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CROP PRODUCTION

Thermal sum of potato plants and tuber sprouting

Dilson Antônio Bisognin[1*] Douglas Renato Müller[2]
Nereu Augusto Streck[1] Francisco Saccol Gnocato[3]

[1]Departamento de Fitotecnia, Centro de Ciências Rurais (CCR), Universidade Federal de Santa Maria (UFSM), 97105-900, Santa Maria, RS, Brasil. E-mail: dilson.bisognin@ufsm.br. *Corresponding author.
[2]Instituto Federal Farroupilha, Campus Frederico Westphalen, Frederico Westphalen, RS, Brasil.
[3]Programa de Pós-graduação em Agronomia, Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brasil.

ABSTRACT: *This study aimed to determine the thermal sum of the different stages of development of potato plants to better understand its relationship with tuber sprouting. The potato clones SMIJ461-1, SMINIA793101-3 and SMINIA97145-2 and the cultivar Macaca were evaluated in spring and autumn crop seasons in Santa Maria and Julio de Castilhos, RS. Emergence (EM), tuber initiation (TI) and onset of senescence (OS) of the plants were determined and the accumulated thermal sum (aTS) was calculated in each phase. After harvesting, tubers were stored at 20°C for 15 days for curing and then stored at 10 or 20°C to quantify the percentage of sprouted tubers and the number of sprouts per tuber at 0, 30, 60 and 90 days of storage. The experiment was a factorial of four potato clones and two growth conditions, season and storage temperature, in a random design with four replications of 20 tubers. The environmental conditions of Julio de Castilhos in the spring resulted in a greater aTS from EM and TI to OS than those of Santa Maria, meaning that different crop locations and even seasons should be considered for making inferences about tuber sprouting based upon aTS. The management of storage temperature can promote or retard tuber sprouting, but its effect depends on the potato clone. Based upon combined correlation estimations, the aTS between EM-OS or between TI-OS is a good estimator for potato tuber sprouting.*
Key words: *Solanum tuberosum L, day-degree, physiological age.*

Soma térmica das plantas e brotação dos tubérculos de batata

RESUMO: *O objetivo foi determinar a soma térmica das diferentes fases de desenvolvimento das plantas de batata para inferir sobre a sua relação com a brotação de tubérculos. Foram avaliados os clones SMIJ461-1, SMINIA793101-3 e SMINIA97145-2 e a cultivar Macaca de batata durante os cultivos de primavera e outono em Santa Maria e Julio de Castilhos, RS. Foram determinados a emergência (EM), o início da tuberização (IT) e o início da senescência (IS) das plantas e calculada a soma térmica acumulada (STa) em cada fase. Após colhidos, os tubérculos foram submetidos a cura por 15 dias a 20°C e armazenados a 10 ou 20°C e quantificados a porcentagem de tubérculos brotados e o número de brotos por tubérculo aos 0, 30, 60 e 90 dias de armazenamento. O experimento foi um fatorial de quatro clones de batata, dois cultivos, dois locais e duas temperaturas de armazenamento, no delineamento inteiramente casualizado, com quatro repetições de 20 tubérculos. Tubérculos produzidos em Julio de Castilhos e na primavera apresentaram maiores valores de STa entre a EM ou IT até IS do que aqueles produzidos em Santa Maria, indicando que diferentes locais e até estações de cultivo devem ser considerados para inferir sobre a brotação dos tubérculos com base na STa. O manejo da temperatura de armazenamento pode ser utilizado para promover ou retardar a brotação dos tubérculos, cujo efeito também depende do clone. As altas estimativas combinadas de correlação permitem concluir que a STa entre a EM-IS ou entre o IT-IS pode ser utilizada para estimar a brotação dos tubérculos de batata.*
Palavras-chave: *Solanum tuberosum L, graus dia, idade fisiológica.*

INTRODUCTION

Tuber initiation is a complex process of potato development that involves the differentiation of stolons into storage organs called tubers, at which point the sink-source relationship of potato plant is reversed and tubers become the main sink, rather than growth and foliar development (HELDWEIN et al., 2009). Tuber initiation (TI) in potatoes is influenced mainly by air temperature and photoperiod (BEUKEMA & VAN DER ZAAG, 1990; STECK et al., 2007; BISOGNIN et al., 2008b;) and short days induce TI in potatoes (STRECK et al., 2007).

The effect of the photoperiod is relatively well known in potatoes. Short days lead to early TI, shorter stolons and a less developed shoot, while long

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days lead to a delayed TI, with long stolons and a more abundant shoot (BEUKEMA & VAN DER ZAAG, 1990). Although, the photoperiod is a determinant of TI, low nighttime temperatures stimulate TI in potatoes. Nighttime temperatures below 17°C and daytime temperatures between 23 and 25°C are the most favorable for tuber production (HELDWEIN et al., 2009), whereas high temperatures stimulate the growth of the shoot, to detriment of tubers (BEUKEMA & VAN DER ZAAG, 1990).

After harvest, storage temperature is the main factor involved in the advancement of the physiological age of tubers (WIERSEMA, 1985; CALDIZ, 2009;). This advancement includes the stages of dormancy (absence of sprouts or dormant buds), apical dominance (just one sprout), full sprouting (several side sprouts) and senescence (intense branching of the sprouts) (WIERSEMA, 1985; STRUIK, 2007; BISOGNIN et al., 2008a). However, the rate of advancement through the different stages is highly dependent on the cultivar (STRUIK, 2007) and the environmental conditions during growth and storage (WIERSEMA, 1985; STRUIK et al., 2006; BISOGNIN et al., 2008a; HELDWEIN et al., 2009). For both scientific and practical purposes, a good indicator of physiological age would be very useful (STRUIK et al., 2006), since it directly influences the yield potential of the tuber seed (STRUIK, 2007).

The indication of new cultivars for subtropical conditions of southern Brazil, where there are two annual crops, implies the need for their adaptation to different conditions of photoperiod and air temperature as well as the need for them to present a short period of dormancy. In this context, the thermal sum method, which is based on the premise that plants respond to a thermal sum to complete each phase of development (PAL et al., 2005), may be a useful tool to estimate potato tuber sprouting, facilitating post-harvest management. Some studies have proposed an estimation of the phases of the potato development cycle (PAULA et al., 2005), but there has been no research seeking to estimate the physiological stage of tubers using the thermal sum method.

The aim of this study was to determine the thermal sum of the different developmental stages of potato plants to understand its relationship with the sprouting of tubers produced and stored under different conditions.

MATERIALS AND METHODS

Potato tubers were produced in fields of the Plant Science Department at the Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brazil (latitude: 29° 43’S, longitude: 53° 48’W, altitude: 95m) and at the State Agricultural Research Foundation (FEPAGRO) in Julio de Castilhos, Rio Grande do Sul, Brazil (latitude: 29° 17’S, longitude: 69° 53’W, altitude: 516m). The representative soil of Santa Maria is a dystrophic, sandy, red-yellow argisol, belonging to the São Pedro mapping unit, and that of Julio de Castilhos is a typical dystrophic dark red latosol, belonging to the Cruz Alta mapping unit (EMBRAPA, 1999).

We evaluated the clones SMIJ461-1, SMINIA793101-3, SMINIA97145-2 and the cultivar Macaca, which is widely cultivated in the central region of Rio Grande do Sul. To simplify, the cultivar Macaca will also be referred to as clone. The experimental unit was four rows of 25 hills, spaced 0.33cm within row and 0.75cm among rows. Each clone was replicated four times in the field. Well-sprouted tubers of each clone were planted at subsequent days in Santa Maria and Julio de Castilhos during spring 2006 and autumn 2007 crop seasons. Emergence (EM), tuber initiation (TI) and onset of senescence (OS) were determined during plant growth. The date of EM was considered that on which 50% of the plants in the plot were visible above the ground. Tuber initiation was considered the date when two of the four plants, sampled daily, showed at least one tuber with 1cm in diameter (HELDWEIN et al., 2009). The date of OS was considered that on which 50% of the plants in the plot showed all yellowed leaves. Plants were desiccated with Paraquat when the last clone reached OS.

After the harvest, the tubers were classified into type A (diameter between 45 and 60mm) and type B (diameter between 23 and 44mm) and were placed in storage at 20ºC for 15 days for curing. All sampling units of all treatments were composed of the same number of tubers of each type, since size affects the physiological age of the tuber (MULLER et al., 2010). The experiment was conducted as a factorial of four clones, two storage temperatures (10 and 20°C±1), two crop seasons (fall and spring) and two locations (Santa Maria and Julio de Castilhos), in a complete random design, with four replicates of 20 tubers. Relative humidity of the air inside of the chambers was maintained at 85% with a variation of ±5%.

Percentage and number of sprouts per tuber were determined at 0, 30, 60 and 90 days of storage. Tubers were recorded as sprouted with at least one sprout of at least 2mm in length (HELDWEIN et al., 2009), and values were expressed in percentage. The number of sprouts larger than 2mm were counted in each tuber. Percentage of sprouted tubers and number of sprouts per tuber during storage were used to calculate the area under the sprouting progression curve (BENEDETTI et al., 2005).

The data of minimum and maximum daily air temperature during the experimental period were collected in Santa Maria, at the Main Climatological Station, belonging to the 8th District of meteorology, National Institute of Meteorology, located approximately 100m from the experimental area and in Julio de Castilhos, at an agrometeorological station, located approximately 500m from the experimental area. Daily thermal sum (dTS, ºC day) was calculated by the equation described by MCMASTER & WILHELM (1997): dTS = (Tmn-Tb) x 1 day. If Tb < Tmn, then Tmn = Tb, where Tmn is the mean daily air temperature, calculated by the arithmetic mean of the daily maximum and minimum air temperatures of the air, and Tb is the base temperature for the development of the potato plant. In this study, Tb = 7ºC was used (PAULA et al., 2005). Accumulated thermal sum (aTS, °C day) from emergence was calculated by aTS =Σ dTS. Duration of the phases EM-TI and TI-OS was calculated in aTS (ºC day).

The data were subjected to analysis of variance for the F test and the clones were compared by Tukey's test, at a 5% level of error probability. In addition, the Pearson analysis of linear correlation was performed between the accumulated thermal sum of the phases EM-TI, TI-OS and EM-OS and the area under the progression curve of percentage of sprouted tubers and the number of sprouts per tuber. All analyses were carried out with the aid of the NTIA program (EMBRAPA, 1997).

RESULTS AND DISCUSSION

In both locations, there were greater mean values of accumulated thermal sum in the EM-TI phase in the autumn crop, and in the TI-OS phase in the spring crop season (Table 1) due to the normal period of higher mean air temperature. This difference in air temperature between the crops was also responsible for the increased tuber yield in the spring, when there is both greater availability of solar radiation (BISOGNIN et al., 2008b) and more favorable temperatures to stimulate TI in potato, of between 16 and 18°C (BEUKEMA & VAN DER ZAAG, 1990). High temperatures cause delayed tuber formation, reduced yield and physiological problems (STRECK et al., 2007).

Thermal conditions in the spring, both for TI and for tuber production, are more favorable than in the fall, leading to a greater accumulation of day-degrees during the potato development cycle, mainly due to greater accumulation of the thermal sum in the TI-OS phase. When comparing the crop locations, the mean aTS was higher for both crops in Julio de Castilhos, except for EM-TI during spring and TI-OS during autumn (Table 1). Thus, the thermal conditions reported in Julio de Castilhos favored greater accumulation of day-degrees, resulting in different values of aTS. If the accumulation of day-degrees is associated with the degree of tuber maturity, the greater aTS accelerates physiological age and, as a result, tubers may sprout earlier.

There were significant interactions among clone, location, crop and storage temperature for both percentage of sprouted tubers (P>F 0.0030) and number of sprouts per tuber (P>F 0.0000). Tubers produced in

Table 1 - Accumulated thermal sum (aTS) in the phases of emergence (EM), tuber initiation (TI), onset of senescence (OS) and EM-OS of potato clones in two crops and locations.

Clones/Cultivar	----aTS (°C day) EM-TI----		----aTS (°C day) TI-OS----		----aTS (°C day) EM-OS---	
	Spring	Autumn	Spring	Autumn	Spring	Autumn
--------Santa Maria--------						
SMINIA793101-3	293.5	346.9	675.2	471.6	968.6	818.5
Macaca	177.9	254.4	745.1	543.5	923.0	797.9
SMIJ461-1	199.0	454.5	727.1	328.4	926.1	782.8
SMINIA97145-2	330.4	399.75	449.5	293.4	779.8	693.1
Mean	250.2	363.9	649.2	409.2	899.4	773.1
--------Julio de Castilhos--------						
SMINIA793101-3	303.3	485.3	805.3	368.3	1108.6	853.5
Macaca	177.7	501.5	878.8	384.0	1056.5	885.5
SMIJ461-1	248.9	307.5	767.5	348.3	1016.3	655.7
SMINIA97145-2	201.3	479.3	892.4	364.0	1093.7	843.2
Mean	232.8	443.4	836.0	366.1	1068.8	809.5

Julio de Castilhos in the spring crop and the ones of clones Macaca and SMINIA97145-2 in the autumn crop presented a higher area below the progression curve of percentage of sprouted tubers and number of sprouts per tuber than those produced in Santa Maria (Table 2). In addition, tubers produced in the spring presented a higher mean aTS in the EM-OS than those produced in the autumn crop (Table 1). BEUKEMA & VAN DER ZAAG (1990) attributed the decrease in tuber dormancy to increasing photoperiod and temperature conditions at the end of the spring crop season, which speeds up the physiological age and sprouting of tubers, reducing the storage time (BISOGNIN et al., 2008a). This may also be related to the tuber hormone level, since environmental factors, such as temperature and photoperiod, can alter the balance between gibberellins and abscisic acid. Progressive decrease of temperature, characteristic of autumn crop season, induce plants to develop freezing tolerance, by increasing levels of endogenous abscisic acid in the leaves, which is an important cause of dormancy in potato tubers (AKSENOVA et al., 2013).

The effect of air temperature on the physiological stage of the tuber, both at the site and at the time of growth, can be ameliorated through proper management of storage temperature, providing suitable sprouting until the time of planting. Tubers stored at 20°C for 90 days sprouted 25.2% and 22.8% more than those stored at 10°C, for spring and autumn crop seasons, respectively (Table 2). A 50% reduction in the period of tuber storage until sprouting was reported only for the effect of crop season (BISOGNIN et al., 2008a) and it was recommended that tuber seeds produced in the fall be stored at 12°C whereas those produced in the spring should be stored at 8 or 4°C, due to these differences in physiological age. Low storage temperatures (<10°C) favor dormancy and reduce apical

Table 2 - Areas below the progression curve of percentage of sprouted tubers (%ST) and number of sprouts per tuber (NS/T) of potato clones produced in two different crops and locations and stored at 10 and 20ºC for 90 days.

Trait	Clones/Cultivar	Location		Storage Temperature	
		Santa Maria	Julio de Castilhos	10ºC	20ºC
Spring Crop					
%ST	Macaca	0.4395b[1] B[2]	0.7621a A	0.5354b B	0.6663b A
	SMIJ461-1	0.2683c B	0.5667b A	0.2868c B	0.5482c A
	SMINIA793101-3	0.3922b B	0.8090a A	0.5541ab B	0.6471b A
	SMINIA97145-2	0.5804a B	0.7942a A	0.5976a B	0.7771a A
	Mean	0.4176	0.7330	0.4934	0.6596
	CV(%) = 6.54				
NS/T	Macaca	0.0202a B	0.0421a A	0.0237a B	0.0385a A
	SMIJ461-1	0.0063c B	0.0147d A	0.0065d B	0.0144c A
	SMINIA793101-3	0.0130b B	0.0356b A	0.0148c B	0.0338b A
	SMINIA97145-2	0.0193 a B	0.0308c A	0.0187b B	0.0314b A
	Mean	0.0147	0.0308	0.0159	0.0295
	CV(%) = 10.68				
Autumn Crop					
%ST	Macaca	0.1707a B	0.2341a A	0.1365a B	0.2683a A
	SMIJ461-1	0.0755bc A	0.0815c A	0.0000c B	0.1571b A
	SMINIA793101-3	0.0896b A	0.0745c A	0.0000c B	0.1642b A
	SMINIA97145-2	0.0497c B	0.1598b A	0.0377b B	0.1718b A
	Mean	0.0963	0.1374	0.0435	0.1903
	CV(%) = 16.11				
NS/T	Macaca	0.0049a B	0.0097a A	0.0040a B	0.0105a A
	SMIJ461-1	0.0009b A	0.0011c A	0.0000b B	0.0020d A
	SMINIA793101-3	0.0015b A	0.0017c A	0.0000b B	0.0032c A
	SMINIA97145-2	0.0008b B	0.0041b A	0.0006b B	0.0043b A
	Mean	0.0020	0.0041	0.0011	0.0050
	CV(%) = 18.60				

[1]Means of clones not followed by the same lowercase letter in the columns differ by the Tukey test at 5% error probability. [2]Means of location and temperature not followed by the same uppercase letter in the rows differ by the Tukey test at 5% error probability.

dominance in tubers, while high temperatures (>25ºC) accelerate sprouting but do not favor breaking of apical dominance (BISOGNIN et al., 2008a; MULLER et al., 2010). Moreover, the advancement of tuber physiological age varies depending on whether storage temperatures are constant or fluctuating (combinations of high and low temperatures) and high temperatures at the end of the storage period are detrimental to cultivars with a high rate of physiological aging (STRUIK et al., 2006). Therefore, temperature is the environmental factor that most affects the period of dormancy and cold storage is the most widely used technology in the world to retard sprouting of potato tubers (ESHEL & TEPER-BAMNOLKER, 2012).

This study evaluated four potato clones that differ in tuber dormancy and adaptation to crop conditions of southern Brazil, since the advancement of physiological age of tubers is highly dependent on the cultivar (STRUIK, 2007). The clones Macaca and SMIJ461-1 presented the greatest difference, with Macaca being the most well adapted to crop conditions associated with short tuber dormancy. When comparing these two clones, Macaca always presented higher aTS in the TI-OS phase than SMIJ461-1, for both locations and crop seasons (Table 1), as well as higher percentage of sprouted tubers and number of sprouts per tuber (Table 2). In addition, even when there were very similar aTS values, as for example, the aTS in the TI-OS phase during the spring season of both locations, Macaca still presented higher percentage of sprouted tubers and number of sprouts per tuber than SMIJ461-1. This confirmed that the advance in physiological age of tubers and, as a result, the post-harvest management in potatoes, are very dependent on the evaluated clone.

Considering mean values of location and crop season, the correlation analysis between aTS in the different phases of the potato development cycle and the percentage of sprouted tubers and number of sprouts per tuber indicated high values of positive correlation for the EM-OS and TI-OS phases and a negative correlation for the EM-TI phase (Table 3). As expected, the TI-OS phase was more important than the EM-TI to predict tuber sprouting, and both EM-OS and TI-OS phases showed high and positive correlations with aTS. Thus, the aTS in the EM-OS and TI-OS phases can be used as an indication of the physiological stage of tubers and to make inferences about their length of their sprouting period. TI is considered the most scientifically accepted inference for measuring the physiological age of tubers (WIERSEMA, 1985), but in practice it is much more difficult to determine TI than EM in plants. In addition, highly significant values ($P<0.01$) of correlation between EM-OS and TI-OS phases were only obtained for tubers produced in Julio de Castilhos, under more favorable temperature conditions, and when combined data from both locations. Therefore, different crop locations and even seasons, as we used in this study, should be considered for making inferences about potato tuber sprouting based on aTS.

Knowing the physiological age is important for post-harvest tuber management, especially when they are used as seed. Physiological age of tuber seed affects important components of yield, such as plant vigor, number of stems, number and size of tubers, rate of plant emergence and TI and OS (STRUIK et al., 2006; STRUIK, 2007). When comparing planting of tubers in the phases of full sprouting or senescence, it has been observed that tubers in full sprouting present late emergence, TI and maturity; however, they present vigorous shoot growth, with a higher number of tubers per stem and final yield. On the other hand, tubers planted in the senescence stage present early emergence, TI and maturity, but reduced shoot growth, number of tubers per stem and final yield (WIERSEMA, 1985; STRUIK, 2007; HELDWEIN et al., 2009).

Different characteristics have been proposed as indicators of dormancy and/or physiological age of the tubers, including morphological, physiological, (bio)

Table 3 - Pearson correlation coefficients and probability (in parentheses) between the accumulated thermal sum (aTS) from emergence (EM) to tuber initiation (TI), from TI to onset of senescence (OS) and from EM-OS, and the area below the progression curve of percentage of sprouted tubers (%ST) and number of sprouts per tuber (NS/T) of four potato clones produced in two crops and locations and stored at two temperatures for 90 days.

aTS[1]	%ST[2]	NS/T[2]
-------------------------Crop in Santa Maria------------------------		
EM-TI	-0.5141 (0.192)	-0.5565 (0.152)
TI-OS	0.5418 (0.165)	0.5655 (0.144)
EM-OS	0.4848 (0.223)	0.4857 (0.222)
----------------------Crop in Julio de Castilhos--------------------		
EM-TI	-0.7843 (0.021)	-0.7335 (0.038)
TI-OS	0.9790 (0.000)	0.9137 (0.002)
EM-OS	0.9257 (0.001)	0.8625 (0.006)
-----------------------Combined crop locations--------------------		
EM-TI	-0.6081 (0.012)	-0.5773 (0.019)
TI-OS	0.8484 (0.000)	0.8143 (0.000)
EM-OS	0.8331 (0.000)	0.8047 (0.000)

[1]aTS = accumulated thermal sum.
[2]Area below the progression curve of percentage of sprouted tubers (%ST) and number of sprouts per tuber (NS/T) during 90 days of storage.

chemical, biophysical and molecular traits (CALDIZ et al., 2001; CALDIZ, 2009). Such indicators are necessary to quantify and explain the differences in the rate of aging of tubers from different cultivars and under different crop and storage conditions and to quantify and model the effects of seed age on the growth and yield of plants (STRUIK et al., 2006). Accordingly, results of this study indicated that it is possible to estimate the sprouting of potato tubers from the aTS in EM-OS or TI-OS phases, comprising an important tool for making inferences about the physiological age and defining post-harvest management strategies in potato tubers produced under different crop conditions. Growing conditions, as crop location and seasons, are important factors to consider for making inferences about potato tuber sprouting based on aTS.

CONCLUSION

The accumulated thermal sum defines the physiological age of potato tubers. The higher the accumulated thermal sum between emergence or tuber initiation and onset of senescence, the higher the percentage of sprouted tubers and the number of sprouts per tuber. The advance in physiological age and the post-harvest management of potato tubers depend on the clone.

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