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Calculation of the thermal units for 13 codes of the BBCH scale of 12 progenies of quinoa in the growing conditions of the Brazilian savanna

Cálculo del tiempo térmico para 13 códigos de la escala BBCH de 12 progenies de quinua en las condiciones de crecimiento de la Sabana Brasileña

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Quinoa plant in the Brazilian savanna.

Photo: W. Anchico-Jojoa

ABSTRACT

The introduction of quinoa (*Chenopodium quinoa* Willd.) in the Brazilian savanna has been successful based on the selection of progeny from valley types. Given the wide variation of environments, an alternative to define the maturation cycle of the plant has been the use of accumulated thermal units (ATU). This measure allows prediction of the plant cycle and supports the definition of phenology duration useful in crop management and quinoa breeding. This study aimed at calculating the ATU for the 13 codes of the BBCH scale of quinoa by evaluating 12 selected progenies grown in two sowing dates, at 15° 56' S and 47° 55' W, altitude of 1.100 m, Brasilia, DF, Brazil. Statistical differences were predominant from the beginning of the BBCH-50 reproductive phases, classifying the progenies as early, mid-cycle and late. Early maturity progenies and respective ATU for BBCH-89 are BRQ4 (1.676,8), BRQ1 (1,685), and AUR (1,691), contrasting with late BLA (2.239), BRQ3 (1,929.1 GDD), and BRQ8 (1,895). The accumulated thermal units for BBCH-89 ranged from 1565.25 to 2381, with a difference between the earliest and latest genotypes of 815.75. Progenies selected from existing cultivars are different in thermal unit accumulation, ensuing efficiency in cultivar acquisition to stagger quinoa cultivation. Accumulated thermal units explain the range of plant maturity cycles in selection. Additionally, the calculation of atu for BBCH scale codes is an effective tool for predicting the phenological cycle of quinoa.

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Additional key words: *Chenopodium quinoa* Willd.; phenology; selection; crop management; degrees day.

RESUMEN

La introducción de la quinua (*Chenopodium quinoa* Willd.) en la Sabana Brasileña ha tenido éxito basada en la selección de progenies de los tipos de valle. Dada la amplia variación de ambientes, una alternativa para definir el ciclo de madurez de la planta ha sido el uso del tiempo térmico acumulado (TTA). Esta medida permite la predicción del ciclo de la planta y proporciona apoyo para definir la duración de la fenología, siendo útil en el manejo y mejoramiento de los cultivos. Este estudio tuvo como objetivo calcular las unidades térmicas para 13 códigos de la escala BBCH de la quinua, mediante la evaluación de 12 progenies seleccionadas y cultivadas en dos fechas de siembra, a 15° 56' S y 47° 55' O, altitud de 1.100 m, Brasilia, DF, Brasil. Las diferencias estadísticas fueron predominantes desde el inicio de las fases reproductivas BBCH-50, clasificando las progenies como precoces, de ciclo medio y tardías. Las progenies de madurez temprana y sus respectivos TTA para BBCH-89 son BRQ4 (1.676,8), BRQ1 (1.685) y AUR (1.691), contrastando con las tardías BLA (2.239), BRQ3 (1.929,1 GDD) y BRQ8 (1.895). Las unidades térmicas acumuladas para BBCH-89 oscilaron entre 1.565,25 y 2.381, con una diferencia entre los genotipos más precoces y los más tardíos de 815,75. Las progenies seleccionadas de los cultivares existentes son diferentes en cuanto a la acumulación de unidades térmicas, lo que implica la eficiencia en la adquisición de cultivares para escalonar el cultivo de quinua. Las unidades térmicas acumuladas explican el rango de ciclos de maduración de las plantas en la selección. Además, el cálculo del TTA para los códigos de la escala BBCH es una herramienta eficaz para predecir el ciclo fenológico de la quinua.

Palabras clave adicionales: *Chenopodium quinoa* Willd.; fenología; selección; manejo del cultivo, grados día.

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INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.), a novel crop to the world, has been continuously selected in the Andes of South America, characterizing its gradual expansion from around Titicaca Lake, between Bolivia and Peru, the probable center of origin (Maughan *et al*., 2004). The expansion of quinoa growth occurred to the North (Ecuador, Colombia, and Venezuela) and to the South (Argentina and Chile), from the Andean Altiplano to the valleys and coastal regions. The expansion of quinoa cultivation occurred slowly, dispersing into environments of great climatic differences (Bertero *et al*., 2004).

Peru and Bolivia have been the major quinoa producers, followed by Ecuador and Argentina (Perez-Rea and Antezana-Gomez, 2018). In Brazil, the interest in quinoa cropping started in the 1990's, as an option for diversification of cropping systems its excellent food source. In addition, with the no-till system evolution, it contributes biomass to protect the soil in the dry season and uses low quantities of seeds in sowing, a favorable factor to expand cultivation (Spehar *et al*., 2015a).

Thermal units, also known as growing degree days and heat units, are a way of incorporating both temperature and time into one measurement to quantify the rate of plant growth in response to temperature. Calculation of thermal units allows defining of the accumulated thermal units (ATU) for each phase of plant growth and development (Renato *et al*., 2013). ATU has been successfully employed in agriculture, particularly in phenological studies. The concept of thermal time, first introduced in 1730 by R. A. F. de Reaumur, to predict phenological events more affected by location and sowing date, as an alternative for the number of days, affected by the temperature of location (McMaster and Wilhelm, 1997).

Employing or calculation of thermal units can be useful in predicting the phases of plant growth and development, such as seedling emergence, early growth, flower initiation, reproductive period, and its subdivisions. Thermal units can be a tool to determine the sowing and harvest time of crops affected by climate change. The rise in temperature speeds up the phases; therefore, using the number of days alone has been no longer valid to assess growth and development phases (Sharma *et al*., 2021). Variations in air temperature can anticipate the phenological phases, turning the events of crop growth less unpredictable when measured in the number of days (Souza *et al*., 2017).

In the calculation of thermal units, one must consider the base temperature (BT), which is specific for every plant crop species. In quinoa it has been reported that BT seems to vary according to phenological phase (Garcia-Parra *et al*., 2020a). Quinoa has shown a high potential to adapt to different environments, being exposed to variable temperatures, affecting the length of plant phenology (Jojoa *et al*., 2021).

Clearly defined phenological stages are of great importance for phenotype reproducibility. Several studies have investigated and described the phenological stages of quinoa. These studies have provided valuable information on crop characterization (Stanschewski *et al*., 2021). Currently, the phenological stages of quinoa are described using the Biologische Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) scale, presenting as main phases germination (0), leaf development (1), formation of lateral buds (secondary stems) (2), inflorescence emergence (5), flowering (6), fruit development (7), ripening (8), senescence (9) (Sosa-Zuniga *et al*., 2017). Secondary phases are adapted to the changing behavior of different cultivars, which are influenced by environmental effects and their generic character (Garcia-Parra *et al*., 2020b).

Quinoa genotypes have shown variability in phenological phases as response to temperature (Anchico *et al*., 2020). Studies using (ATU) to describe quinoa growth and development are scarce and do not provide comprehensive information to predict the phenological phases of the crop. The information is essential to guide research on crop breeding and management for efficient production. In view of this, the study had the objective to calculate the thermal units for 13 codes of the BBCH scale of quinoa from the evaluation of 12 selected progenies grown in two sowing dates in the Brazilian Savannah.

MATERIALS AND METHODS

Physiographic characteristics of location and soil management

Two experiments (Season 1 - March / June 2018 and Season 2 -May / August 2019) were conducted in Água Limpa Farm, University of Brasilia (UnB), Federal District, Brazil, coordinates of 15° 56' S and 47° 55' W, at an altitude of 1,100 m. It is located in the core of the Cerrado Region (Brazilian Savannah physiognomy). The climate has been described according to Köeppen, as Aw, characterized by rainy period, October to April, and dry period, May to September (Kottek *et al*., 2006). Mean temperature during the

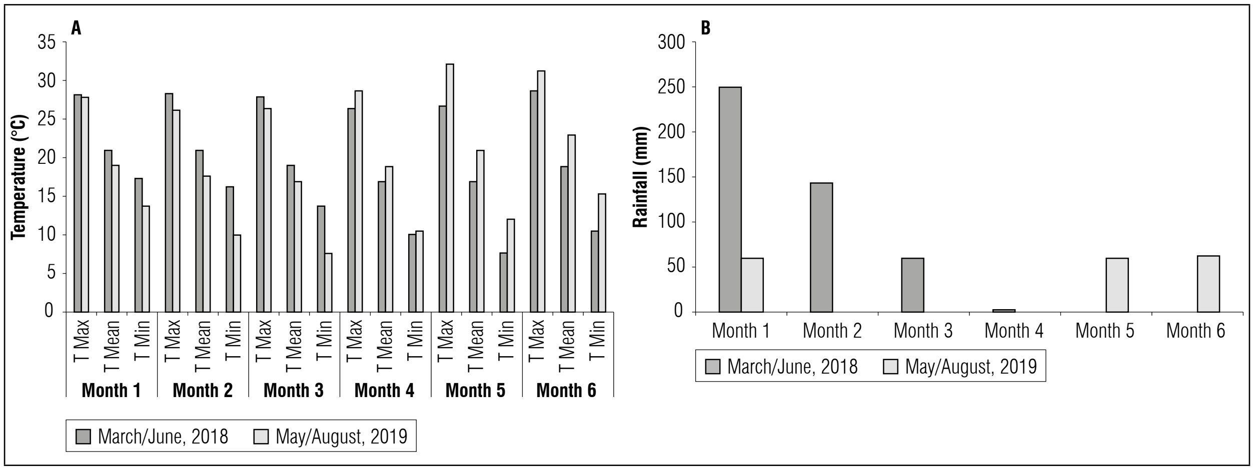

Figure 1. Temperature and rainfall during two growing periods: (March/June, 2018) and (May/August, 2019).

experiments was 19.0 and 19.45°C, with maximum mean temperature of 27.6 and 28,8°C, and minimum mean temperature of 12.5 and 11.5°C. Rainfall was 451.7 mm and 141.5 mm, respectively for the two sowing dates (Fig. 1).

Prior to setting experiments, the area was fertilized according to the requirements of quinoa cropping with N, P_2O_5, and K_2O sources in the proportion of 12:90:48 kg ha^{-1}, harrowed, leveled off, and rows equally spaced by 0.5 m were opened (Spehar *et al*., 2015b). Thirty days after emergence, the plots received N in the dose of 40 kg ha^{-1}, band applied, and were kept weed-free by hand hoeing. The experiments were sprinkler irrigated when water tension reached 40 kPa based on tensiometers installed in the area. For the quinoa cycle, 350 mm of irrigation water was required.

Quinoa genotypes and selected progenies

Progenies were obtained in Brazil and in Colombia at altitudes of 1,100 e 1,800 m by individual plant selection in existing cultivars (Anchico *et al*., 2020): a) Progenies BRQ1, BRQ 2, BRQ 3, BRQ 4, BRQ 5, BRQ 6, BRQ 8, and BRQ 10, from cultivar BRS Syetetuba (Brazil), of plant maturity cycle between 95 to 121 d and yield in the range of 1,500 and 2,200 kg ha^{-1}; b) progeny from cultivar Aurora (AUR) (Colombia) of 97 d to maturity and 2,121 kg ha^{-1} yield; c) progeny from cultivar Blanca Dulce de Jerico (BLA) (Colombia) 150 d to maturity and 1,500 kg ha^{-1} yield; d) progeny of the cultivar Tunkahuan (TUN) originally from Ecuador and selected in Colombia, 118 d to maturity and 1,300 kg ha^{-1} yield e) cultivar Piartal (PRI) originally from Ecuador and selected in Colombia, 109 d to maturity and 1,500 kg ha^{-1} yield.

Phenological evaluation

The first evaluations were made between March and June 2018 and the second between May and August 2019. The phenological stages of quinoa in this research were classified according to the BBCH scale, which are described below: BBCH-08 (Hypocotyl with cotyledons growing towards soil surface, BBCH-10 (Cotyledons fully emerged), BBCH-11 (First pair of leaves visible) , BBCH-12 (Second pair of leaves visible), BBCH-13 (Third pair of leaves visible), BBCH-20 (Visible lateral buds or expanded leaves without lateral stems), BBCH-50 (Inflorescence present but still enclosed by leaves), BBCH-51 (Leaves surrounding inflorescence separated, inflorescence is visible from above), BBCH-59 (Inflorescence visible, but all the flowers are still closed), BBCH-69 (Complete anthesis: main inflorescence flowers with senesced anthers), BBCH-81 (Milky grain, easily crushed with fingernails, liquid content and green pericarp), BBCH-85 (Thick grain, easily crushed with fingernails, white pasty content, green, beige, red or black pericarp), BBCH-89 (Ripe grain, difficult to crush with fingernails, dry content, the grain has a beige, red or black colour on its outside. Ready to harvest) (Sosa-Zuniga *et al*., 2017).

Determination of thermal units

Thermal units were determined for the thirteen phenological phases of quinoa growth and development of 12 progenies, on the basis of maximum and minimum daily temperatures obtained in the meteorological station of Água Limpa Farm, UnB.

Calculation of accumulated thermal units (ATU) for quinoa considered the base temperature of 3.1°C according to (Bertero *et al*., 1999). This temperature is the minimum at which the quinoa plant paralyzes growth.

Accumulated thermal units (ATU) was estimated according to the method proposed by Arnold (1959). Two equations were used

$$TU = \frac{MT - mt}{2} - BT \qquad (1)$$

where, *TU* was thermal units, *MT* the maximum daily temperature, *mt* the minimum daily temperature and *BT* the base temperature.

The thermal summation or (ATU), was calculated by equation 2.

$$\text{ATU} = \sum TU_i \ni TU\, D_i\, n_{\ i} = 1 \qquad (2)$$

where, *n* was number of days to reach each plant growth and development phase.

Experimental design and statistical analysis

The experiments were conducted based on the randomized complete block design. Each block was consisted of eight progenies of selected individual plants from cultivar BRS Syetetuba, recommended for cultivation in the Brazilian Savannah (Spehar *et al*., 2011), in the period 2016-2018 and four progenies, two from Colombian cultivars Blanca Dulce de Jerico (BLA) and Aurora; and two from Ecuadorian cultivars Tunkahuan and Piartal. The four progenies were selected in 2017-2018. Altogether, each block contained 12 plots corresponding to progenies on six repetitions. The plot had four rows 2 m long, equally spaced by 0.5 m, with a distance between plots of 1 m. The plant density on the row was 30 plants/m^{-1}.

An analysis of variance of the values of (ATU) for phenological phases between genotypes and sowing dates was carried out and compared by Tukey's test using SPSS software. Additionally, a hierarchical analysis was performed to evaluate the relationship between progenies and (ATU) values for phenological phases and a dendogram was obtained, using the Euclidean distance, for similarity grouping (Ward, 1963).

RESULTS AND DISCUSSION

Quinoa progenies had statistically significant F test differences at $P \leq 0.01$and $P \leq 0.05$ of (ATU) for BBCH-11 to BBCH-89. (Tab. 1). Comparisons were made by ATU, standardizing the values independently of the growing environment (Zapata *et al*., 2015). Therefore, it is expected in this experiment that the genotype grown on the two sowing dates present similar ATU values. This holds to other crops of different base temperatures as soybeans (Spehar *et al*., 2015a).

The progenies studied here had variable ATU, turning into a reference to compare adaptability to cropping systems in environments different from quinoa's Andean origin (Anchico *et al*., 2020). All progenies had seedling emergence (BBCH-08) in 3 d in 2018 and 2019, with 56,98 and 50,66 ATU (Tab. 1), expressing sensitivity to the temperature at this phase, as already described experimentally in Argentina (González *et al*., 2017). This early phase of quinoa has shown more sensitivity to temperature. For the remaining phases, there were different values of ATU as related to days, turning evident the effect of temperature in plant development (Salazar-Gutiérrez *et al*., 2013). In Cotyledons fully emerged (BBCH-10), there were no statistical differences among progenies, with ATU of 112.55 in 2018 and 100.11 in 2019. In the BBCH-11 (first pair of leaves visible), there were statistical differences in the 2018 experiment; progenies AUR and PRI had less accumulated thermal units, 191.95, than the other progenies of 232.53. In 2019 all progenies had 202.17 ATU at BBCH-11. When progenies for the two experiments were compared, three groups of ATU were formed (Tab. 1).

At BBCH-12 progenies, PRI and BLA had different accumulated thermal units (ATU) at first sowing date of 394.83 and 373.48, respectively. In the second experiment, all progenies had an ATU of 305.75 for the same phase (Tab. 1). At the BBCH-13, mean values were ATU 405, with a smaller mean value in the second year with a mean ATU of 364,17. Progeny with higher ATU was BLA with 481.93. At BBCH-20, the mean ATU was 505.81, while progenies in the second year had smaller ATU, although BLA had 481.93. These differences, although statistically significant, are still acceptable to compare accumulated thermal units (ATU) for progenies at each growth and development phase in quinoa. Other uncontrolled environmental factors such as rainfall, relative air moisture, evapotranspiration, solar radiation could have influence in the plant vegetative and early reproductive phases (Parra-Coronado *et al*., 2015).

The statistical differences were more predominant from BBCH-50, separating the progenies into early, mid-cycle and late maturity. In the first experiment, progenies with smaller ATU were AUR and BRQ 1, with 933,34 and 910.24 respectively, while the largest were BRQ 3 and BRQ 2 with 1063.52 and 1048.02 ATU (Tab 1). Differences are accentuated from the beginning of the reproductive phase. A similar finding was reported for Cucurbita moschata (Souza *et al*., 2017). At BBCH-51, progenies had an ATU larger mean value of 1,164.23; for the same phase mean value was 843.72 in the second experiment, AUR 613.97 was the least thermal unit accumulator progeny (Tab. 1). BBCH-50 and BBCH-51showed a similar trend, with AUR (661.34), BRQ1 (676.48), and BRQ4 (747.11), early progenies having the least ATU, while BRQ2 and BRQ6 were late (1,160.58). At BBCH-69, significant differences were found among progenies of early, mid-cycle, and late maturity grouping. Early AUR (761.65) and BRQ 1 (777.24) contrasted with late BRQ 6 (1292.09) and BRQ 2 (1270.19G) (Tab. 1).

In the second experiment, the progenies reduced the number of days until the BBCH-59, which was reflected in the accumulated thermal units. Temperature fluctuations could have influenced these variations at flowering reflecting in the following phases (Reguera *et al*., 2018). The mean ATU between BBCH-69 and BBCH-81 was 304.5 with the least

Table 1. Accumulated thermal units (ATU) of quinoa progenies for the two planting dates (March / June, 2018) and (May / August, 2019) at BBCH-08 (hypocotyl with cotyledons growing towards soil surface), BBCH-10 (cotyledons fully emerged), BBCH-11 (first pair of leaves visible), BBCH-12 (second pair of leaves visible), BBCH-13 (third pair of leaves visible), BBCH-20 (visible lateral buds), BBCH-50 (inflorescence present but still enclosed by leaves), BBCH-51 (leaves surrounding inflorescence separated,), BBCH-59 (inflorescence visible), BBCH-69 (complete anthesis), BBCH-81 (milky grain), BBCH-85 (thick grain), and BBCH-89 (ripe grain).

SEASON 1 - MARCH / JUNE 2018													
P/E.F.	BBCH-08	BBCH-10	BBCH-11	BBCH-12	BBCH-13	BBCH-20	BBCH-50	BBCH-51	BBCH-59	BBCH-69	BBCH-81	BBCH-85	BBCH-89
AUR	56.98 a	112.55 a	191.95 c	305.75 c	434.24 c	533.13 d	933.34 f	1057.30 h	968.14 j	1093.28 i	1382.28 h	1608.81 k	1817.32 h
PRI	56.98 a	112.55 a	191.95 c	394.83 a	454.37 b	572.26 b	1035.58 bcd	1185.72 d	1110.9 f	1220.81 f	1600.02 d	1819.83 e	1981.49 e
BRQ1	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	536.38 cd	910.24 g	1032.42 i	987.29 i	1051.11 j	1307.55 i	1605.88 k	1804.81 i
BRQ4	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	539.70 cd	968.14 e	1075.96 g	1016.56 h	1110.90 h	1376.13 h	1600.02 k	1788.43 j
BRQ5	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	533.13 d	1019.59 d	1204.04 c	1125.99 de	1237.52 d	1435.65 g	1638.50 j	1885.21 g
BRQ10	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	533.13 d	1047.84 abc	1204.04 c	1141.61 bc	1250.76 c	1466.01 f	1714.83 h	2008.15 d
TUN	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	533.14 d	1038.74 bcd	1185.72 kd	1135.31 bcd	1224.17 ef	1468.78 f	1684.84 i	1918.39 f
BRQ6	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	533.13 d	1032.42 cd	1244.20 a	1160.58 a	1292.09 a	1600.02 d	1770.44 f	1918.39 f
BRQ2	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	539.63 cd	1048.02 abc	1224.17 b	1160.58 a	1270.19 b	1617.6 c	1734.97 g	2008.15 d
BRQ8	56.98 a	112.55 a	232.53 b	354.07 b	434.24 c	533.13 d	1022.94 d	1129.01 f	1087.50 g	1179.45 g	1644.29 b	1908.39 b	2031.27 c
BRQ3	56.98 a	112.55 a	232.53 b	394.83 c	454.37 b	552.67 c	1063.52 a	1224.17 b	1147.91 ab	1270.19 b	1667.84 a	1983.83 a	2099.23 b
BLA	56.98 a	112.55 a	232.53 b	373.48 ab	434.24 c	533.33 d	1044.92 abc	1204. 04 c	1132.16 cde	1234.18 de	1670.67 a	1898.96 c	2096.65 b
SEASON 2 -MAY / AUGUST 2019													
P/E.F.	BBCH-08	BBCH-10	BBCH-11	BBCH-12	BBCH-13	BBCH-20	BBCH-50	BBCH-51	BBCH-59	BBCH-69	BBCH-81	BBCH-85	BBCH-89
AUR*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	613.97 l	689.54 n	661.34 o	761.65 q	1066.83 k	1346.81 p	1565.25 n
BRQ1*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	613.97 l	704.16 m	676.48 n	777.24 p	1066.83 k	1346.81 p	1565.25 n
BRQ4*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	704.16 k	777.24 l	747.11 m	841.35 o	1066.83 k	1346.81 p	1565.25 n
BRQ5*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	761.65 j	841.35 k	816.43 l	912.11 m	1234.21 j	1391.76 n	1612.88 k
BRQ10*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	761.65 j	841.35 k	816.43 l	912.11 m	1234.21 j	1565.25 l	1759.04 k
BRQ6*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	777.24 ij	841.35 k	816.43 l	912.11 m	1234.21 j	1377.30 o	1565.25 n
BRQ8*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	777.24 ij	841.35 k	816.43 l	912.11 m	1234.21 j	1565.25 l	1759.04 k
BRQ2*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	777.24 ij	841.35 k	829.61 k	897.63 n	1234.21 j	1461.42 m	1630.12 l
BRQ3*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	777.24 ij	841.35 k	829.61 k	912.11 m	1234.21 j	1565.25 l	1759.04 k
PRI*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	792.23 hi	868.14 j	841.35 k	943.14 l	1234.21 j	1565.25 l	1759.04 k
TUN*	50.66 a	100.11 a	202.17 c	305.75 c	364.17 d	451.14 e	803.89 h	868.14 j	841.35 k	958.26 k	1234.21 j	1565.25 l	1759.04 k
BLA*	50.66 a	100.11 a	202.17 c	305.75 c	481.93 a	704.16 a	1052.98 ab	1169.31 e	1121.17 ef	1234.21 de	1565.25 e	1924.92 a	2381.00 a
S.D.	3.18	6.24	16.00	32.35	39.90	61.16	148.50	186.53	167.14	173.63	195.88	189.10	203.7
C.V. %	5.89	5.87	7.45	9.65	9. 83	12.09	16.67	18.58	17.45	16.40	14. 30	11.64	11.10
MEAN	53.83	106.33	213.97	335.20	405.79	505.81	890.78	1003.93	957.85	1058.78	1369. 85	1624.64	1834.9

In each column means followed by same letters in column do not differ significantly based on the Tukey test ($p \leq 0.05$).

values for AUR*, BRQ1*, and BRQ4*, accumulating 1,066.83 heat units (Tab. 1). Progenies BRQ3 and BLA accumulated 1,667.84 and 1,670.67 heat units. AUR had the least ATU, confirming results obtained in Colombia (Anchico *et al*., 2020; Montes-Rojas *et al*., 2018). ATU at BBCH-85 showed the same trend for AUR, BRQ1, and BRQ4 accumulating 1.346.81 thermal units, while BRQ3 (1.983.83) and BLA (1.924.92) were the latest. At BBCH-89, there were statistical differences for progenies and sowing dates. The phenological plant cycle, in days, for late maturity progenies extended to 145 d, while early maturity AUR*, BRQ1* and BRQ4* with respective ATU of 2,096.65, 2,099.23, and 2,381.00. The mean ATU difference was 223.11, indicating a reduction in phenological phases (Fig. 2).

Progenies selected from BRS Syetetuba had statistical differences for BBCH-89, demonstrating ample variability, attained by possible segregation for the lateness in the cultivar originated from natural crosses (Spehar *et al*., 2015b). The spread of progenies into early, mid-cycle and late maturity has kept the relationship among them when tested in Colombia at different altitudes and temperatures, althoughs kept the relationship when tested in Colombia at different altitudes and temperatures. However, the ATU at BBCH-89 were not statistically different (Anchico *et al*., 2020).

In this experiment, progenies were classified up to BBCH-89, expressing potential adaptability relating to the environment they were selected (Bois *et al*., 2006). Progeny BLA of cultivar Blanca Dulce de Jerico had the highest ATU (2.239) (Tab. 2), extending the plant maturity cycle to180-214 d at environments above 2,000 m a.s.l. and low temperature (Montes-Rojas *et al*., 2018). This would be predicted by the use of accumulated heath units in quinoa cultivation instead of the number of days to maturity.

The use of ATU helped to describe the duration of phenological phases of quinoa, which can be useful to manage the crop in all phases best, guiding the time for fertilization, plant protection, irrigation and in genotype selection to originate different maturity groupings (Anandhi, 2016). Moreover, predictability ATU of phenological phases can direct selection in quinoa to face climate changes (Sharma *et al*., 2021).

When the two sowing dates are considered, progenies accumulated less heat units in May/August 2019, although the number of days was higher. This could be explained by uncontrolled factors, as moisture availability. The experiment conducted in March/June 2018 received more water because, in addition to irrigation, there was considerable rainfall in the period, whereas in May/August experiment relied almost entirely on irrigation. Excess water in the first experiment and lower temperatures in the second

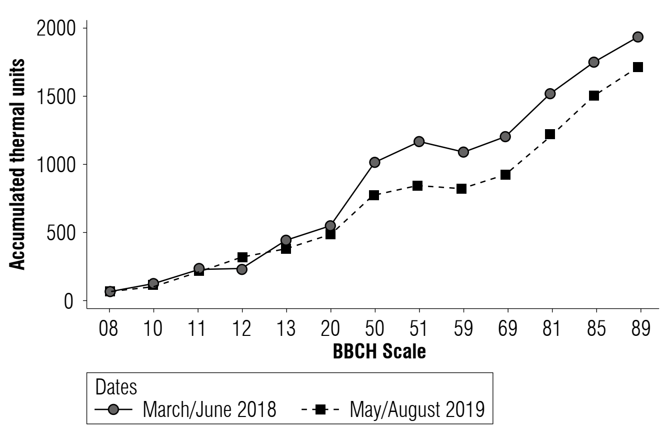

Figure 2. Accumulated thermal units (ATU) for the two growing periods for BBCH-08 (hypocotyl with cotyledons growing towards soil surface), BBCH-10 (cotyledons fully emerged), BBCH-11 (first pair of visible leaves), BBCH-12 (second pair of visible leaves), BBCH-13 (third pair of visible leaves), BBCH-20 (visible lateral buds), BBCH-50 (inflorescence present but still enclosed by leaves), BBCH-51 (leaves surrounding inflorescence have separated,), BBCH-59 (inflorescence visible), BBCH-69 (complete anthesis), BBCH-81 (milky grain), BBCH-85 (thick grain), and BBCH-89 (ripe grain).

Table 2. Accumulated thermal units (ATU) of 12 quinoa progenies in BBCH-08 (hypocotyl with cotyledons growing towards soil surface), BBCH-10 (cotyledons fully emerged), BBCH-11 (first pair of leaves visible), BBCH-12 (second pair of leaves visible), BBCH-13 (third pair of leaves visible), BBCH-20 (visible lateral buds), BBCH-50 (inflorescence present but still enclosed by leaves), BBCH-51 (leaves surrounding inflorescence separated,), BBCH-59 (inflorescence visible), BBCH-69 (complete anthesis), BBCH-81 (milky grain), BBCH-85 (thick grain), and BBCH-89 (ripe grain).

Progenies	BBCH-08	BBCH-10	BBCH-11	BBCH-12	BBCH-13	BBCH-20	BBCH-50	BBCH-51	BBCH-59	BBCH-69	BBCH-81	BBCH-85	BBCH-89
BRQ1	53.822a	106.33a	217.35a	329.91a	399.2b	493.8b	762.1b	868.3b	831.9b	914.2b	1187.2d	1476.3e	1685d
BRQ2	53.822a	106.33a	217.35a	329.91a	399.2b	495.4b	912.6ab	1032.8ab	995.1ab	1083.9ab	1425.9abc	1598.2bcde	1819.1bcd
BRQ3	53.822a	106.33a	217.35a	350.3a	409.3ab	501.9b	920.4ab	1032.8ab	988.8ab	1091.2ab	1451ab	1774.5ab	1929.1b
BRQ4	53.822a	106.33a	217.35a	329.91a	399.2b	495.4b	836.1b	926.6b	881.8b	976.1b	1221.5cd	1473.4e	1676.8d
BRQ5	53.822a	106.33a	217.35a	329.91a	399.2b	492.1b	890.6ab	1022.7ab	971.2ab	1074.8ab	1334.9bcd	1515.1de	1749bcd
BRQ6	53.822a	106.33a	217.35a	329.91a	399.2b	492.1b	904.8ab	1042.8ab	988.5ab	1102.1ab	1417.1abc	1573.9cde	1741.8bcd
BRQ8	53.822a	106.33a	217.35a	329.91a	399.2b	492.1b	900.1ab	985.2ab	952ab	1045.8ab	1439.3abc	1736.8abc	1895.2b
BRQ10	53.822a	106.33a	217.35a	329.91a	399.2b	492.1b	904.7ab	1022.7ab	979ab	1081.4ab	1350.1bcd	1640bcde	1883.6bc
AUR	53.822a	106.33a	197.06b	329.91a	399.2b	492.1b	773.7b	873.4b	814.7b	927.5b	1224.6cd	1477.8e	1691.3cd
PRI	53.822a	106.33a	197.06b	350.3a	409.3ab	511.7b	913.9ab	1026.9ab	976.1ab	1082ab	1417.1abc	1692.5bcd	1870.3bcd
TUN	53.822a	106.33a	214.82ab	342.9a	393.4b	485.3b	901.7ab	1000.5ab	964.4ab	1069.1ab	1332.2bcd	1615.1bcde	1825.4bcd
BLA	53.296a	106.33a	217.35a	339.6a	458.09a	618.7a	1048.95a	1186.68a	1126.66a	1234.2a	1618a	1911.94a	2239a
S.D.	0,15	0,29	7,82	8,31	17,22	36,32	74,33	85,05	82,489	85,71	120,67	136,23	154,95
CV (%)	0.28	0.28	3.66	2.48	4.25	7.19	8.36	8.49	8.63	8.11	8.82	8.39	8.45
MEAN	53.78	106.24	213.76	335.20	405.31	505.23	889.14	1001.78	955.85	1056.86	1368.24	1623.795	1833.8

In each column means followed by same letters in column do not differ significantly based on the Tukey test ($P \leq 0.05$).

could help explaining differences in ATU and in days to each phase (Tab. 1). Differences for ATU among the phases, although were statistically different, showed a similar pattern in the groupings (Tab.2). Higher temperatures in the second experiment could explain the anticipation of growth and development phases in quinoa (Asseng *et al*., 2011; Parra-Coronado *et al*., 2015).

In general, progenies accumulating lower thermal units were BRQ4 (1.676,8), BRQ1 (1,685), and AUR (1,691). The ones with higher ATU were BLA (2.239), BRQ3 (1,929.1 GDD), and BRQ8 (1,895) (Tab. 2). Late progenies were identified from BBCH-13 onwards, presenting higher ATU values, a characteristic that was maintained until BBCH-89 (Tab. 2).

Between the beginning of the reproductive phase BBCH-50 and the mature grain phase BBCH-89, an ATU of 944.66 (Tab. 2) was presented, representing 51% of the total of the studied cycle.

Temperatures, higher than in Andean Valleys and in Colombia, conditioned reduction in days to plant cycle, accelerating enzymatic activities in the plant and the phenological phases (Asseng *et al*., 2011; Souza *et al*., 2017).

Euclidean distance of 5 was used for the 12 progenies based on accumulated thermal units in the 13 codes of the BBCH scale, according to (Hair *et al*., 2005). Five hierarchical groups of similarity were defined (Fig. 3).

Group I was formed by three progenies, two selected from BRS Syetetuba (BRQ 1 and BRQ 4) and one Aurora (AUR). These progenies presented lower thermal units, therefore they were the most precocious.

Grupo II contained five progenies, all selected from BRS Syetetuba (BRQ2, BRQ6, BRQ5, BRQ8, BRQ10). These differed from the preceding groups, with higher ATU.

Group III had two progenies, one from BRS Syetetuba (BRQ3) one from Piartal (PRI), dissimilar to the group I.

Group IV is made up of one progeny of Tunkahuan (TUN), dissimilar to preceding groups I, with higher ATU.

Group V had one progeny of Blanca Dulce de Jerico (BLA), being the highest thermal unit accumulator and dissimilar to other groups.

Hierarchical clustering allowed determining the similarity of genotypes in the accumulation of thermal units, showing a significant difference between genotypes in the first and fourth groups. This helped to identify early, medium and late genotypes. The grouping helped to visualize the relationship among progenies and relate the plant maturity cycle to the ATU. There were other factors differentiating the experiments as excess water in the first sowing date that could have caused a departure from expected results. Even though they were statistically different, there was a similar trend, turning the predictable definition of maturity groups based on ATU.

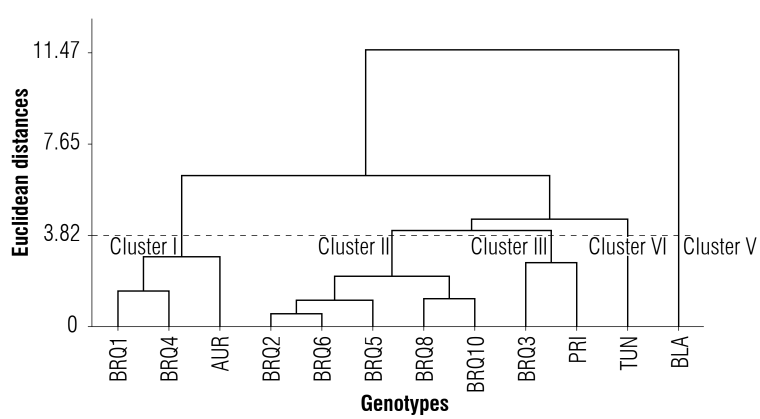

Figure 3. Dendrogram for hierarchical grouping of 12 quinoa progenies using accumulated thermal units (ATU).

CONCLUSION

The use of accumulated thermal units allows the prediction of phenological events in quinoa of different maturity groups. The BRQ4, BRQ1 and AUR progenies were the earliest with the lowest Accumulated Thermal Units (ATU) values, averaging 1676, 1685 and 1691, respectively. However, the progenies BLA and BRQ 3 were the later with ATU values of 2239 and 1929, respectively. The accumulated thermal units for BBCH-89 ranged from 1565.25 to 2381, with a difference between the earliest and latest genotypes of 815.75. Progenies selected from existing cultivars are different in thermal unit accumulation, ensuing efficiency in cultivar acquisition to stagger quinoa cultivation. Accumulated thermal units explain the range of plant maturity cycles in selection. The calculation of ATU for the BBCH scale codes is an efficient tool to predict the phenological cycle of quinoa.

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