Modeling Respiration Rate of Five Varieties of Sweetpotato (*Ipomoea batatas* (L) Lam) at Different Temperature Ranges by Applying the Mass Balance Principle.

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ABSTRACT. Respiration rates of five different varieties of sweetpotato (Ipomoea batatas (L) Lam), ‘Beauregard’, ‘Covington’, ‘Evangeline’, ‘Hatteras’ and ‘Carolina Rose’, were calculated applying the principle of mass balance. The sweetpotato roots used in the study were grown and stored in central North Carolina. All the roots were U.S. No 1 grade. The roots were stored in an environmentally controlled room at the following temperature ranges: 14.4 - 16.6, 16.7 - 18.8, 18.9 - 21.1, and 21.2 - 23.3°C. All samples were held at 85 ± 5% relative humidity. Temperature, relative humidity and weight of sweetpotatoes were measured every hour for a period of 10 months by a data acquisition system designed and built for this specific application. Mass balance was achieved applying the respiration equation and assuming that the substrate loss was entirely glucose. Temperature and variety significantly ($P<0.05$) affected respiration rates . Respiration rates were lower at low temperatures and increased as temperature increased. ‘Beauregard’ and ‘Covington’ had the lowest respiration rate at the recommended temperature range from the tested varieties. ‘Carolina Rose’ showed the highest response to temperature during the study. Calculating respiration rates by measuring the substrate consumed in respiration as glucose is a valid and accurate method. This method is especially suitable for commodities that can be stored for long periods, such as sweetpotatoes. Environmental conditions are a determining factor in the respiration rate of sweetpotatoes, but the genetic characteristics are the most important contributing aspect in the rate of respiration. Modeling the respiration rate of

sweetpotatoes by applying the mass balance principle revealed differences in the respiration rate of different varieties at different temperatures.

Introduction

Sweetpotatoes (*Ipomoea batatas* (L) Lam) have been classified as a tropical underground vegetable; a storage root typically with relatively low respiration rates (Kader et al., 2002). This classification is important, especially for the postharvest practices because they are storage organs. Sweetpotatoes are primarily composed of carbohydrates with a naturally long shelf life. (Kader et al., 2002). After harvest sweetpotatoes continue respiring, therefore the effectiveness of the storage conditions in extending shelf life can be evaluated by measuring the respiration rates (Bower et al., 1998). Respiration rate is also an indicator of the overall rate of metabolism (Kays, 2004)

The most basic explanation of the respiration process is that “it is the mechanism that living cells use to release energy through the breakdown of carbon compounds, which are converted into carbon skeletons necessary for maintanence and synthetic reactions after harvest“ (Kays, 2004). Sweetpotatoes are very low producers of ethylene, a ripening hormone, emitting <0.1 µl kg^{-1} hr^{-1} at 20˚C (Kader et al., 2002;Kays, 2004). Other volatile compounds are also produced in extremly low ammounts, therefore the production of those gases is neglegible for the calculation of respiration rates. Another product of respiration is thermal energy, which is called vital heat or respiration heat and contributes to the refrigeration load in the storage facility(Saltveit, 2004; Boyette, Wilson and Estes, 1994). It is important to remove that heat because failing to do so will raise the temperature inside the storage room, which could cause an increase in the

respiration rate (a positive feedback loop) and a subsequent reduction in the shelf live of the sweetpotatoes. Therefore, keeping a low respiration rate will maintain other metabolic reactions low as well. Storingsweetpotato roots at the correct temperature would contribute to the maintainance of quality, reduce shinkage and extend the shelf life. The factors which affect respiration rates of sweetpotatoes after harvest are largely internal. Internal factors are the chemical composition of the roots and how susceptible they are to environmental conditions. Internal factors are dictated by the genotype of the sweetpotatoes (Saltveit, 2004); Therefore, it is the necessary for comparing how sweetpotato cultivars contribute to the success of long term storage.

An external factor that affects respiration rate of sweetpotatoes during long term storage is temperature. The increase on respiration rate due to temperature is measured by the temperature quotient, for every interval of 10˚C which is known as Q10 (Saltveit, 2004). Other factors affecting respiration are chilling stress and heat stress. In sweetpotatoes chilling stress occur when the roots are exposed to temperatures below 10˚C to 12˚C (Saltveit, 2004). Heat stress occurs when sweetpotatoes are exposed to very high temperatures and the quotient of respiration rate becomes negative. Other factors that influence respiration rates are the concentration of O_2 and CO_2 in the storage room (Saltveit, 2004; Kays, 2004; Chang and Kays, 1981). Treatments like control atmosphere (CA) and modified atmosphere (MA) can control the concentration of gases, although neither CA nor MA is used for sweetpotatoes. Another possible treatment is gamma irradiation but it has little effect extending the shelf life of sweetpotato along with CA and MA, when compared with the results of maintaining

proper storage temperature (Kays, 2004). Therefore, there is no commercial use of these technologies in sweetpotato storage. However, it is important to keep these possibilities in mind as new markets and new discoveries emerge.

Respiration rates can be measured in different ways, these methods rely on either the ability to measure the consumption of substrates or the production of metabolic compounds (Saltveit, 2004). One of the most common strategies is to measure the production of CO_2. Another less common technique is to measure the absorption of O_2. A possible innovative technique that can be employed to measure either or both of those gasses is the use of a “respirometer”, which measures the consumption of O_2 utilizing sensors and replenishes the gas in order to avoid changes in the air concentration (Bower et al., 1998). A gas concentration can be measured in two different ways. The first is by passing a flow of air with known concentrations of O_2 and CO_2 through the enclosure where the fruit or vegetable is located, then measuring initial and final concentrations of O_2 and/or CO_2. The difference of these two would be the result of respiration. This system is dynamic and can detect changes in the respiration rate over time. (Bower et al., 1998) (Saltveit, 2004). The second method consists on placing the fruit or vegetable in an enclosure with a known concentration of O_2 and/or CO_2, and after a specific amount of time, the air inside the enclosure is sampled. The gas concentration from the sample is compared to establish the difference with the original concentration. This difference will be the respiration rate per unit of weight and unit of time. This is known as the static method. In general it is easier to measure CO_2 over O_2 concentrations, because changes in O_2 concentration are small compared to the total concentration (Bower et al., 1998).

Another third method of measuring the respiration rate is by measuring the loss of substrate which represents the loss of dry weight. For a commodity like sweetpotatoes that must survive long storage terms, the loss of dry weight due to respiration can be significant (Saltveit, 2004). The loss of substrate, consumption of oxygen, production of carbon dioxide and heat are expressed in the following respiration equation:

$$C_6H_{12}O_6 + 6O_2 + 6H_2O \rightarrow 6CO_2 + 12H_2O + 673\ kcal \quad (1)$$

Based on the respiration equation, once the consumption of substrate is known the production of the other compounds could be derived. Therefore the respiration rate could be determined from the change in weight over time (Saltveit, 2004) assuming the substrate consumed is glucose. From the respiration rate (R_{rt}) the respiration heat (R_{ht}) may be found (Stewart, et al. 2000). According to Hardenburg et al. (1986), 2.55 calories or 10.676 J of energy is released to the atmosphere per mg of CO_2 emitted during respiration;. Cantwell and Suslow, 2001, recommend that R_{ht} could be calculated by multiplying ml CO_2 kg^{-1} hr^{-1} by 440 to get Btu ton^{-1} day^{-1} or by 122 to get kcal metric-ton^{-1} day^{-1}.

The objective of this study was to calculate the respiration rate (R_{rt}) of cured sweetpotato roots from five commercially grown sweetpotato varieties, ‘Beauregard’, ‘Carolina Rose’, ‘Evangeline’, ‘Hatteras’ and ‘Covington’ during long term storage. R_{rt} was calculated based in the consumption of glucose as substrate. The glucose consumed was calculated from the dry weight change during the storage periods. The experiment was conducted at two scales. The first one was at laboratory scale with approximately 20 kg per variety per repetition. During the lab experiment the sweetpotatoes were stored at four temperature ranges: 14.4°C - 16.6°C, 16.7°C -

18.8°C, 18.9°C - 21.1°C, 21.2°C - 23.3°C. The second was a commercial scale study, with approximately 6,900 kg per repetition. The cured roots in the commercial scale study were the sweetpotato cultivar ‘Covington’ only. The commercial experiment was replicated at five different grower facilities at the recommended temperature range of 14.5 ±1˚C.

Methods

Measuring respiration rates has been largely considered as a very important postharvest indicator of metabolic activity inside fruits and vegetables after they are detached from the plant. The substrate is assumed to be entirely glucose, a hexose sugar that is the basic substrate for the respiration reaction expressed in equation 1.

To calculate the substrate loss to the environment due to respiration, it is necessary to monitor the weight of the sweetpotatoes over time plus the environmental conditions and the dry matter percentage content. A data acquisition system was design and built specifically for collecting the weight of the sweetpotatoes in two circumstances. The first was a lab scale study conducted in a controlled environment room on-campus at North Carolina State University, Raleigh, North Carolina, where five sweetpotato varieties were in plastic lugs with a total gross weight of approximately 20 kg. They were placed over bending beam load cells sensors (TEDEA RL 1042, City of Industry, CA) with a maximum capacity of 30 kg. Each variety was replicated four times, and the experimental design was complete randomized block (CRB). The second condition is a commercial scale experiment, where a platform with four load cell sensors (Transcell Technology RF model: SBS-5KSE, Buffalo Grove, IL) with the capability to measure up to 2,273 kg for each sensor, giving a total of 9,100 kg per platform. Five platforms of the

same characteristics were built; each platform was located in a different commercial facility. All of the commercial storage rooms that participated in this study were equipped with negative horizontal ventilation (NHV) storage systems. NHV systems are widely used and are capable of maintaining consistent temperature and RH conditions throughout storage rooms with capacities of as much as 454,545 kg of sweetpotatoes.

In both tests described above, weight, temperature and RH were recorded hourly by data loggers (HOBO U12-013 and U12, Pocasset, MA) and downloaded to the computer utilizing specialized software (HOBOware, Pocasset, MA). The data was collected during three storage seasons, (2010, 2011 and 2012). Each period for the lab scale experiment lasted 10 months; In the commercial storage rooms the periods lasted 8 to 10 months according to the needs of each grower. Up to five growers participated in this study in a single storage period. Sweetpotato roots tested in the lab-scale experiment were from the following commercial varieties: ‘Beauregard’, ‘Evangeline’, ‘Covington’, ‘Carolina Rose’, and ‘Hatteras’. All these varieties are of similar characteristics: they are primarily for fresh consumption, have orange flesh and a dry matter content of 20 ±2%. Sweetpotato roots where produced and hand harvested in eastern North Carolina. Immediately after harvest, the roots were cured in the cure-storage rooms at the Horticultural Crops Research Station in Clinton, NC. The curing conditions were 29.4°C and 85% RH for 7 days. After curing only sweetpotatoes grading U.S. No. 1 were selected for the lab-scale study. The experimental design for this study included five varieties, and four repetitions. The sweetpotatoes were treated with three temperature cycles, each cycle lasted 90 days. Cycles were divided in periods of 15 days; each 15 days period had constant temperatures in the following

order: 14.5, 17, 14.5, 19, 14.5, and 21°C. The lower limit temperature of the cycle is the minimum temperature that sweetpotato can withstand without developing chilling injury (Boyette, 2009); Above 21°C, sweetpotatoes, will sprout after a few days. Relative humidity was held at 85% ±5. After collecting the weight of the sweetpotatoes over time, the other parameter necessary for the calculations was the dry matter content of the roots. During the second storage season, three samples per variety of sweetpotatoes were collected after three, seven, ten, and eleven, months of storage. Each sample was composed of two roots randomly selected; the dry matter content was determined by the quotient of the fresh weight by the dry weight. The dry weight was measured after the roots were dried in a lyophilizer or freeze dryer. Dry percentage values are in table 1.

Table 1: Dry Matter Content for Five Sweetpotato Varieties

VARIETY	DRY MATTER PERCENTAGE
Beauregard	**20.8%**
Carolina Rose	**21.7%**
Covington	**21.9%**
Evangeline	**23.1%**
Hatteras	**21.5%**

Also three samples per each commercial scale study were taken at two, three, five, seven, and nine, months of storage, determining the dry matter content at each location.

Dry percentage average values of the sweetpotato roots variety ‘Covington’ stored in different commercial facilities are in table 2.

Table 2: Dry Matter Content for Five Commercial Growers of Sweetpotatoes Variety Covington

VARIETY	DRY MATTER PERCENTAGE
Grower 1	**20.5%**
Grower 2	**19.3%**
Grower 3	**19.9%**
Grower 4	**20.0%**

The dry matter percentage of sweetpotato stays constant through the storage periods at 20±2% because as a living organism it tries to maintain homeostasis (Kays, 2004). Thus in order to calculate the respiration rate for each case, the dry percentage that will be employed is the season average of each variety or each grower.

Therefore the weight loss is calculated with the following equations:

$$weight_j - weight_i = \Delta weight \tag{2}$$

The result from equation 2 is the change in weight over a period with upper limit *j* , and lower limit *i*. Then it is multiplied by the percentage of dry matter, equation 3. The result is the dry weight loss:

$$\Delta weight \cdot \%\, Dry\ matter = \text{Dry weight loss} \tag{3}$$

In order to calculate the respiration rate from the dry weight loss, it is assumed that the complete mass of the substrate is glucose. The composition of sweetpotatoes varies according to variety, climatic conditions, and duration of storage. The only sources of energy available for respiration in sweetpotato roots are reducing sugars and starch. Reducing sugars are mostly glucose. Starch will react with amylase and starch-phosphorylase to form glucose-1-phosphate. Glucose kinase, or hexose phosphate isomerase, will be transformed into glucose-6-phosphate (Kays, 2004); this last compound will enter in the glycolysis process and then complete the respiration cycle.

From equation 1 the substrate, glucose $C_6H_{12}O_6$, produces 6 molecules of carbon dioxide CO_2. Using the atomic weights of the elements involved in this reaction, 180 g of glucose are lost for each 264 g of carbon dioxide produced. Therefore the rate of respiration could be modeled by applying equation 4.

$$mg\ CO_2\ \mathrm{kg}^{-1}\ \mathrm{hr}^{-1} = \frac{\text{Dry weight loss}(\mathrm{g\ kg}^{-1}\ \mathrm{hr}^{-1})}{0.68\mathrm{x}10^{-3}(\mathrm{g\ mg}^{-1})} \qquad (4)$$

Data analysis was conducted using the Statistical Analysis System version 9.3 for Windows (SAS Institute, Cary, NC). ANOVA analysis means and standard error of the data was calculated. Results were statically significative at $P<0.05$.

Results

In order to establish if the differences between varieties were statistically significant, it was necessary to analyze the interaction between factors and between varieties. The analysis was done in the statistical software SAS by applying the general linear model

(GLM) procedure where the variable that was analyzed was the respiration rate per variety per day over the entire storage period using data from three storage periods. Each period lasted 10 months. The statistical tools used in the study were the analysis of variance (ANOVA) test, means and standard error calculations.

The linear model included fixed effects for variety, temperature range and the interaction of variety and temperature range with linear dependence on time. The results from the ANOVA test showed that there was significant interaction of variety and temperature range, $P<0.0001$. Also the analysis of the interaction between variety and temperature range showed that the effects of variety depend on temperature range, $P<0.0001$. Analyzing the F-tests for fixed effects in the model suggests that respiration rate depends on both variety and temperature range. The F-ratios for the ANOVA tests were 7.88 and 31.91 for the analysis of sweetpotato varieties stored under varying conditions and for the sweetpotatoes stored in commercial facilities respectively, both with $p<.0001$. The average values of the respiration rates for each variety at the different temperature ranges are shown in table 3.

Table 3: Respiration Rate for Five Sweetpotato Varieties at Different Temperature Ranges Obtained during the Storage Seasons 2010 and 2011

		Mean	Std Error
Variety	**Temp Range °C**	**mg CO_2 kg^{-1} h^{-1}**	
Beauregard	14.4 - 16.6	5.5	0.2
	16.7 - 18.8	7.0	0.4
	18.9 - 21.1	7.0	0.5
	21.2 - 23.3	7.1	0.3
Covington	14.4 - 16.6	5.5	0.2
	16.7 - 18.8	6.3	0.3
	18.9 - 21.1	7.0	0.3
	21.2 - 23.3	9.9	0.5
Evangeline	14.4 - 16.6	5.6	0.4
	16.7 - 18.8	6.6	0.3
	18.9 - 21.1	6.2	0.4

	21.2 - 23.3	8.5	0.5
Hatteras	14.4 - 16.6	5.6	0.2
	16.7 - 18.8	7.8	0.6
	18.9 - 21.1	8.7	0.8
	21.2 - 23.3	8.2	0.3
Carolina rose	14.4 - 16.6	6.4	0.2
	16.7 - 18.8	8.0	0.4
	18.9 - 21.1	9.0	0.4
	21.2 - 23.3	8.5	0.4

In General, ‘Beauregard’ is the variety that consistently had the lowest respiration rate, while ‘Carolina Rose’ was consistently the highest. ‘Covington’ had low respiration rates up to 18.8˚C, after that level its respiration rate increased very rapidly. The increase of respiration rate of ‘Covington’ sweetpotatoes showed that this variety has great susceptibly to high temperatures. There were some differences in rankings from one storage season to the next among the varieties, but in average ‘Beauregard’ and ‘Covington’ exhibited low respiration rates over the range tested

During the three storage seasons, up to five commercial storage rooms were monitored. Each room located in a different grower production unit, at each location the change in weight of 13,000 to 17,000 lbs of sweetpotato roots from the variety ‘Covington’ was monitored. The roots were stored in commercial facilities with a temperature range of 14.4˚C to 16.6˚C, where the average respiration rate was 4.9 ± 0.2 $mg\ CO_2\ \mathrm{kg}^{-1}\ \mathrm{hr}^{-1}$. The difference between the respiration rate obtained from the commercial facilities and the rate from the variable temperature experiment on ‘Covington’ is because the roots kept at constant lower temperature reached a dormant state. Sweetpotato roots reach a very low metabolic activity in response to environmental conditions, extending the length of time the roots can be successfully stored.

Discussion

Reported respiration rates in sweetpotato vary greatly, but most investigators agree that sweetpotatoes have very low respiration rates as compared to fast growing tissue and many fruit and vegetables. Cantwell and Suslow, (2001) reported for cured sweetpotato at 10°C, a respiration rate of 13.9 mg CO_2 kg^{-1} hr^{-1} and at 15°C 0 to 23.8 mg CO_2 kg^{-1} hr^{-1}. Hardenburg et al., (1986), reported that the respiration rate of cured sweetpotatoes at 15°C to 16°C is 20 to 24 mg CO_2 kg^{-1} hr^{-1}. Reported respiration rates for cured sweetpotatoes at different temperatures by Stewart, et al. (2000) for sweetpotato roots variety 'Beauregard' stored at 15, 20, 25 and 30˚C were 8.7, 10.2, 26.9 and 27.7 mg CO_2 kg^{-1} hr^{-1} , respectively. The values reported in this research are closer to the values reported by Stewart, et al. (2000). The respiration rates in this research are specific to the five different varieties previously named at 4 different temperature conditions. These respiration rate values could become a very important tool for postharvest physiologists and engineers involved in managing and designing sweetpotato storage facilities.

Measuring respiration rates by measuring the consumption of the substrate, which corresponds to the dry weight of the commodity is a method that had been published in the literature, (Salviet, 2004) However, there are no reports of this method having been utilized in previous research work. Thus the work presented in this paper is the first to explore an innovative and very useful technique in the measuring of respiration rates. Furthermore, the fact that the calculated values presented in table 3 are in the same ranges as values previously reported supports the validity of this method. It also supports the assumption that essentially all the dry weight loss by the sweetpotato is

glucose. Additionally the fact that sweetpotato roots are very low producers of ethylene supports the assumption that the production of other volatiles is negligible.

The respiration rate of the variety ‘Covington’ stored under varying temperature is slightly higher than the sweetpotato roots of the same variety stored under stable conditions by the growers who participated in this study. The effect of temperature and variety were very important in the statistical result of the ANOVA test, proving the theory that the most important factor that contributes to the respiration rate is the genetic characteristics.

Conclusions

Calculating respiration rates by measuring the substrate consumed in respiration as glucose is a valid and accurate method. This method is especially suitable for commodities that can be stored for long periods, such as sweetpotatoes.

“Beauregard” is the sweetpotato variety with the lowest respiration rate, from the tested varieties. ‘Carolina Rose’ and ‘Hatteras’ are consistently the ones with the higher respiration rates. The other two varieties ‘Evangeline’ and ‘Covington’ vary in their results, with the remark that ‘Covington’ along with ‘Beauregard’ had the lowest respiration rate at the recommended temperature range, 14.4˚C - 16.6˚C

In order to reach the lowest possible respiration rate by any sweetpotato variety, it is necessary to avoid fluctuations in environmental conditions. Temperature is the environmental condition that has the greatest impact on respiration rates.

Environmental conditions are a determining factor in the respiration rate of sweetpotatoes, but the genetic characteristics are the most important contributing aspect in the respiration rate of sweetpotato roots.

Breeders and growers can use the method presented in the present study to measure respiration rate of sweetpotatoes or other commodities, in order to make better variety selection.

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