing chilling requirements of the currently grown genotypes. New trials have recently started at the Udzungwa uplands to test performances of well identified peach cultivars and rootstocks in the upland conditions, and first results suggest poor performance of some imported rootstocks in comparison to the local genotypes. One future objective will be to graft low-chill (150–300 CU) peach cultivars coming from specific breeding programs onto local genotype rootstocks to improve the productive performances.

ACKNOWLEDGMENTS

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