HEAT TRANSFER MODEL FOR SUGAR BEET STORAGE PILE

By

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ABSTRACT

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Harvested sugar beet (*Beta vulgaris* L.) are stored in cold regions in large piles exposed to ambient weather conditions and fluctuate temperatures during the winter storage period, which lasts for four months. To better understand the impact of air temperature on the pile temperature. A two-dimensional (2D) heat transfer steady-state model was designed to predict the temperature profile of the pile. To validate the model, temperatures obtained from the model were compared with the temperatures measured from onsite commercial piles during the storage seasons from November 2011 to January 2012 in the first season and from November 2012 to February 2013 in the second season in Reese, MI.

The model tended to underestimate the pile temperature (°C). The mean difference between measured and modeled temperature values was significant ($P \leq 0.05$). Daily rate of sugar loss (kg/metric ton/day) based on measured and modeled temperatures were calculated and compared for model accuracy. The mean of the daily sugar loss based on the modeled pile temperature was significantly ($P \leq 0.05$). Additionally, three zones (upper, middle and lower) of the pile were studied for the model accuracy. There was a significant difference between the modeled and measured pile temperature between the three zones in the second season, whereas the first season didn't show difference between the temperatures of the upper and the middle zones ($P \leq 0.05$). Moreover, a comparison of predicted sugar loss as a function of pile geometry was conducted under 2012 air temperature and a 3°C increase in air temperature relative to 2012 data.

This thesis is dedicated to Dr. Sherine Awad and My Family.
Thank you for being who you are.

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KEY TO SYMBOLS

T ambient temperature (K).

Q energy ($W \cdot m^{-3}$).

ρ density ($kg \cdot m^{-3}$).

C_p the specific heat at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$).

u the velocity ($m \cdot s^{-1}$).

∇T the temperature gradient ($K \cdot m^{-1}$).

q heat flux ($W \cdot m^{-2}$).

k_{eff} the effective thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

θ_p porosity (%).

k thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

k_{disp} Dispersive thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

L_m= Estimated cumulative sugar loss (kg/metric ton) based on pile measured temperature.

L_d= Estimated cumulative sugar loss (kg/metric ton) based on pile modeled temperature.

INTRODUCTION

ECONOMIC IMPORTANCE OF SUGAR

Sugar (sucrose) is an important product around the world for home use and in numerous industries (Asadi, 2005; FAOSTAT, 2014). Sugar is mainly produced from two sources, sugarcane (*Saccharum officinarum*) and sugar beet (*Beta vulgaris L.*) (FAOSTAT, 1994).

In 2014, the world production of sugarcane and sugar beet were 2010.4 and 277.7 million metric tons of raw product, respectively (FAOSTAT, 2014). The total crop values of production in 2014 were about $224.9 and $14.8 billion for sugarcane and sugar beet, respectively (FAOSTAT, 2014).

SUGAR BEET PRODUCTION AND STORAGE

USA was ranked as the 11th largest producer of sugarcane in 2014 with 27.6 million metric tons. The production of sugar beet in 2014 was 28.4 million metric tons, making the USA the 4th largest sugar beet producer (FAOSTAT, 2014). Sugar beet accounted for 57% of the USA sugar production in 2014, while sugarcane accounted for 43% (McConnell and Riche, 2015). This represents a substantial increase of the sugar beet share from 25% in 1920 (Reference for Business, 2011).

Sugar beet was originally grown in temperate zones in winter and/or summer (Draycott, 1972). However, it is now cultivated all over the world in summer in cooler regions and with supplemental irrigation in arid and semi-arid regions (Draycott, 1972). USA sugar beet production is distributed over several regions; the Red River Valley (Minnesota and North Dakota), the far west area (California, Idaho, Oregon and Washington), the Central High plain area (Colorado, Montana, Nebraska and Wyoming) and the Great Lakes area (Michigan) with a contribution of 47.45%, 24.13%, 14.41% and 14.01% of the total USA sugar beet production, respectively (USDA, 2015).

In production areas with relatively cold temperatures, harvested roots are stored in large piles and exposed to ambient environmental conditions during winter (Bugbee, 1993; Huijbregts et al., 2013). A single hectare of sugar beet produces approximately 45 metric tons of roots, with a volume of about 80 m^3 (Campbell and Klotz, 2006; Draycott and Christenson, 2003). According to McConnell (2015), approximately 538,000 ha of sugar beet is grown in the USA. The scale of production prevents immediate processing, as the processing capacity of the beet extraction plant can reach up to 17,000 metric tons per day (BMA, 2010), thus providing storage facilities is required.

Beet harvest in Michigan begins at the end of September and continues until the middle of November (Ruhlman, 2018). After harvest, the roots are transferred to the processing plant or placed in specially built piling for storage grounds until processing (Bugbee, 1993; Huijbregts et al., 2013). The storage period lasts for approximately 120 days (Van Eerd et al., 2012) and during this period, the beet piles are exposed to the surrounding environment. During sugar beet storage period in Michigan (October - April), the air temperature ranges from -28.7 °C to 29.8 °C (according to the data obtained by our team from MSU extension station, located at the MSU Saginaw Valley Beet and Bean Research Farm, Frankenmuth, MI. (Enviro-weather, 2011) for air temperature in the piling areas for 2009-2014 storage seasons). In 2005, elevated ambient temperatures during storage in the Great Lakes area contributed to increased respiration and promoted many cases of microbial activity (Poindexter, 2012). Both phenomena were responsible for a considerable amount of sugar loss that reached $25 million after such storage season in Michigan alone (Beaudry and Loescher, 2008).

SUGAR BEET LOSS DURING STORAGE

Elevated storage temperature enhances the rate of root metabolism and thereby raises the respiration rate (Vukov, 1977). During respiration, stored sugar is oxidized to CO_2, converted to needed metabolites and yields the energy for maintaining cell metabolic activities (Siedow and Day, 2017). Over a storage campaign of 130 d, sugar losses are around 14 pounds per ton of roots, about 4% of the total sucrose (Wyse and Dexter, 1971). Barr et al. (1940) estimated that 60% of this sugar loss was attributable to respiratory losses and Wyse and Dexter (1971) calculated that respiration accounted for roughly 80% of the sugar loss, with the remainder being lost due to the interconversion of sucrose to invert sugars and other impurities. Wyse and Dexter (1971) also noted that the respired CO_2 exceeded that accounted for by sugar loss and that a significant proportion (~38%) of the respired CO_2 was derived from non-sucrose compounds.

Fluctuating temperatures during storage of bulk fresh crops can cause considerable loss (Ullah et al., 2014; Wyse, 1978). Fluctuating storage temperatures increase the respiration rate and encourage condensation (Hylmó et al., 1976). Free water, in combination with elevated temperature, can promote virulence and root deterioration by some storage pathogens such as *Phoma betae* (Cormack and Moffatt, 1961). Temperature fluctuation additionally reduces the root quality when the temperature decreases sufficiently to cause freezing (Wyse, 1978). Upon freezing, the root cell membranes rupture and cellular leakage occurs (Ullah et al., 2014; Wyse, 1978). Upon thawing, the leaked sucrose-rich solution is available to bacteria, which form polysaccharide gums that interfere with sugar extraction during the processing (Campbell and Klotz, 2006).

Storage rot of beet roots is another reason for sugar loss and varies in severity according to storage temperature (Gaskill and Seliskar, 1952; Liebe and Varrelmann, 2016) and is an important reason for understanding the temperature patterns inside the storage pile. *Phoma betae* Frank, *Botrytis cinerea* L, *Penicillium vulpinum* (Cooke & Massee) Seifert & Samson (formerly *Penicillium claviforme* Bainier) and *Rhizopus stolonifera* are storage rot pathogens (Bugbee, 1982; Bugbee, 1986). Low storage temperature (<10 °C) slows the development of the rot by *P. betae* and *R. stolonifera* (Cormack and Moffatt, 1961; Fugate and Campbell, 2009; Miles et al., 1977), while *B. cinerea* and *P. vulpinum* can maintain their activity under a wider range of temperature (Gaskill, 1952; Mumford and Wyse, 1976).

Respiratory sugar loss and fungal growth can be minimized by maintaining storage temperature between 1.5 and 5 °C, relative humidity between 95% to 98% and oxygen and carbon dioxide levels at 5% and 6%, respectively (Karnik et al., 1970). These conditions avoid cell rupture and reduce dehydration and fungal growth (Bugbee, 1993; Campbell and Klotz, 2006; Wyse, 1978). In areas such as the Red River Valley region and parts of Canada where the winter temperature is cold enough to 'deep freeze' beet piles (i.e., where weather temperatures remain below -5 °C during the storage period), piles are kept frozen until processing (Bugbee, 1993; Campbell and Klotz, 2006; Wyse, 1978). Deep freezing can be used for large 'super' piles with a base equal to 66 m wide (Bugbee, 1993), but is also useful for smaller piles (e.g., 23 m width) if an increased surface area for heat exchange is needed (Bugbee, 1993).

OPTIMIZING SUGAR BEET STORAGE CONDITIONS THROUGH MATHEMATICAL MODELING

Empirical approaches have been employed to achieve optimal storage conditions. These include covering the pile with straw (Akeson et al., 1974) or woven polypropylene (Perry, 1989), forced air cooling or ventilation (currently applied in some locations in Michigan) (Clark, 2012), deep-freezing (Bugbee, 1993) and storing in small piles or covered clamps (List, 2015). Although empirical approaches help solve some of the storage problems to obtain uniformity and condition optimization (Kumar and Kalita, 2017), they are not very useful for modifying storage techniques or developing new approaches. On the other hand, mathematical models can test possible solutions before practical implementation, with relatively low costs (Ambaw et al., 2013; Xie et al., 2006). Therefore, mathematical models for optimizing post-harvest handling and storage conditions have been of interest to researchers (Ambaw et al., 2013; Verboven et al., 2006) and numerical models have been proposed to simulate and predict fluid flow and heat and mass transfer during transportation and storage for agricultural commodities (Ambaw et al., 2013; Verboven et al., 2006).

APPLICATION OF MODELING BIOLOGICAL SYSTEMS

Modeling approaches have been extensively applied to biological systems since the early 2000s (Rennie and Tavoularis, 2009a; Rennie and Tavoularis, 2009b; Verboven et al., 2006). Many studies were recently performed to simulate and predict the cooling behavior and airflow for individual products and packaged and bulk food or have simulated the effect of cooling and/or airflow on the change in storage conditions and ventilation.

1. Models for Individual and Packed Products

Thorpe G. (2006) formulated a transient numerical model using individual products as discrete entities to determine the efficiency of a hydrocooler for cooling spherical elements. The model quantifies the time needed for a horticultural produce to reach a target temperature after exposure to specific water temperatures. The study recommends the use of the mass-weighted average temperature of the produce to calculate the time needed for cooling instead of using the core temperature, because reaching the target temperature is significantly faster in the recommended method.

A transient mathematical model for forced air cooling of apple was created by Arêdes Martins et al. (2011) to describe the temperature of two apples as a function of the surrounding airflow. The model explains the cooling in the tandem arrangements on apple trays. The results demonstrated a delay of cooling in the downstream apple relative to the upstream apple.

Ferrua and Singh (2009a); Ferrua and Singh (2009b); Ferrua and Singh (2009c) developed a mathematical model to predict the behavior of the airflow and temperature of the strawberry and the clamshell packaging during the forced-air cooling of strawberry packages. Airflow calculations were validated using a particle image velocimetry (PIV) approach as well as temperature calculations. Later, Ferrua and Singh (2011) improved the commercial strawberry storage system by improving the design of the clamshells and trays as well as the behavior of the airflow across the cooling chambers, using the early designed model.

2. Models for Bulk Stored Products

To investigate the change of the airflow, temperature and moisture content in bulk stored potatoes, Xu and Burfoot (1999) developed a transient three-dimensional (3D) computational fluid dynamics (CFD) model for forced air cooling of potato. Temperature and weight loss were used for model validation. The difference between simulated temperature and experimental temperature of a potato bed with 2.4m height and 0.7m diameter reached 1.4 °C lower in the model than the measured temperatures. There also were variation in weight loss between experimental and simulated results reached 5%, due to excessive water evaporation of potato tubers and the possible fluctuation of air speed and increase of the humidity near the inlet air.

As a further example, a transient 3D airflow heat and mass transfer model was designed for bulk storage of chicory roots to study the commercial storage systems, and validate the ability of the refrigerated store to maintain root quality (Hoang et al., 2003), by predicting airflow, dehydration and temperature of chicory roots through a wind tunnel (a closed chamber that can measure and/or control the parameters of the air passing through). Measured and predicted results of temperature and moisture content were compared to validate the model. The simulated results underestimated the actual root temperature. Also, the roots lost more moisture than predicted, which was assumed to be due to the low relative humidity (RH) of the ambient air in the storage, variation in the size of the voids between the roots, non-uniformity in the size of the roots and the large size of the roots compared with the size of the voids between the roots.

Markarian et al. (2006) proposed a mathematical model that predicts potato temperature and the surrounding relative humidity (RH) throughout cold storage. The model also described the respiration and transpiration rate of the tubers during storage. The experiment was conducted in a highly controlled condition and the findings were compared to measurements found in the literature with a considerable agreement. The mean of absolute difference in temperature was 0.01 °C, the maximum absolute difference was 0.49 °C.

To study the airflow and energy transfer characteristics in ventilated layered and bulk apple packages, Zou et al. (2006a) designed transient computational fluid dynamics CFD model based on equations used for porous media. In a second study, Zou et al. (2006b) introduced user-friendly software to solve the mathematical equations, then the model results were compared with experimental temperature measurements for validation. The model underpredicted the product temperature. This was thought to be due to errors in the positions of thermocouples, model input values and/or model assumptions.

For potato, Chourasia and Goswami (2007a) examined the effect of several parameters, such as rate of generated respiratory heat, void diameter in the medium, RH, tuber size and temperature, on heat and mass transfer patterns in potato bulk storage. The study also included steady-state and transient models and validated the models using experimental measurements of temperature and moisture loss. In general, the simulation overestimated temperature and moisture loss with an average error of 1.2 °C and 11.5%, respectively. Later, in another study by Chourasia and Goswami (2007b), a 2D CFD-based model was developed to compute the change in airflow, heat transfer and moisture content in potato bulk storage and they again examined the model accuracy by comparing the modeled data with experimental data obtained from commercial potato storage. The model was able to predict the potato temperature with an average error of approximately to 0.5 °C, while the model over-predicted moisture loss by 61%. The difference between simulated and experimental measurements was thought to be a result of changing storage conditions for stored tubers due to the unloading of stored potatoes throughout three months of storage.

Thorpe G.R. (2008) measured the change in temperature and moisture content of stored grain and designed a CFD model. The model predicted the variation of temperature and moisture content of the stored grains, but the results were not evaluated for accuracy by comparing the modeled data with experimental measurements.

Xie et al. (2006) applied a CFD model to obtain the optimal flow and temperature parameters for controlled cold storage of apples. The proposed 2D model was used to show the behavior of airflow and temperature transport during forced air cooling. The model was also used to evaluate the effect of several stacking patterns on the airflow and temperature of stored foodstuffs. The model was reliable; the error range in temperature was ± 2 °C.

Airflow through a random arrangement of horticultural products in packages was modeled by Delele et al. (2008), the model was developed based on measurements of low resistance according to changes in a confinement ratio, void to product ratio and box vent ratio in random stacking. Literature measurements were used for validation with good agreement.

The influence of product position and package vent arrangement on airflow and temperature characteristics was studied by Tutar et al. (2009). A transient CFD model was used for the simulation. The study showed a significant effect of the inflow rate compared with the vent rate on airflow and product temperatures. However, model validation was not performed.

To investigate the change of spherical produce temperature according to a change of vent area, Dehghannya et al. (2011) used solid polymer balls for simulation and developing a transient 2D airflow and energy transfer simulation model. The model results confirm the hypothesis that improving ventilation by increasing the number of package vents from 1 to 5 (with area equal to 2.4% to 12.1% of the package area, respectively) can improve temperature uniformity inside the package between the produce units as demonstrated by a reduced heterogeneity index from 61.5% to 5.6%. Validation occurred by comparing the modeled core temperature by measured temperature of the balls. Deviation from the modeled temperature was found due to some inaccurate parameter inputs such as the velocity and temperature of airflow, the thermal properties of the simulating balls and the failure of the numerical model to reach an iterative solution.

Tanaka et al. (2012) used a CFD modeling system to study the behavior of the airflow in a semi-loaded truck and its influence on product temperature. The model was validated with measurements of temperature and air velocity with a mean error of 1.4 °C and 0.36 m s^{-1}, respectively. Later the model was used to find the best loading configuration of the packages as the results suggested arranging the packages flat with considerable gaps is optimal for homogeneity of air cooling and temperature distribution. These findings were not validated with a real experiment. However, the results were consistent with expectations, because this way of arranging packages allows the cold air to consistently reach the commodities and achieve temperature uniformity.

3. Modeling Sugar Beet Storage

There have been several attempts to model sugar beet storage. Bakker-Arkema and Bickert (1966) designed a model to simulate the airflow and energy transfer of a ventilated deep-bed of sugar beet. Significant differences between measured and modeled cooling rate were found and thought to be from excluding mass transfer between beets and surrounding fluid. Later, Andales et al. (1979) used the finite difference approach to develop a 2D model for the temperature and weight loss of a ventilated sugar beet pile. They compared measured and modeled values for model validation. Deviations between measured and modeled values were mainly attributed to the change of porosity and heat loss at the pile walls. Holdredge and Wyse (1982) developed a relatively simple model, comparing to that of Andales et al. (1979), the model was reduced to one dimension as they found no significant variation of temperature in the horizontal plane. The model was verified and tested using an insulated box simulating a section of the commercial pile. The model validation showed good agreement between experimental and simulated values under the low and moderate airflow 5.2 and 10.4 m^3/ks-metric ton (10 to 20 cfm/ton), respectively. However, the fit was poor under the high airflow rate applied (20.8 m^3/ks-metric ton; 40 cfm/ton), which the authors attributed to non-continuous fan operation by the company's technicians trying to avoid blowing hot air into the pile.

The previous studies focused on modeling a ventilated pile. No models exist to describe the temperature profile inside unventilated beet piles. However, in Michigan about 50% of the piles are currently unventilated (J. Stewart, Michigan Sugar Company, personal communication). Further, there is a 2 to 4 °C increase in the average global temperature is predicted within this century (New et al., 2011). Thus, more effective pile architectures could be of increasing value. Therefore, the main objective of this project was to develop a two-dimensional mathematical model using a finite-element approach to simulate heat transfer in commercial beet piles under non-ventilated conditions. Such a model can be used to describe the temperature profile of an unventilated sugar beet pile that directly affects sugar loss and microbial activity during storage. Designing such a model can assist in decisions regarding pile management (size and duration). The second objective was to study the effect of the spatial variation of the pile on temperature distribution and sugar loss. Finally, we used the model to better understand how pile shape and ventilation presence affects sugar loss during storage.

MATERIALS AND METHODS

Modeling a sugar beet pile's temperature involved several steps. The first step contains developing and solving model equations for beets, air and ground thermal properties and input data (i.e. air temperature, air velocity and relative humidity (RH)) as stated in the model description section. The second step was monitoring the pile temperature by measuring the temperature of predefined points in a storage pile then comparing the collected temperatures with the temperatures obtained from the model at the same points to test the accuracy of the model. The third step was calculating sugar loss using the measured temperature and comparing it with the sugar loss calculated using modeled temperature. The fourth step was to evaluate the pile as three horizontal zones to help understand the model accuracy for each zone. The fifth step was to use the model to predict how new systems of storage affect root storability then giving a recommendation for the best storage system according to decreased predicted sugar loss.

The model design and simulations in this research were based on the pile structure and conditions measured at a commercial sugar beet pile of the Michigan Sugar Company at the Gera road piling ground, Reese, Michigan (43.409337° N, 83.739412° W). The dimensions of the commercial pile were 45.7 m, 27.4 m and 4.9 m for the base, top and height, respectively as illustrated in Fig. 1.

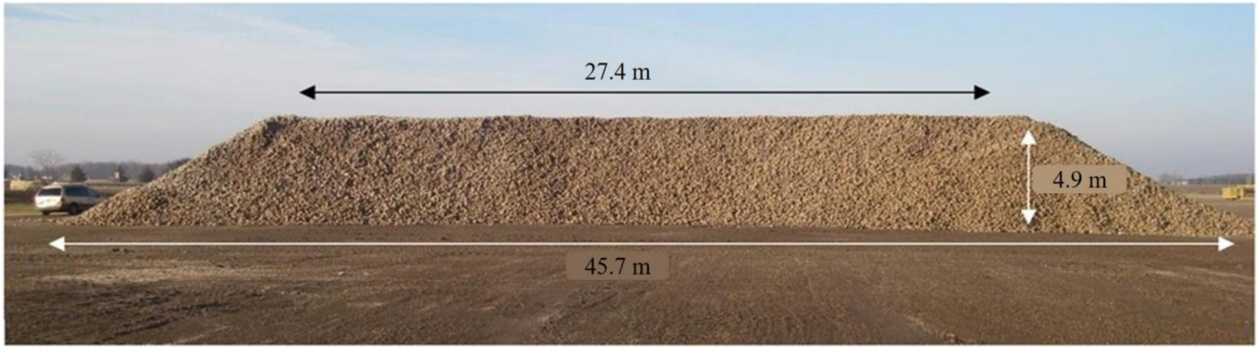

Figure 1: Photograph: Presents a cross section of the studied sugar beet pile showing the dimensions of the studied pile, which is located at Reese, Michigan for 2011-2012 and 2012-2013 seasons, to study the heat flux distribution inside the pile.

Important input parameters were required for the model including: soil and sugar beet thermal properties (described below) and heat of respiration generated by the sugar beet, in addition to air temperature, air velocity and relative humidity (RH) were obtained from the weather station located at the MSU Saginaw Valley Beet and Bean Research Farm, Frankenmuth, MI., (43.3995° N, 83,6980° W) (Enviro-weather, 2011).

MODEL DESCRIPTION

Input parameters underwent in a finite element analysis through a mathematical model to calculate the rate of heat gain from the ground and respiratory activity and heat loss to the environment. The model was built and integrated using finite element software COMSOL (COMSOL Multiphysics ® 4.3b, COMSOL AB, Stockholm, Sweden). For simplification of the calculations, the model was developed assuming a steady-state heat transfer condition in two dimensions (2D) on a daily basis, which means the environmental conditions changed from day to day but was considered constant during the day. However, this assumption might not be accurate during the day especially with the fluctuating weather in the piling site based on observations. The model included heat convection at the pile surface and heat conduction inside the pile between beets and between the pile and the ground.

MODEL PARAMETERS

1. Sugar Beet Thermal Properties

Tabil et al. (2003a), measured the thermal properties of sugar beet roots including density and specific heat (Table 1) which were used in the model. Root thermal conductivity (k_p) was calculated as a function of temperature (K) and was taken to equal 0.6 $W.m^{-1}.K^{-1}$. The thermal conductivity for frozen roots on the other hand was taken as 1.16 $W.m^{-1}.K^{-1}$; freezing occurs at temperatures equal to or lower than -5 to -2 °C (Campbell and Klotz, 2006).

Table 1: Model parameters for sugar beet roots and soil used in developing the heat transfer simulation of stored sugar beet pile in Reese, MI (Ochsner et al., 2001; Tabil et al., 2003a).

Parameter	Value	Unit
Soil density	1700	$kg \cdot m^{-3}$
Soil thermal conductivity	0.525	$W \cdot m^{-1} \cdot K^{-1}$
Soil specific heat	1.615	$kJ \cdot kg^{-1} \cdot K^{-1}$
Root specific heat	3.5464	$kJ \cdot kg^{-1} \cdot K^{-1}$
Root density	1169.9	$kg \cdot m^{-3}$

2. Heat of Respiration of Sugar Beet

The respiration rate of sugar beet roots was calculated on the average rate measured for 38 cultivars. Three beet samples from each cultivar were stored in three different temperatures (3, 10 and 20 °C). Each sample was weighed then stored in 20-L high-density polyethylene pails. The respiration rate was measured using the closed system method (Guevara et al., 2006; Hagger et al., 1992; Lee, 1987; Song et al., 1992). To obtain accurate readings, respiration rate for each sample was measured only after reaching system equilibrium. Each measurement took place by manually injecting gas samples that were derived from the desired pail into a CO_2 analyzer (Model ADC225-MK3, Analytical Development Co., Hoddesdon, England) that uses N_2 as the carrier gas (N_2 flow rate = 100 $mL \cdot min^{-1}$). Respiration rate was calculated using Eq.1

Equation 1: Respiration rate CO_2 ($mL \cdot kg^{-1} \cdot hr^{-1}$) = (outlet CO_2 (%) - inlet CO_2 (%)) x flow rate ($mL \cdot hr^{-1}$)/sample wt (kg)

A simple linear regression relationship was performed to obtain the best-fit line to predict the respiration rate as a function of the ambient temperature. Eq. 2 shows the best-fit respiration rate for CO_2 production ($mg \cdot kg^{-1} \cdot h^{-1}$) as a function of ambient temperature T (K)

Equation 2: Respiration rate = $0.97 \cdot T - 262.06$

where: T is ambient temperature (K).

To calculate the portion of heat released from the total energy of respiration, Siedow and Day (2017) estimated that plant cells retain approximately 33% of the respiration energy for metabolic processes. Therefore, 67% of the energy associated with respiration was assumed to be released as heat, producing the exponential relationship between the energy of respiration (Q) per unit volume ($W \cdot m^{-3}$) and the ambient temperature (T) as follows:

Equation 3: $Q = \exp(-6291 \times (1/T) + 25.472)/182)$

Where T is in units of K. Equation 3 can be applied in the case of unfrozen roots, while for frozen roots respiration ceases (Campbell and Klotz, 2006).

3. Soil Thermal Properties

Reese, MI is characterized by its clay and loam soil type (Boring, 2009; Meyer, 2009) for which thermal properties are known (Table 1) (Ochsner et al., 2001).

4. Air Thermal Properties

The thermal properties of moist air are built in the COMSOL software and were used to develop the model. Table 2 shows the air thermal properties at 0°C.

Table 2: Air parameters used in developing the heat transfer simulation of stored sugar beet (Datta, 2002).

Parameter	**Value**	**Units**
Air density	1.225	$kg \cdot m^{-3}$
Air thermal conductivity	0.0243	$W \cdot m^{-1} \cdot K^{-1}$
Air specific heat	1.005	$kJ \cdot kg^{-1} \cdot K^{-1}$

MODEL ASSUMPTIONS

Several assumptions were required to simplify model development; these include:

- Heat energy transfers through the shortest two dimensions of the pile (width and height), whereas the energy transfers through the length can be negligible due to the relatively long dimension.
- Root density and specific heat do not vary significantly within the temperature range for beet piles through the storage period.
- Ground density, specific heat and thermal conductivity do not vary significantly within the temperature range throughout the storage period.
- The pile was considered as a porous material.
- Enthalpy due to the water vapor diffusion from beets was negligible.

- Inlet air conditions changed daily depending on the average temperature, RH and the average wind velocity. However, the air direction will be assumed constant from south to north based on prevailing wind conditions.
- COMSOL Multiphysics predicts the flow pattern of the air, either laminar or turbulent according to Reynolds number as a function of the air velocity and pile dimensions, which is provided as an input in the model.
- The ground temperature from November to April at 50 cm deep at Reese MI is 5.5 °C (Schaetzl et al., 2005). Therefore, ground temperature was considered constant at that temperature and depth.
- Root moisture content was considered constant at 70% to 80% (Tabil et al., 2003b) during the experiment.
- Porosity is assumed to be constant during the experiment as 41.37% (Tabil et al., 2003b).

GEOMETRY AND BOUNDARY CONDITIONS

A geometric representation of the studied pile base, height and top, the dimensions of which are 45.7 m, 4.9 m and 27.4 m, respectively, is constructed (Table 3, Fig. 2 for 2011 and Fig. 3 for 2012). We assumed that there are defined boundaries for the active air that interact with the pile, beyond these limits there is no effect from the air on the pile. These boundaries are assigned to be 9.75 m in height and 91.44 m in width, roughly 2x pile dimensions (Table 3). The assumed boundaries were obtained based on our preliminary work and for simplicity.

Table 3: Sugar beet pile geometry and boundary conditions used to develop the mathematical model.

Type	Base (m)	Height (m)	Top (m)
Pile geometry	45.7	4.9	27.4
Boundary dimensions	91.44	9.75	91.44

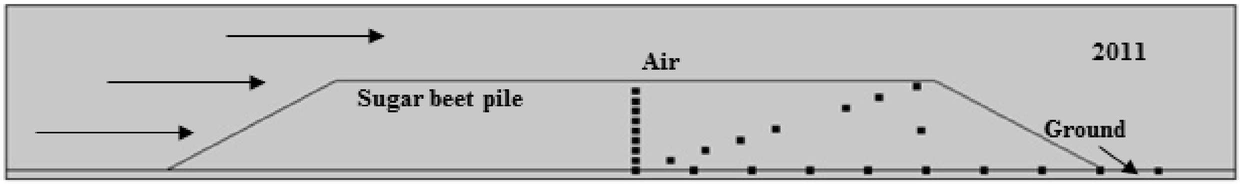

Figure 2: Schematic design: Illustrates the sugar beet pile and pile's boundaries included in the model for the 2011season. The data used to predict pile temperature included inlet air temperature, wind speed and ground temperature at 50 cm depth (5.5 °C (Schaetzl et al., 2005)). The pile dimensions are 45.7 m, 4.9 m and 27.4 m for the base, height and top, respectively. The black dots are the positions of the thermocouples in the middle of the. The boundaries are assigned to be 9.75 m in height and 91.44 m in width. Arrows on the left side show the direction of the inlet air.

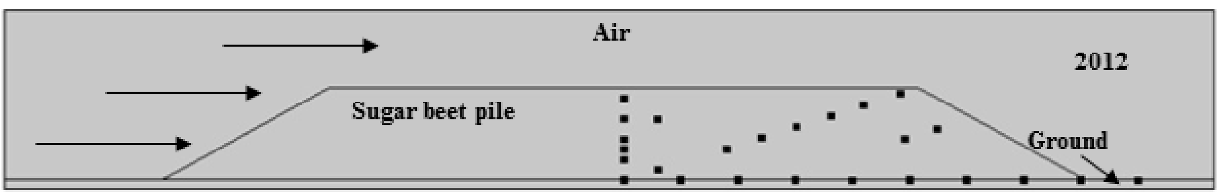

Figure 3: Schematic design: Illustrates the sugar beet pile and pile's boundaries included in the model for the 2012 season. The data used to predict pile temperature included inlet air temperature, wind speed and ground temperature at 50 cm depth (5.5 °C (Schaetzl et al., 2005)). The pile dimensions are 45.7 m, 4.9 m and 27.4 m for the base, height and top, respectively. The black dots are the positions of the thermocouples in the middle of the pile. The boundaries are assigned to be 9.75 m in height and 91.44 m in width. Arrows on the left side show the direction of the inlet air.

MODEL EQUATIONS

For the numerical solution of the proposed problem, the heat transfer governing differential equations were built in and calculated using COMSOL software (COMSOL_Multiphyics, 2013a; COMSOL_Multiphyics, 2013b).

1. Equations for Heat Transfer in the Sugar Beet Pile

The beet pile was considered a porous medium with sugar beet roots as the solid phase and moist air as the fluid phase as described by equations 4, 5 and 6 (COMSOL_Multiphyics, 2013a; COMSOL_Multiphyics, 2013b).

Equation 4: $\rho C_p u . \nabla T + \nabla . q = Q$

where:

Equation 5: $q = -k_{eff} \nabla T$

and:

Equation 6: $k_{eff} = \theta_p k_p + (1- \theta_p)\, k + k_{disp}$

where:

ρ: is the density of the beet ($kg \cdot m^{-3}$),

C_p: is the specific heat of the beet at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$),

u: is the velocity of the moist air inside the pile ($m \cdot s^{-1}$),

∇T: is the temperature gradient ($K \cdot m^{-1}$),

q: is the conductive heat flux ($W \cdot m^{-2}$),

Q: is the respiration heat per unit volume ($W \cdot m^{-3}$),

k_{eff}: is the effective thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$),

θ_p: porosity (%),

k_p: beet thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$),

k: moist air thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$),

k_{disp}: Dispersive thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

2. Equations for Heat Transfer in the Ground

The ground was considered as a solid material and the following equations were used to solve for the ground temperature (COMSOL_Multiphyics, 2013a; COMSOL_Multiphyics, 2013b):

Equation 7: $\rho C_p\, u\, .\nabla T + \nabla . q = Q$

Equation 8: $q = -k_g \nabla T$

where:

k_g= ground thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$),

ρ: is the density of the soil ($kg\cdot m^{-3}$),

C_p: is the specific heat of the soil at constant pressure ($J\cdot kg^{-1}\cdot K^{-1}$),

u: is the velocity field defined by the translational motion sub-node when parts of the model are moving in the material frame ($m\cdot s^{-1}$),

∇T: is the temperature gradient ($K\cdot m^{-1}$),

q: is the conductive heat flux ($W\cdot m^{-2}$),

Q: is the heat flux ($W\cdot m^{-3}$).

3. Equations for Heat Transfer in the Air

Pile cooling occurs by natural convection (Beukema, 1980); therefore, moist air was considered as a fluid material and relative humidity (RH) was used as an input quantity of moisture. The following equations solve for air temperature (COMSOL_Multiphyics, 2013a; COMSOL_Multiphyics, 2013b):

Equation 9: $\rho C_p\, u\, .\nabla T + \nabla . q = Q$

Equation 10: $q = -k\nabla T$

Where ρ: is the density of moist air ($kg \cdot m^{-3}$),

C_p: is the specific heat of the moist air at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$),

u: is the air velocity ($m \cdot s^{-1}$),

∇T: is the temperature gradient (K),

q: is the conductive heat flux ($W \cdot m^{-2}$),

Q: is the heat flux from the heat source (or sink) ($W \cdot m^{-3}$),

k: moist air thermal conductivity (W/m. ◦K).

MONITORING PILE TEMPERATURE

To monitor the pile temperature, wiring harnesses of T-type (copper/constantan) thermocouples (OMEGA Engineering™, INC., Norwalk, CT, USA), encased in 6-mm i.d. polypropylene tubing for protection, were installed in the middle of the beet piles in late October in 2011 and in early November in 2012.

Harnesses were placed on the sloping face of the pile when the pile was partially constructed. Following placement of the harnesses, pile construction was completed, burying the thermocouples within the pile at predefined locations (Fig. 2 for 2011 and Fig. 3 for 2012). Each harness had from 1 to 10 thermocouples, depending upon their position in the pile. One harness was placed vertically down the face of the pile at the midpoint and another harness was placed diagonally across the face of the pile from its outer shoulder to the base at its midpoint. A third harness ran horizontally along the base of the pile to its midpoint and a fourth harness (thermocouples only, no protective tubing used) was buried about 5 cm below the soil surface along the base of the pile to its midpoint. One additional thermocouple was embedded in the pile between the vertical harness and the diagonal harness and another two thermocouples were embedded in the pile between the diagonal harness and the horizontal harness. A total of 26 (in 2011 season) and 25 (in 2012 season) locations were monitored. There was 1 failed thermocouple in the 2012 season leading to a decrease in the number of locations in the later season.

Temperature measurements were collected every minute using digital dataloggers (CR-10, Campbell Scientific, Inc., Logan, Utah, USA) and the average for each hour recorded. Temperature data that was used for model validation was collected from November to January in 2011, and from November to February in 2012. The 2011 storage season was dry and warm, limiting storage to two months.

CALCULATING SUGAR LOSS

Evaluating the sugar loss and decrease in quality in the roots during storage are the main ways to evaluate any storage system for sugar beet (Huijbregts et al., 2013). Thus, Cumulative sugar loss (kg/metric ton) was estimated using measured and modeled temperatures to evaluate the model accuracy and to study the effect of various modeled geometries and ventilation designs of the pile which can be recommended sugar beet storage in the future.

Cumulative sugar loss was calculated as a function of the daily average of either the pile's measured temperature or modeled temperature. To calculate the daily sugar loss, Eq. 2 was used to solve for the temperature to obtain the predicted CO_2 respiration rate (mg kg^{-1} hr^{-1}). Daily sucrose loss (mg kg^{-1} hr^{-1}) is equal to the daily CO_2 respiration rate divided (mg kg^{-1} hr^{-1}) by 1.55, as the mass of CO_2 is 1.55 times that of sucrose (Azcón-Bieto and Osmond, 1983; Siedow and Day, 2017). To predict Cumulative sugar loss, calculated daily sugar loss was added for every day of the period tested. Sugar loss was also used to compare between different pile zones, measured and modeled temperatures and to test three designs of sugar beet storage systems (described in the Pile design evaluation section later) compared to the actual sugar loss.

Three differing pile designs were developed to determine the effect of pile architecture on beet root temperature, assuming a 3°C increase in air temperature relative to 2012 data. The Cumulative sugar loss was calculated for the modeled scenarios.

PILE ZONE COMPARISONS

To simplify the interpretation of the results, the pile was divided into three zones. The lower zone; from the base of the pile up to 1.6 m high, the middle zone; from the lower zone to 3.2 m high and the upper zone; from the middle zone to the top of the pile (4.9 m). Each zone contained 6 to 14 collected temperature points (Fig. 4 for 2011 and Fig. 5 for 2012). The average temperature of the points in each zone was used as the temperature of that zone. A comparison between sugar loss was obtained based on average zone temperature.

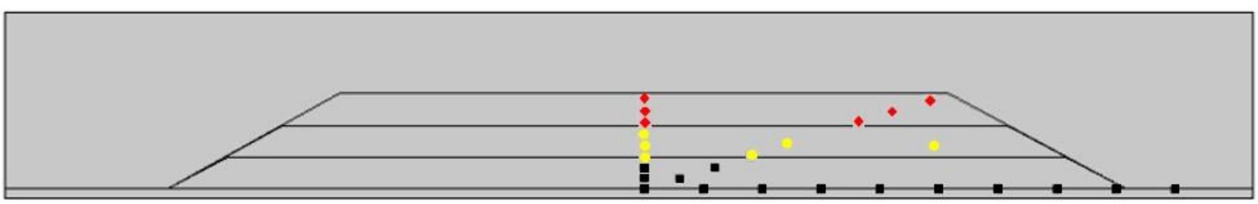

Figure 4: Schematic design: Illustrates the sugar beet pile divided into three zones, lower (■), middle (●) and upper (♦) for the 2011 season. The colored symbols illustrate the thermocouple locations as distributed in each zone.

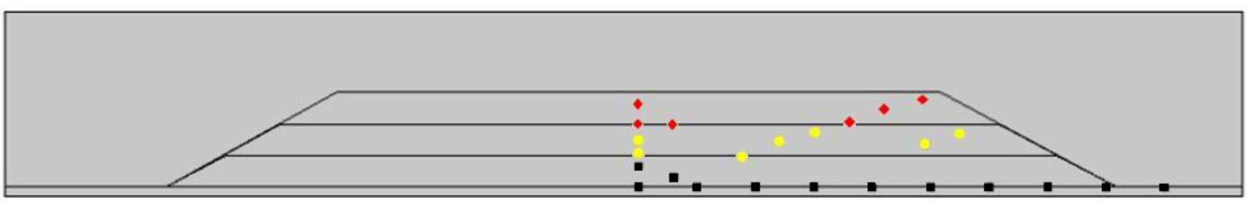

Figure 5: Schematic design: Illustrates the sugar beet pile divided into three zones, lower (■), middle (●) and upper (♦) for the 2012 season. The colored symbols illustrate the thermocouple locations as distributed in each zone.

PILE DESIGN EVALUATION

Three pile designs differing in height (50% decrease and 50% increase relative to a commercial pile) and ventilation (by creating a pass underneath the pile that allows cold air to flow under the pile to cool the base), were designed using the built model with some modifications in each system to predict the effect of these design variables on temperature (Table 4). Modeled temperature obtained from each design was used to estimate the daily and Cumulative sugar loss during storage, which was used to compare the three designs.

Table 4: Dimensions for different pile designs used for developing heat transfer models in sugar beet storage piles.

Pile shape	**Pile height (m)**	**Pile width (m)**
Commercial	4.8	45.7
50% Decrease	2.4	45.7
50% Increase	7.3	45.7
Ventilated	4.8	45.7

In the “decreased height” beet pile system (Fig. 6), the main pile height was decreased by 50%, while all other parameters were the same as the main pile.

Figure 6: Schematic design: Illustrates the suggested “decreased height” sugar beet pile. The outer pile-shape describes the commercial pile, the insider pile-shape describes the “decreased height” pile. Arrows show the air direction for the model.

In the “increased height’ beet pile system shown in Fig. 7, the main pile height was increased` by 50%, while all other parameters were the same as in the main pile.

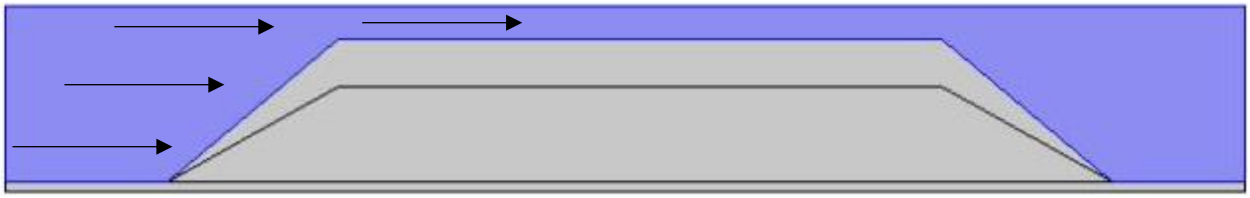

Figure 7: Schematic design: Illustrates the suggested “increased height” sugar beet pile. The outer pile-shape describes the “increased height” pile, the insider pile-shape describes the commercial pile. Arrows show the air direction for the model.

In the ventilated system (Fig. 8), the area of that system was kept the same as the commercial pile area and natural convection ventilation was added below the pile to cool the base while all other parameters were the same as the main pile.

Figure 8: Schematic design: Illustrates the suggested “ventilated” sugar beet pile. The air domain is surrounding the pile from all sides. Arrows show the air direction for the model.

For validation, the calculated temperatures were compared with measured temperatures obtained during 132 days total for both years from an actual commercial storage pile. In the first year, the air temperature was higher than usual, leading to a short storage period, and we were able to obtain data for only 37 days. In the second year, the temperature was at the normal range, so we were able to obtain data for 95 days. The pile temperature was used to calculate the respiration rate of stored beets and thereby estimate sugar loss during the storage campaign.

DATA HANDLING, STATISTICAL ANALYSIS AND EXPERIMENTAL DESIGN

In the current study, the model yielded one temperature value per day for each point among the 26 (in the 2011 season) and 25 (in the 2012 season) predefined points in the pile. However, each data logger recorded 24 temperature measurements (i.e. one value per hour) for each thermocouple of the 26 or 25 thermocouples used in each pile. To achieve consistency between the measured and modeled temperatures, the daily average of the 24 measurements from each thermocouple was obtained. The average temperature of all the predefined points was calculated to obtain the pile temperature for each day for the primary analysis.

Analysis of variance (ANOVA) was used to test the relationship between the measured and modeled temperatures and estimated cumulative sugar loss. In this stage of analysis, only the average daily temperature of the whole pile was calculated from the 26 daily temperature values in 2011 and the 25 daily temperature values in 2012. Thus, the total number of analyzed points was 37 and 95 for the 2011 and 2012 seasons, respectively. Additionally, another ANOVA was conducted to study the effect of pile zones (lower, middle and upper) on the difference between the measured and modeled temperatures. In this stage, the average daily temperature was considered for each zone and each season, calculated from 14, 6 and 6 daily temperature values for the lower, middle and upper zones, respectively for 2011, and 12, 7 and 6 daily temperature values for the lower, middle and upper zones, respectively for 2012. Thus, the total number of analyzed points for the 2011 season were 37 points for each zone. Whereas, the total number of analyzed points for the 2012 season were 95 points for each zone. In each of the above tests, the significance level was chosen to be 0.05.

If a significant effect of any of the studied independent variables was found according to the ANOVA test, a mean comparison was carried out using the least significant difference (LSD)

T-test with a significance level of $\alpha \leq 0.05$. Besides, a correlation analysis was conducted to study the relationship between cumulative sugar loss for measured and modeled temperatures with a level of significance as ($\alpha \leq 0.05$) and the correlation coefficient (r) was used to estimate the strength of this relationship. To predict Lm (the Cumulative sugar loss based on measured temperature) as a function of Ld (the Cumulative sugar loss based on modeled temperature), a simple linear regression analysis was conducted and the coefficient of determination (R^2) was calculated. The statistical analysis was performed using the PROC GLM procedure in SAS 9.4 (2014, SAS Institute Inc., Cary, NC, USA).

RESULTS

The pile temperature distribution changed throughout the day in response to changing air temperature (Fig. 9). The temperature of the pile typically declined from the inside to the outside of the pile. The center of the pile was usually the warmest region of the pile and of the three zones chosen for analysis, the lower zone of the pile, near the ground surface, was usually warm compared to the upper zone of the pile. The base of the pile typically ranged from 2.8 to 11 °C warmer than the surface of the pile. During a warm period, when the air temperature was around 2 °C, large portions of the pile (>70%) had root temperatures above 7 °C. During a cool period, when the air temperature was -7 °C, about 30% of the pile still had temperatures in the 4.5 °C range, and almost half of the pile had temperatures below freezing.

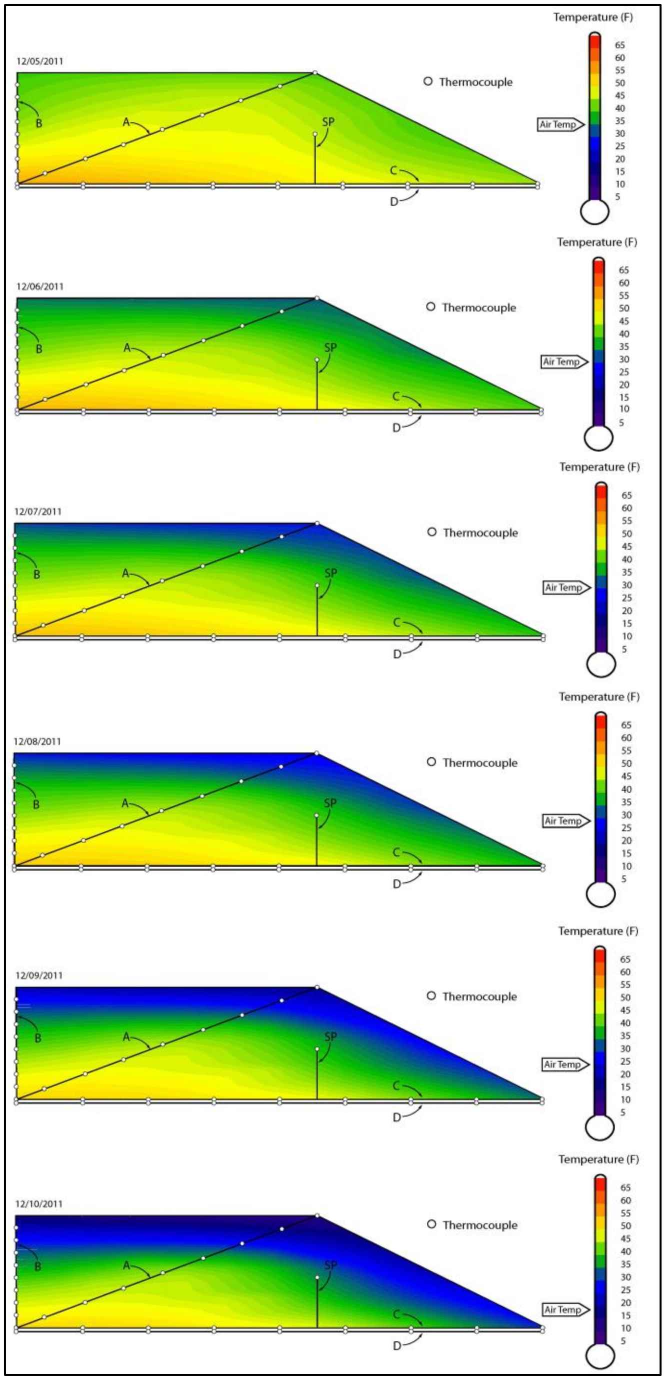

Figure 9: Heat transfer diagram: Illustrate the temperature profile of the Gera Road beet pile on December 5-10, 2011. The average air temperature is given in the thermometer to the right of each panel. A, B, C, D and SP indicate five thermocouple harnesses; harness D was embedded approximately 5 cm into the soil. White circles indicate locations of individual thermocouples.

MODEL ACCURACY BASED ON PILE TEMPERATURE

The modeled daily average temperatures for the whole pile were compared with measured daily average temperatures for both storage seasons. The model tended to underestimate temperature (Fig. 10 for 2011 and Fig. 11 for 2012). The mean difference between measured and modeled temperature values was significant ($P \leq 0.05$) (Table 5), and a boxplot shows the mean of the modeled temperatures was lower than the mean of measured temperatures for both seasons (Fig. 12 for 2011 and Fig. 13 for 2012). Due to some technical problems with dataloggers, some measuring data was lost, resulting in gaps in temperature measurements in Fig. 10 and similar subsequent figures.

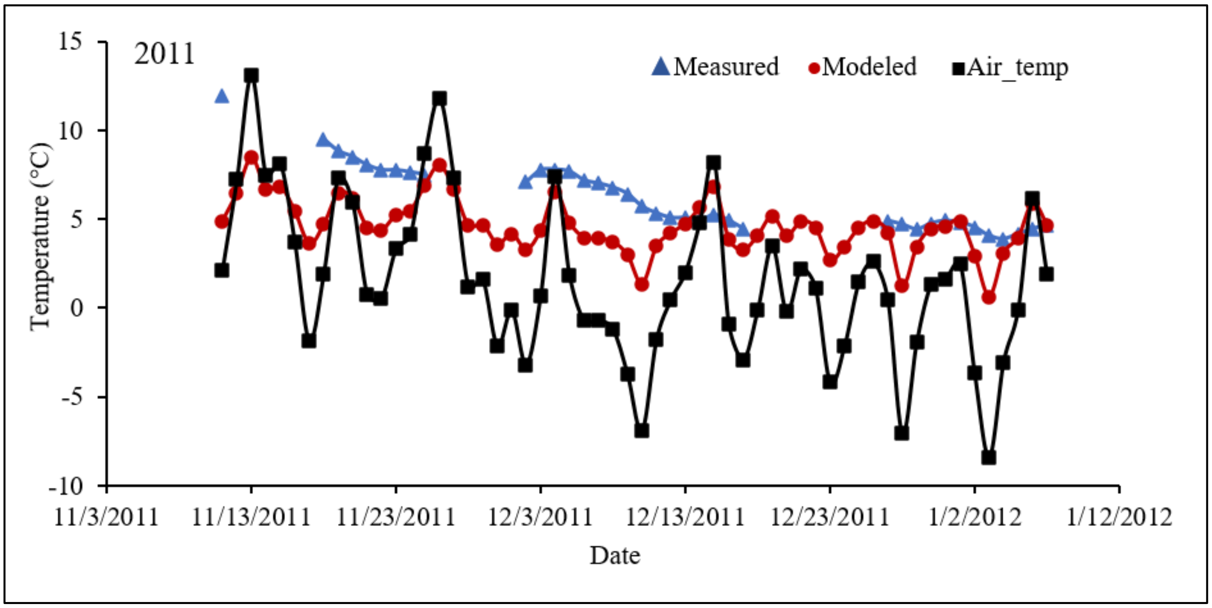

Figure 10: Graph: Shows the measured (▲) and modeled (●) sugar beet whole pile temperatures for the 2011 season in relation to air temperature (■).

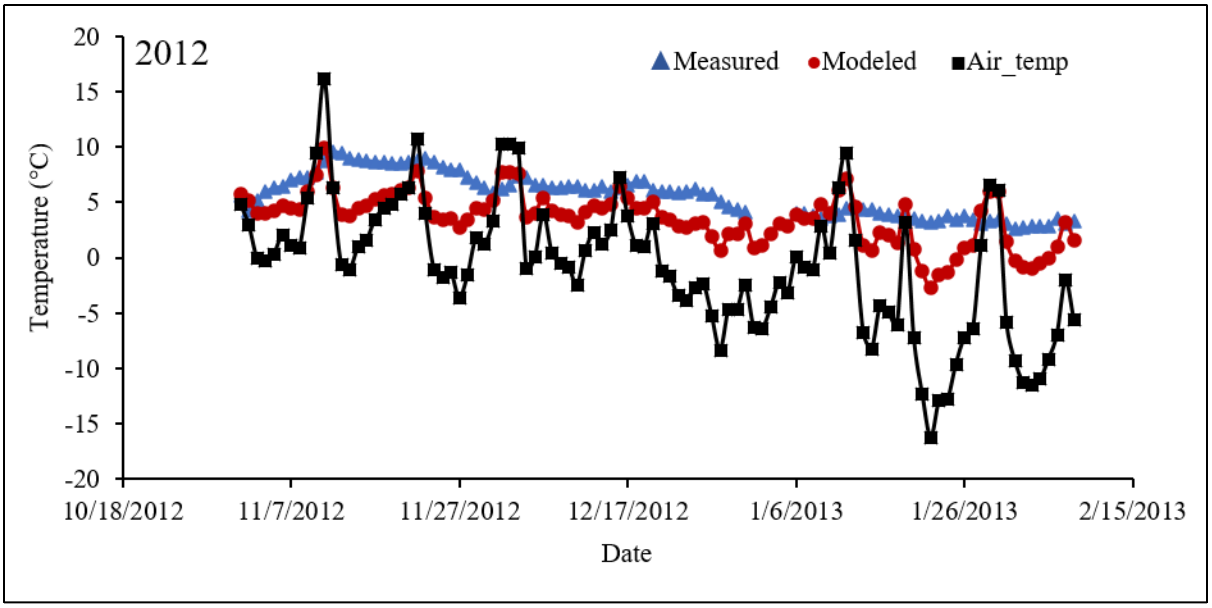

Figure 11: Graph: Shows the measured (▲) and modeled (●) sugar beet whole pile temperatures for the 2012 season in relation to air temperature (■).

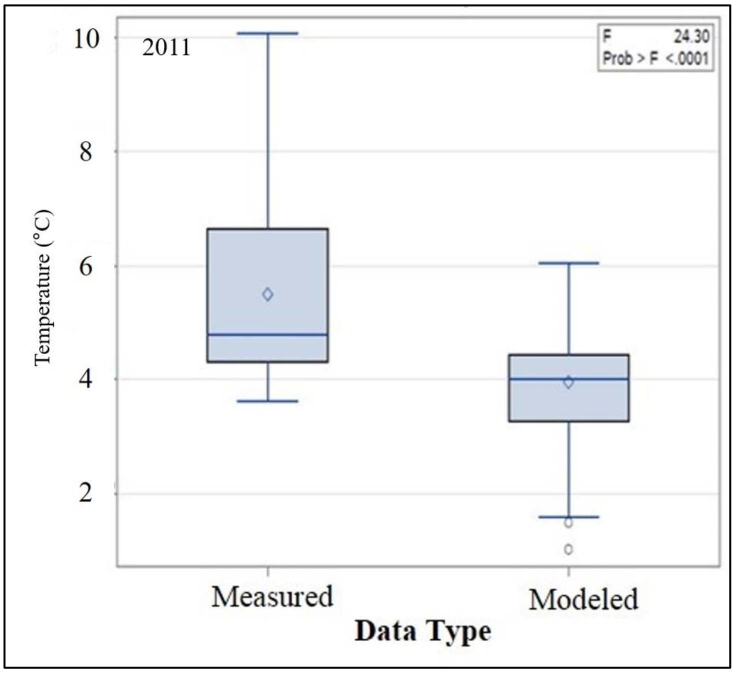

Figure 12: Boxplot: Displays the distribution of the values of measured and modeled temperatures for the beet pile temperature for the 2011 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

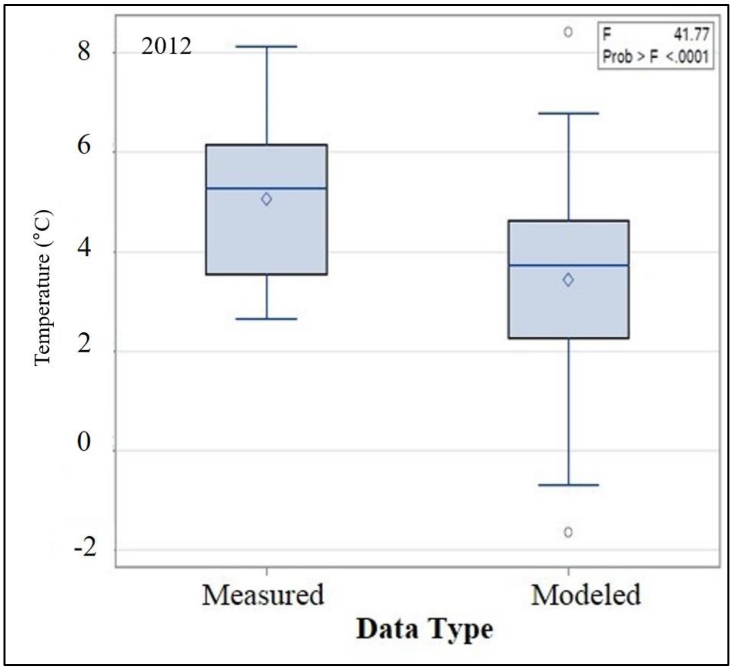

Figure 13: Boxplot: Displays the distribution of the values of measured and modeled temperatures for the beet pile temperature for the 2012 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 5: Measured and modeled beet pile temperatures (°C) for 2011 and 2012 averaged across the storage campaign.

	Pile temperature (°C)	
Data source	2011[a]	2012[b]
Measured	6.21 A	5.68 A
Modeled	4.3 B	3.64 B

* Values followed by different letters within a column differ based on LSD test ($\alpha \leq 0.05$).
[a]LSD = 0.7714 for the 2011 season.
[b]LSD = 0.6222 for the 2012 season.

MODEL ACCURACY BASED ON SUGAR LOSS

1. Daily Sugar Loss

Daily rate of sugar loss (kg/metric ton/day) based on measured and modeled temperatures were calculated (Fig. 14 for 2011 and Fig. 15 for 2012) and boxplot (Fig. 16 for 2011 and Fig. 17 for 2012) and mean different analysis (Table 6) were obtained. The mean of the daily sugar loss based on the modeled pile temperature was significantly (P≤0.05) lower than the mean of the daily sugar loss based on the measured pile temperature, which means that the calculations based on the modeled pile temperature values underpredict the amount of sugar loss.

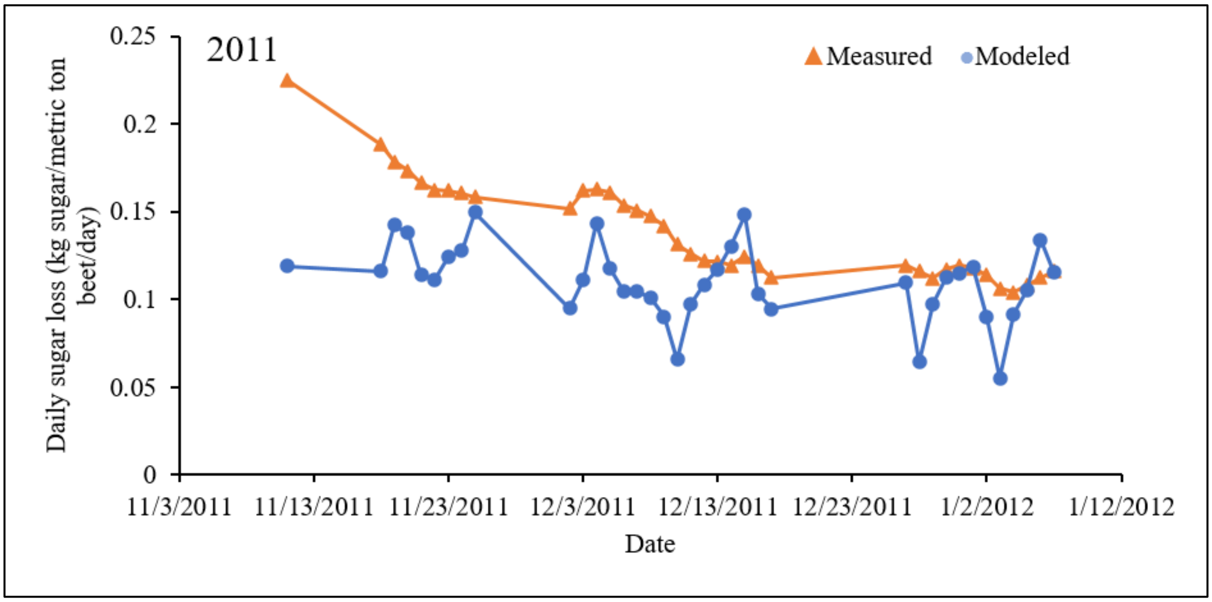

Figure 14: Graph: Shows the daily sugar loss (kg/metric ton /day) from field-stored sugar beets calculated from measured (▲) and modeled (●) pile temperatures for the 2011 season.

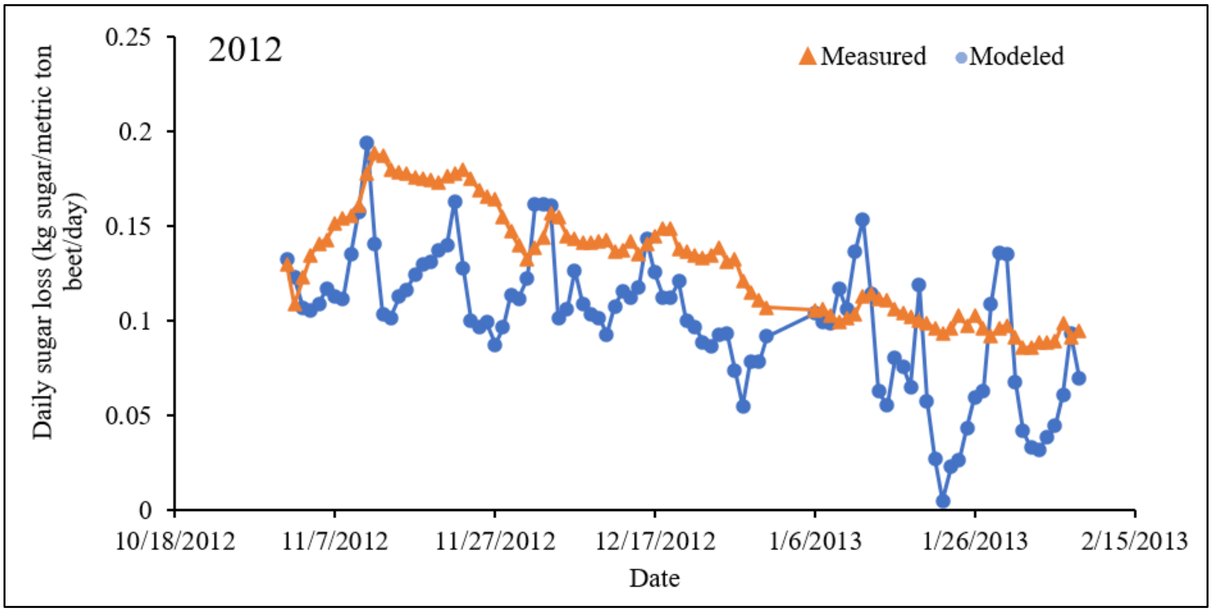

Figure 15: Graph: Shows the daily sugar loss (kg/metric ton /day) from field-stored sugar beets calculated from measured (▲) and modeled (●) pile temperatures for the 2012 season.

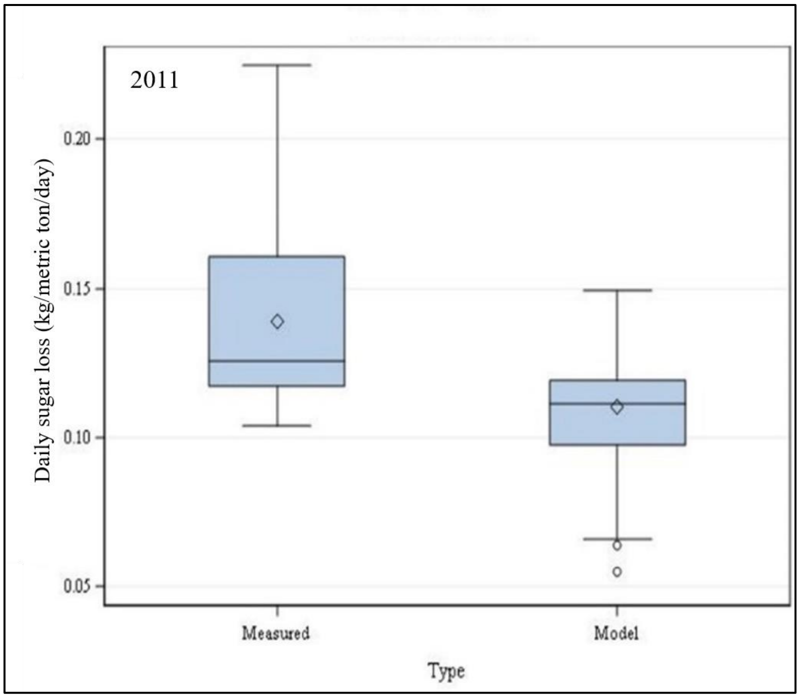

Figure 16: Boxplot: Displays the distribution of the daily rate of sugar loss (kg/metric ton/day) due to respiration as a function of measured or modeled sugar beet pile temperature for the 2011 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

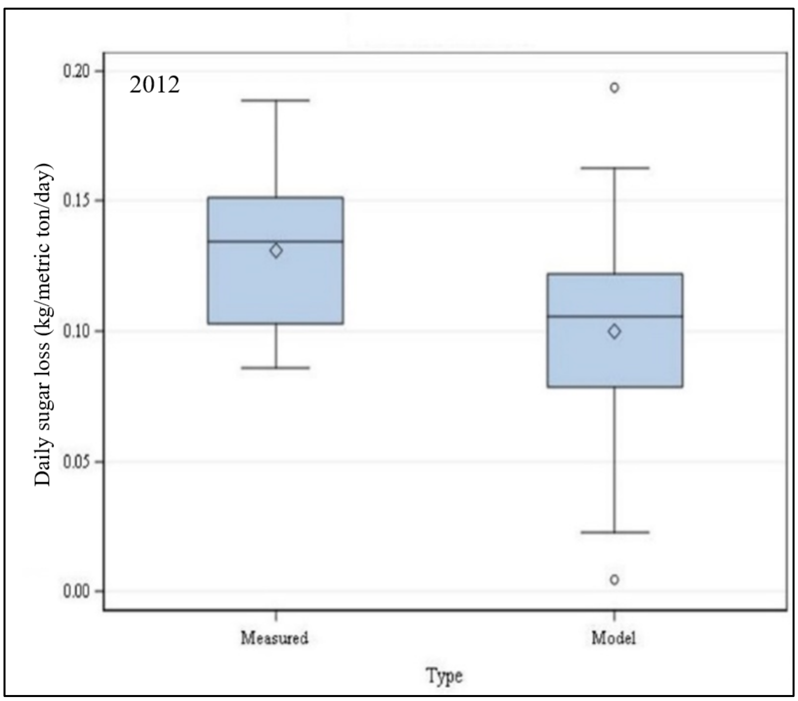

Figure 17: Boxplot: Displays the distribution of the daily rate of sugar loss (kg/metric ton/day) due to respiration as a function of measured or modeled sugar beet pile temperature for the 2012 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 6: Sugar loss estimates based on measured and modeled beet pile temperatures for 2011 and 2012 (°C) averaged throughout the storage campaign.

2011[a]		**2012[b]**	
Rate of sugar loss (kg/metric ton/day)	**Type**	**Rate of sugar loss (kg/metric ton/day)**	**Type**
0.14 A	Measured	0.13 A	Measured
0.11 B	Modeled	0.10 B	Modeled

*Values followed by different letters within a column differ based on LSD test ($\alpha \leq 0.05$).
[a]LSD = 0.0116 for the 2011 season.
[b]LSD= 0.0094 for the 2012 season.

2. Cumulative Sugar Loss

There was a high correlation between Cumulative sugar loss (kg/metric ton) based on daily average values of measured temperatures (Lm) and modeled temperatures (Ld) with a coefficient of correlation (r) of 0.997 and 0.999 for the 2011 and 2012 seasons, respectively. The total number of days in storage was 37 days in 2011, and 95 days in 2012 (Fig. 18 for 2011 and Fig. 19 for 2012). A mean comparison (Table 7) and a boxplot (Fig. 20 for 2011 and Fig. 21 for 2012) show that there was a significant difference between the Lm and Ld ($P \leq 0.05$). The mean values of Ld were significantly lower than the mean values of Lm by 1.06 (kg/metric ton) for the 2011 season and 2.91 (kg/metric ton) for the 2012 season.

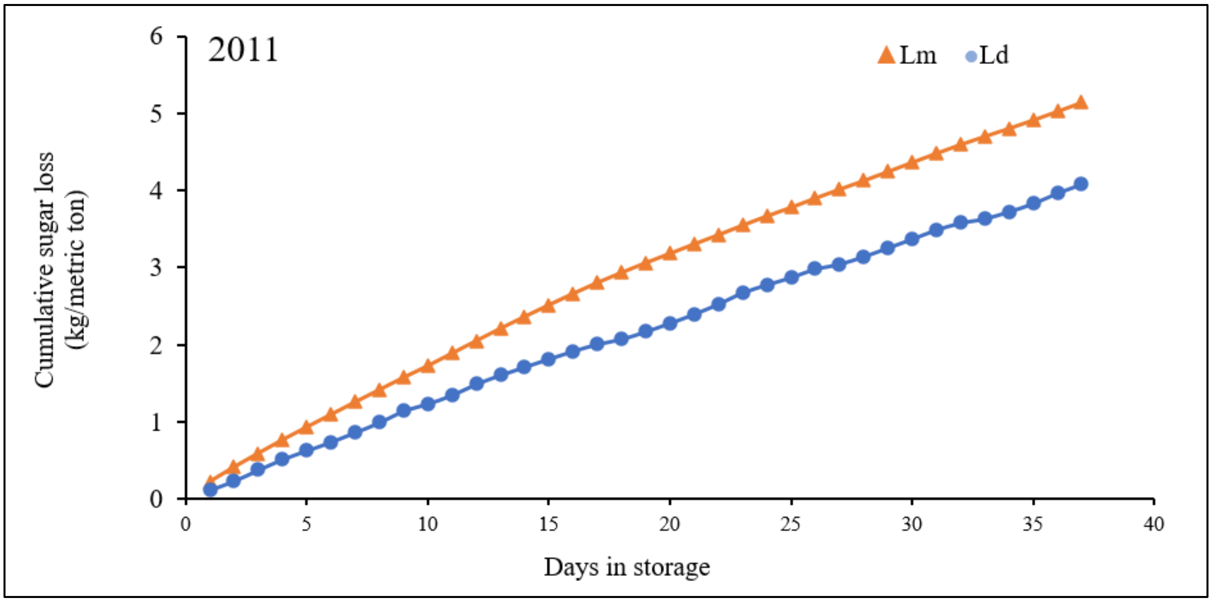

Figure 18: Graph: Shows the cumulative sugar loss (kg/metric ton) from field-stored sugar beets calculated from measured (▲, Lm) and modeled (●, Ld) pile temperatures for the 2011 season.

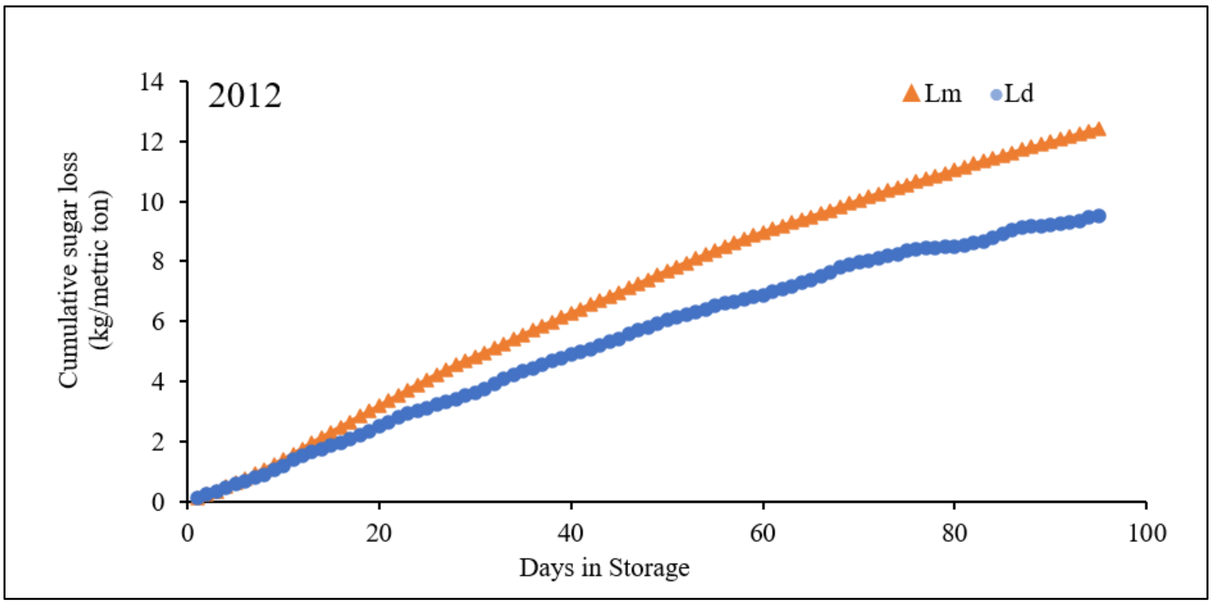

Figure 19: Graph: Shows cumulative sugar loss (kg/metric ton) from field-stored sugar beets calculated from measured (▲, Lm) and modeled (●, Ld) pile temperatures for the 2012 season.

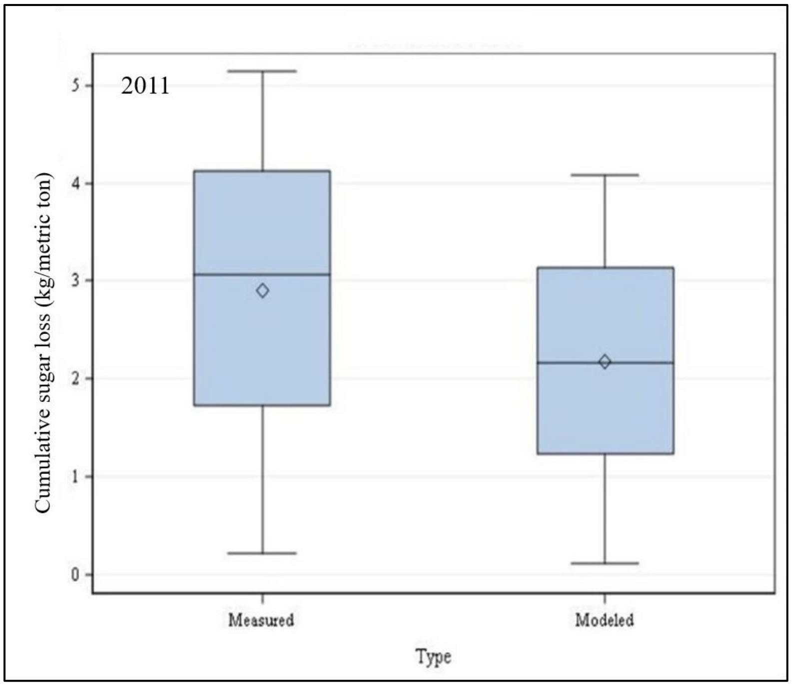

Figure 20: Boxplot: Displays the distribution of measured or modeled Cumulative sugar loss (kg/metric ton) for the 2011 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

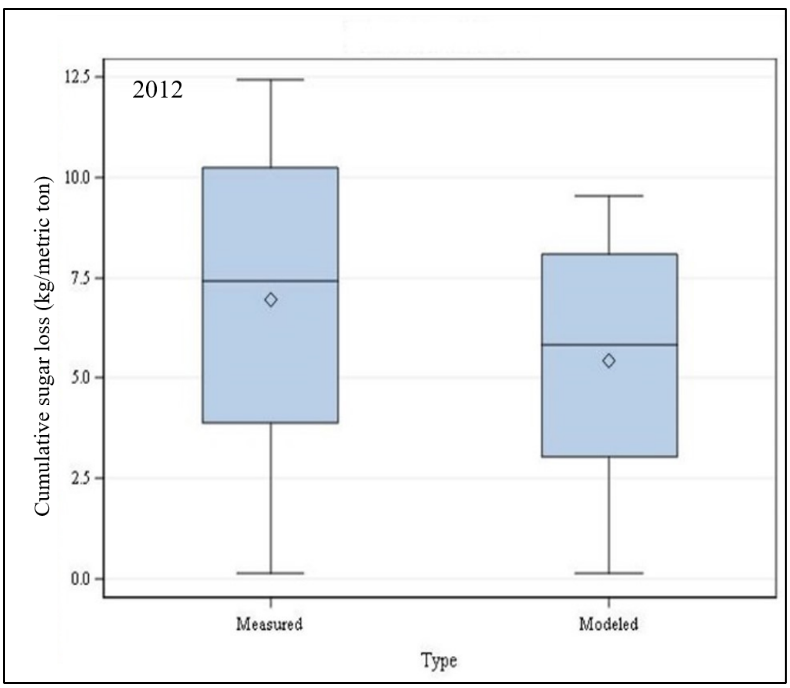

Figure 21: Boxplot: Displays the distribution of measured or modeled Cumulative sugar loss (kg/metric ton) for the 2012 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 7: Calculated cumulative sugar loss (kg/metric ton) in field-stored sugar beets based on measured and modeled pile temperature for 2011 and 2012.

2011[a]		**2012[b]**	
Cumulative sugar loss (kg/metric ton)	**Type**	**Cumulative sugar loss (kg/metric ton)**	**Type**
2.91 A	Measured	6.97 A	Measured
2.18 B	Modeled	5.43 B	Modeled

* Values followed by different letters within a column differ based on LSD test ($\alpha \leq 0.05$).
[a]LSD = 0.6142 for the 2011 season.
[b]LSD= 0.943 for the 2012 season.

The cumulative sugar loss (kg/metric ton) for the 2011 and 2012 seasons were pooled together to conduct simple linear regression analysis between sugar loss estimated from modeled and actual temperatures. Cumulative sugar loss was estimated by the pile temperature based on the model was used as an independent variable to predict Cumulative sugar loss based on the actual temperature measured in the beet pile. The coefficient of determination (R^2) was equal to 0.999. The equation (Eq. 11) can be used to correct the modeled data using the cumulative sugar loss based on measured temperatures. The equation can be used to obtain an estimate of the cumulative sugar loss for models of different designs of the storage piles.

Equation 11: $L_d = 0.7784\ L_m - 0.021$

L_m= Estimated cumulative sugar loss (kg/metric ton) based on pile measured temperature.

L_d= Estimated cumulative sugar loss (kg/metric ton) based on pile modeled temperature.

PILE ZONE COMPARISON

1. Variation of the Measured Temperature Inside the Pile

To study the spatial variation of temperatures inside the pile, the pile was virtually divided into upper, middle and lower zones. The temperature in the upper zone was the lowest followed by the temperature of the middle zone and finally the lower zone (Fig. 22 for 2011 and Fig. 23 for 2012). Boxplot analysis (Fig. 24 for 2011 and Fig. 25 for 2012) and mean comparison t-test between measured temperatures of the different zones were conducted (Table 8). The average temperature for the storage season of the three zones differed ($p \leq 0.05$). The temperature of the upper zone was significantly lower than the temperature of the middle and lower zones, and the temperature of the middle zone was significantly higher than the temperature of the lower zone in both seasons.

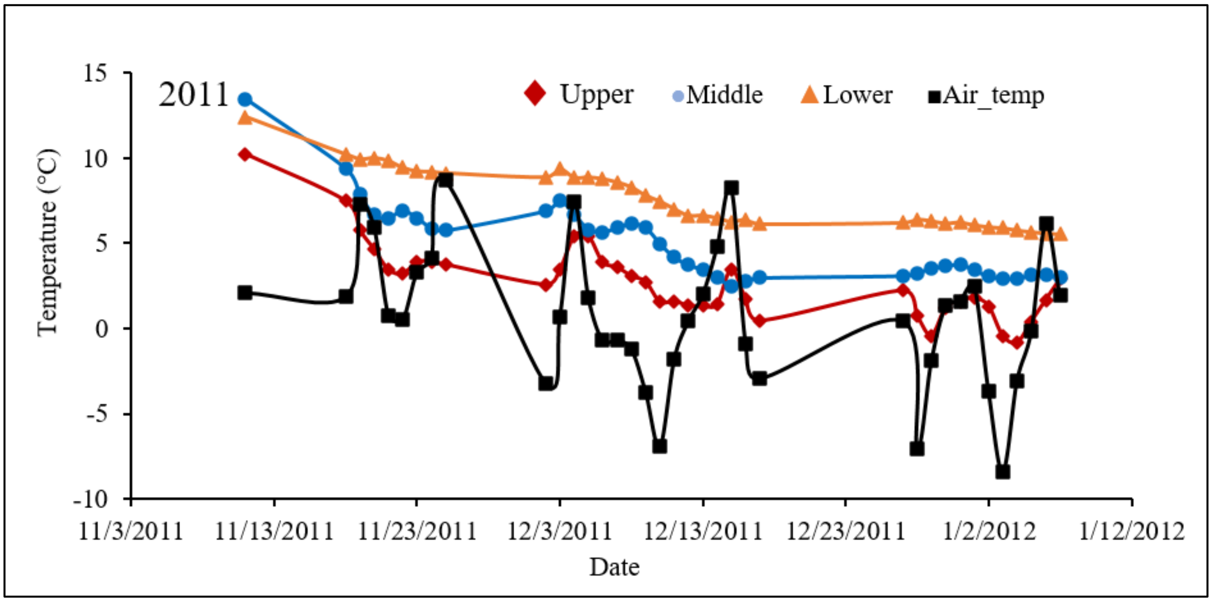

Figure 22: Graph: Shows the temperatures (°C) of the lower (▲), middle (●) and upper (♦) zones of the sugar beet pile and the average daily air temperature (■) for the 2011 season.

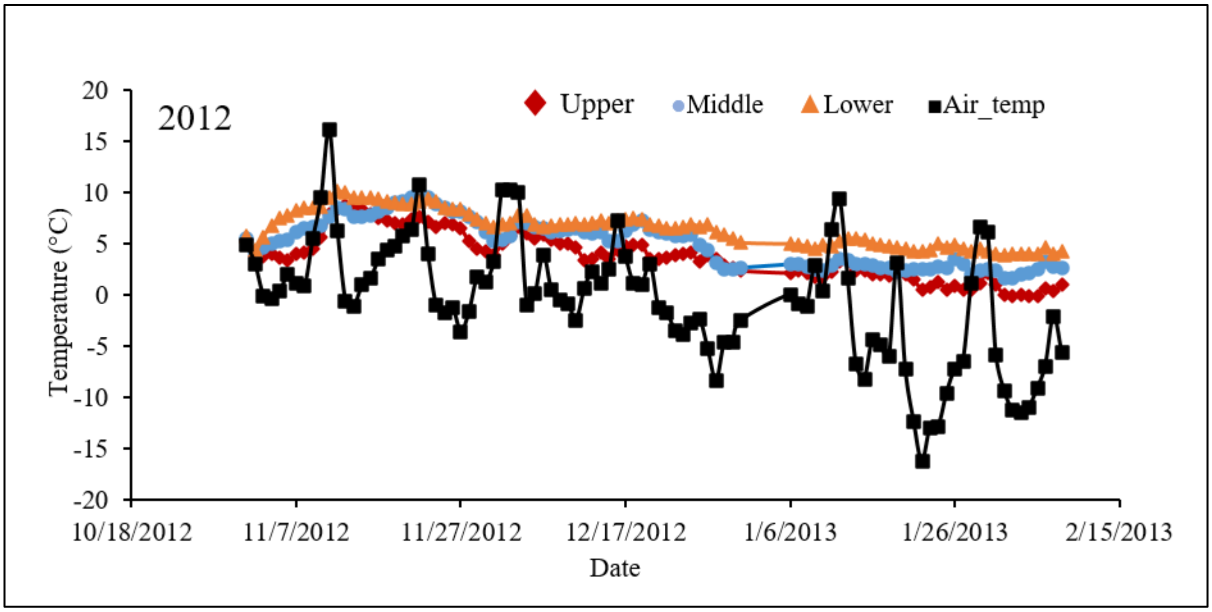

Figure 23: Graph: Shows the temperatures (°C) of the lower (▲), middle (●) and upper (♦) zones of the sugar beet pile and the average daily air temperature (■) for the 2012 season.

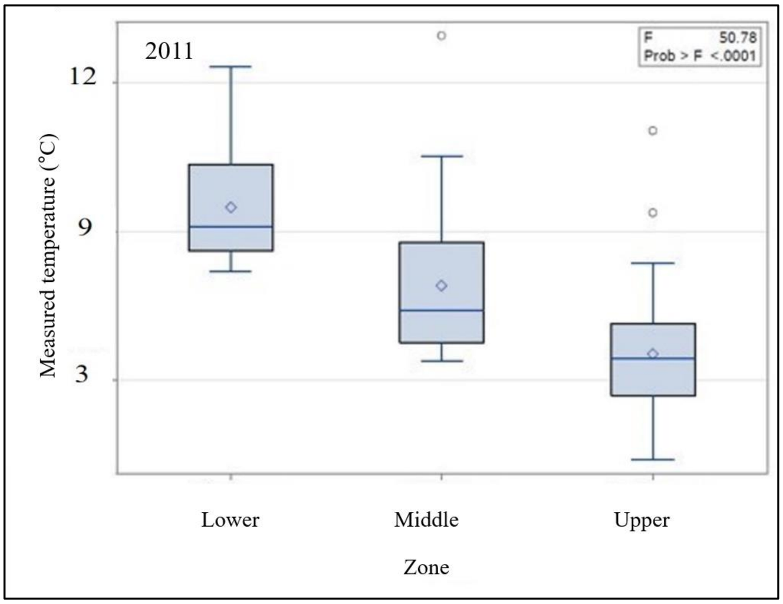

Figure 24: Boxplot: Displays the average temperatures (°C) throughout the storage campaign of lower, middle and upper zones of the sugar beet pile for the 2011 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

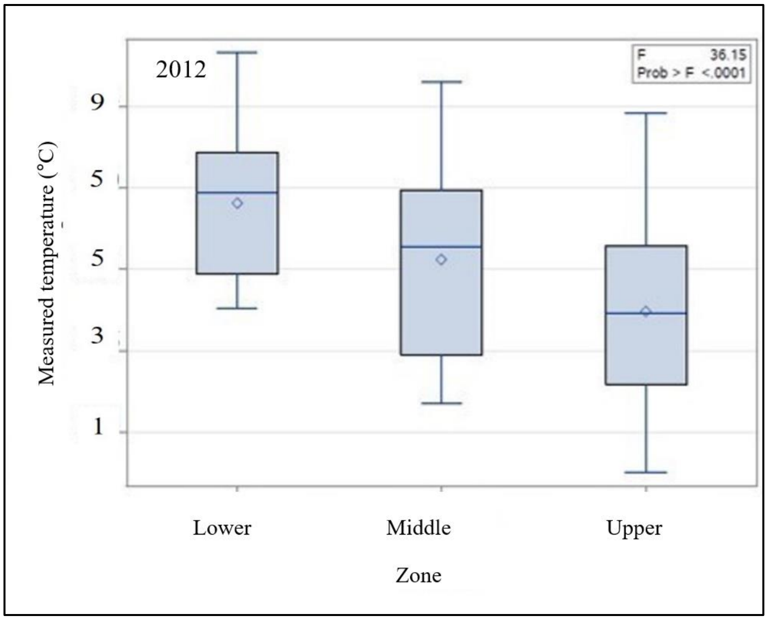

Figure 25: Boxplot: Displays the average temperatures (°C) throughout the storage campaign of lower, middle and upper zones of the sugar beet pile for the 2012 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 8: Temperatures of the lower, middle and upper zones of the sugar beet pile in 2011 and 2012 averaged across the storage campaign. Means are the average of 37 d in 2011 and 97 d in 2012.

	2011[a]	**2012[b]**
Zone	**Temperature (°C)**	**Temperature (°C)**
Lower	7.65 A	6.45 A
Middle	5.05 B	5.05 B
Upper	2.75 C	3.85 C

*Values followed by different letters within a column differ based on LSD test ($\alpha \leq 0.05$).
[a]LSD = 0.9678 for the 2011 season.
[b]LSD= 0.6171 for the 2012 season.

2. Daily Sugar Loss Comparison Between Pile Zones

The calculated daily sugar losses (kg/ton/day), based on measured temperatures from each of the three zones, were higher at the beginning of the storage season than the end of the season (Fig. 26 for 2011 and Fig. 27 for 2012). The upper zone was predicted to have the lowest sugar loss of the three zones and the lower zone had the highest (Fig. 28 for 2011 and Fig. 29 for 2012) and (Table 9).

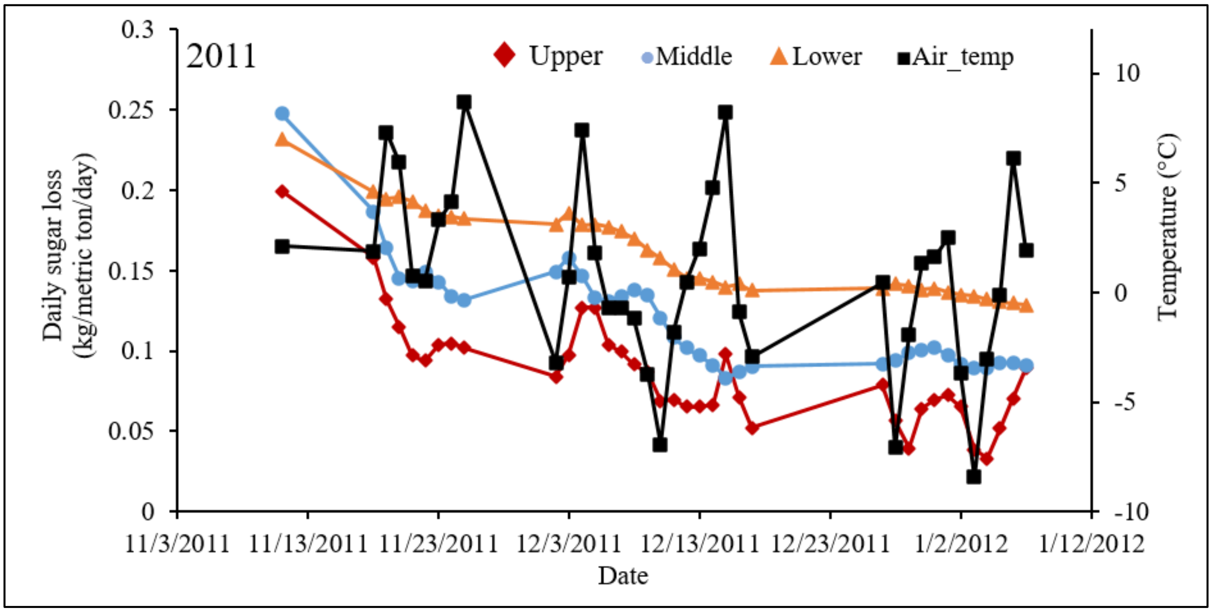

Figure 26: Graph: Shows the calculated daily rate of sugar loss (kg/metric ton/day) based on measurements of pile temperature (°C) for the lower (▲), middle (●) and upper (♦) zones of the pile for the 2011 season. The secondary vertical axis is the average daily air temperature (■).

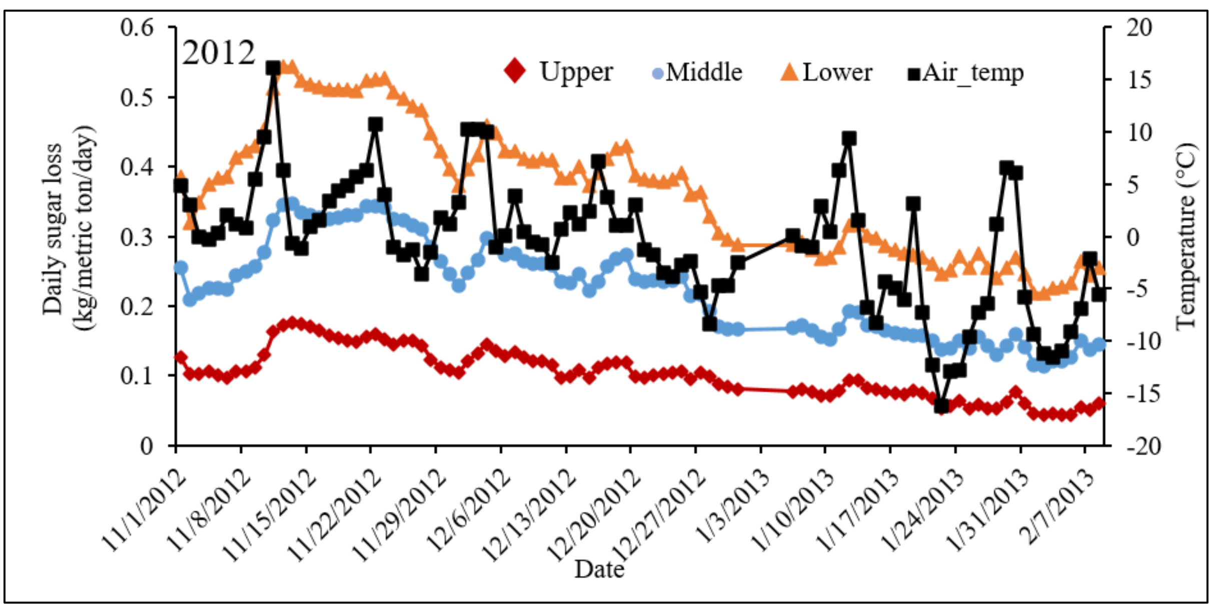

Figure 27: Graph: Shows the calculated daily rate of sugar loss (kg/metric ton/day) based on measurements of pile temperature (°C) for the lower (▲), middle (●) and upper (♦) zones of the pile for the 2012 season. The secondary vertical axis is the average daily air temperature (■).

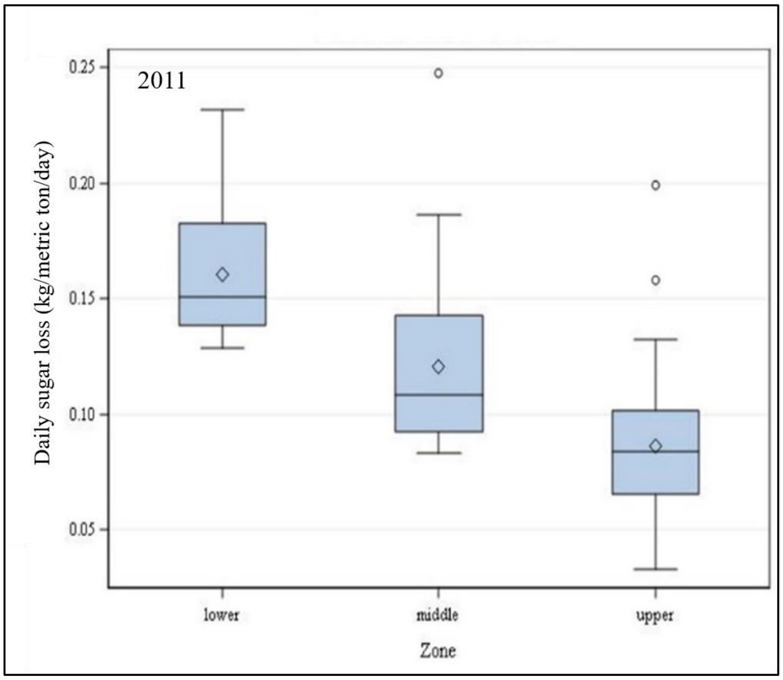

Figure 28: Boxplot: Displays the average calculated daily sugar loss (kg/metric ton/day) based on measured temperatures (°C) of lower, middle and upper zones of a sugar beet pile for the 2011 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

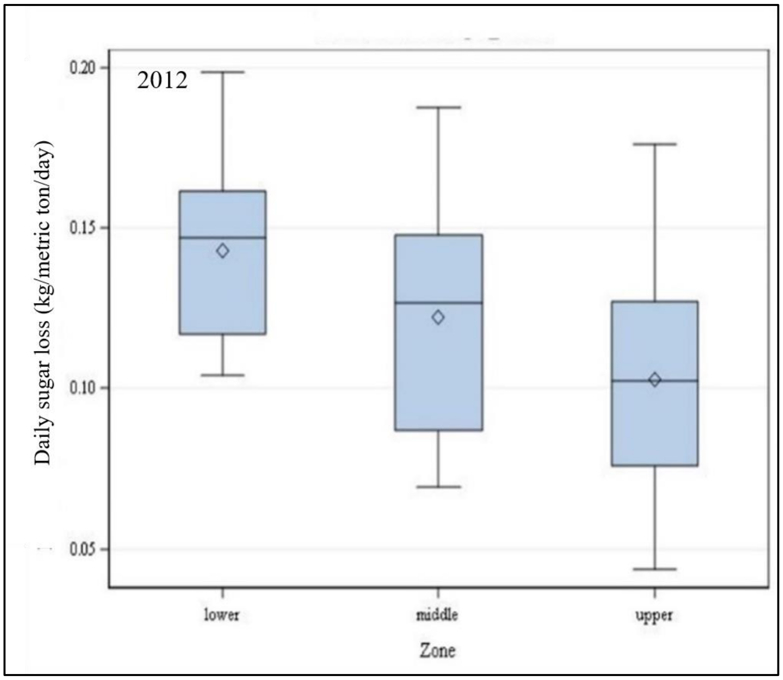

Figure 29: Boxplot: Displays the average calculated daily sugar loss (kg/metric ton/day) based on measured temperatures (°C) of lower, middle and upper zones of a sugar beet pile for the 2012 season. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 9: Estimated rate of sugar loss (kg/metric ton/day) for field-stored sugar beets in the upper, middle and lower zones of the beet pile based on measured temperature.

	2011[a]	**2012[b]**
Zone	**Rate of sugar loss (kg/metric ton/day)**	**Rate of sugar loss (kg/metric ton/day)**
Lower	0.161 A	0.143 A
Middle	0.121 B	0.122 B
Upper	0.087 C	0.103 C

*Values followed by different letters within a column differ based on LSD test ($\alpha \leq 0.05$).
[a]LSD = 0.0145 for the 2011season.
[b]LSD= 0.0093 for the 2012 season.

3. Cumulative Sugar Loss Comparison Between Pile Zones

The amount of sugar loss was estimated to be highest in the lower zone and lowest in the upper zone in both seasons (Table 10).

Table 10: Estimated cumulative sugar loss (kg/metric ton) in the 2011 season (37 days) and the 2012 season (95 days) calculated from the measured temperature of the lower, middle and upper zones of the beet pile.

Zone	**2011 (37 days)**	**2012 (95 days)**
Upper	3.21	9.78
Middle	4.48	11.60
Lower	5.94	13.59

MODEL ACCURACY IN DIFFERENT ZONES

1. Temperature Comparison Between Pile Zones

Based on the measured and modeled data, the temperature values obtained from the model were generally lower than the measured temperatures. However, in some days the modeled temperatures in the upper (Fig. 30 for 2011 and Fig. 31 for 2012) and middle zones (Fig. 32 for

2011 and Fig. 33 for 2012) overestimated the measured temperatures, possibly due to the rapid fluctuation in air temperatures. In the case of the lower zone, there was consistent temperature underestimation by the model (Fig. 34 for 2011 and Fig. 35 for 2012).

According to ANOVA analysis (Table 11), there was no significant ($P \leq 0.05$) difference between the measured and modeled temperatures in the upper and middle zones in the 2011 season. This illustrates that the model has accuracy for predicting the pile temperatures in these zones. This finding contrasts with the results for the lower zone. In the 2012 season, there was a significant difference between the measured and modeled temperatures in all studied zones ($P \leq 0.05$).

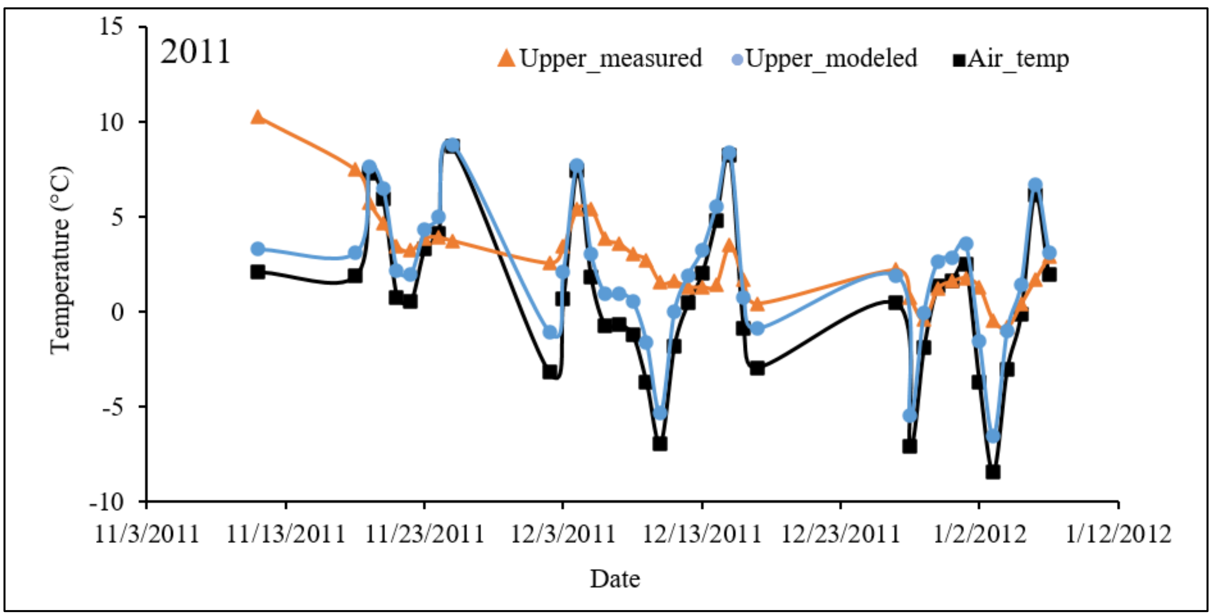

Figure 30: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the upper zone of the sugar beet pile for the 2011 season in relation to air temperature (■).

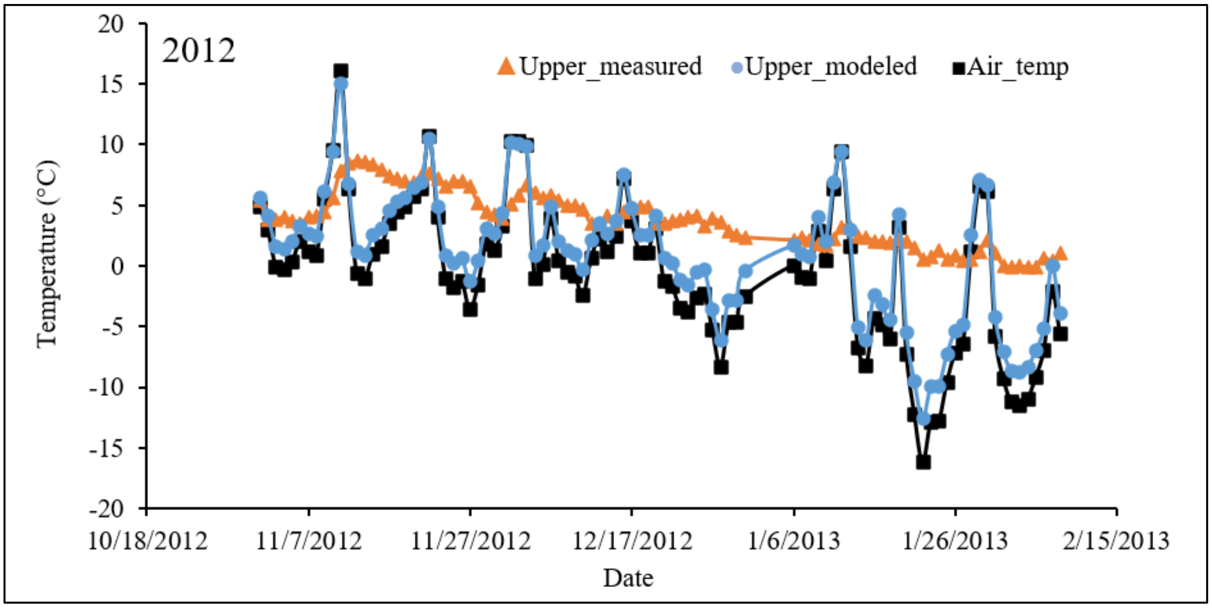

Figure 31: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the upper zone of the sugar beet pile for the 2012 season in relation to air temperature (■).

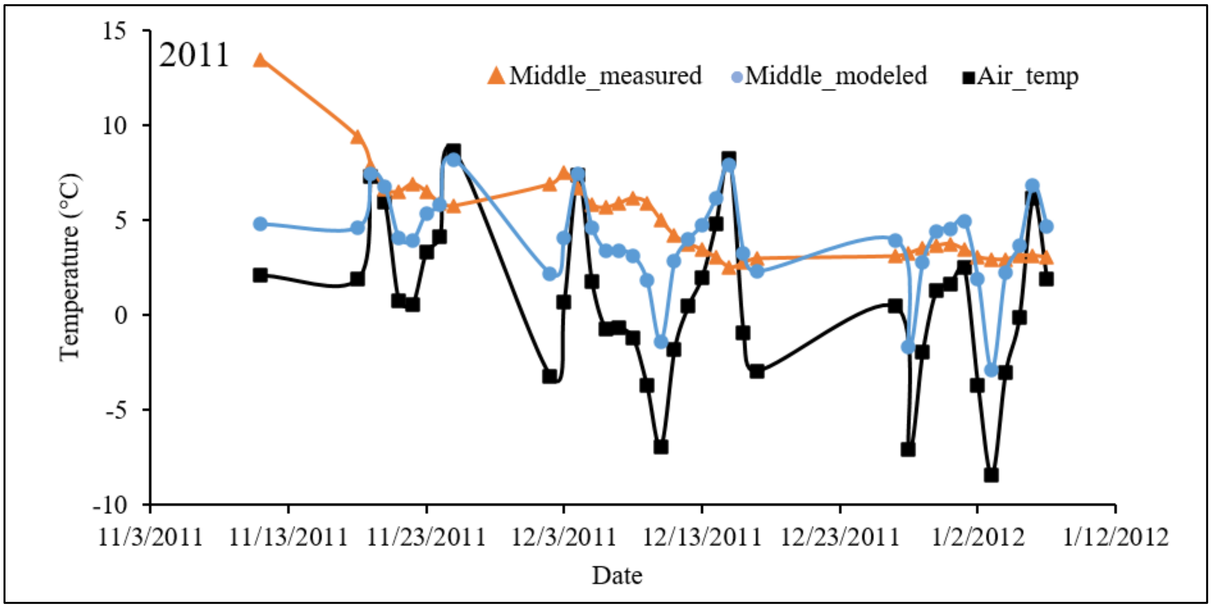

Figure 32: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the middle zone of the sugar beet pile for the 2011 season in relation to air temperature (■).

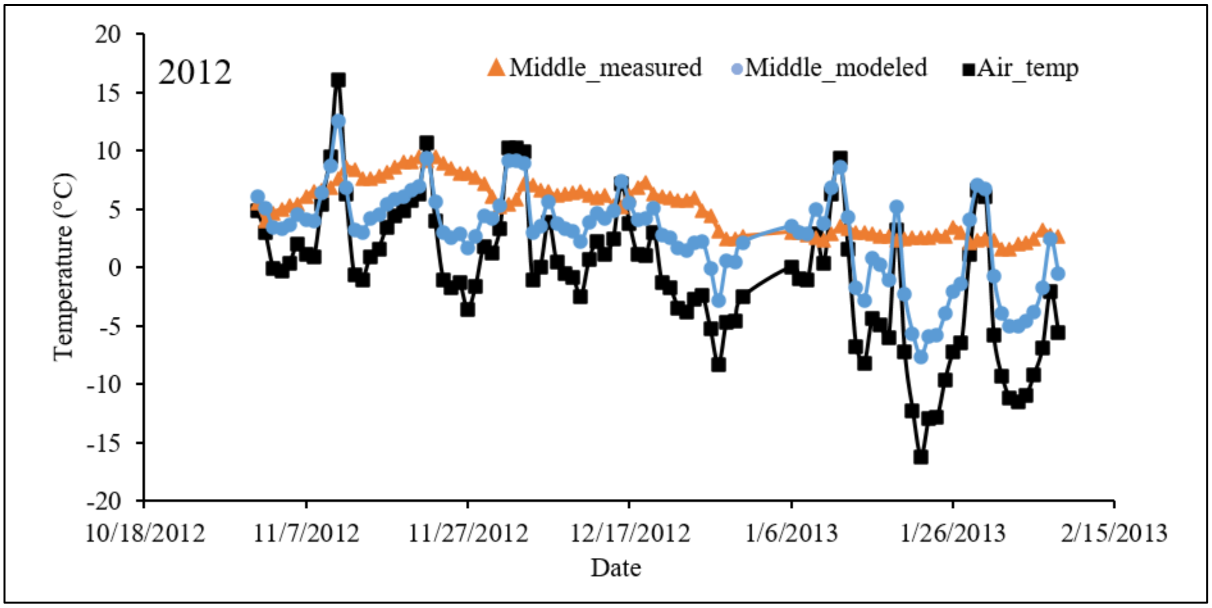

Figure 33: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the middle zone of the sugar beet pile for the 2012 season in relation to air temperature (■).

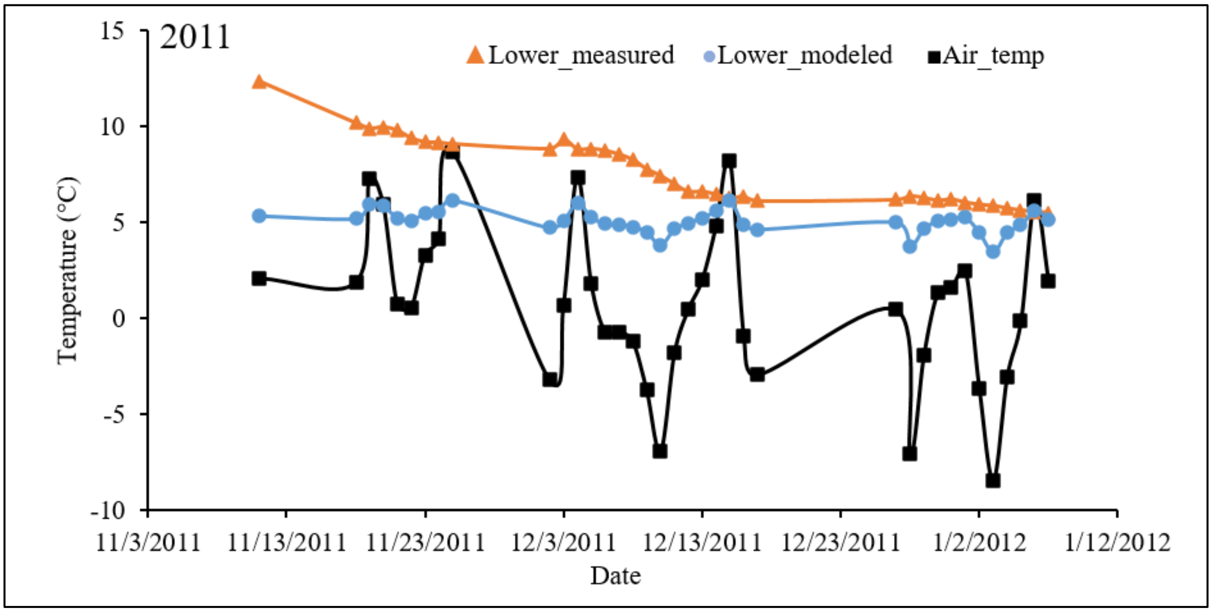

Figure 34: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the lower zone of the sugar beet pile for the 2011 season in relation to air temperature (■).

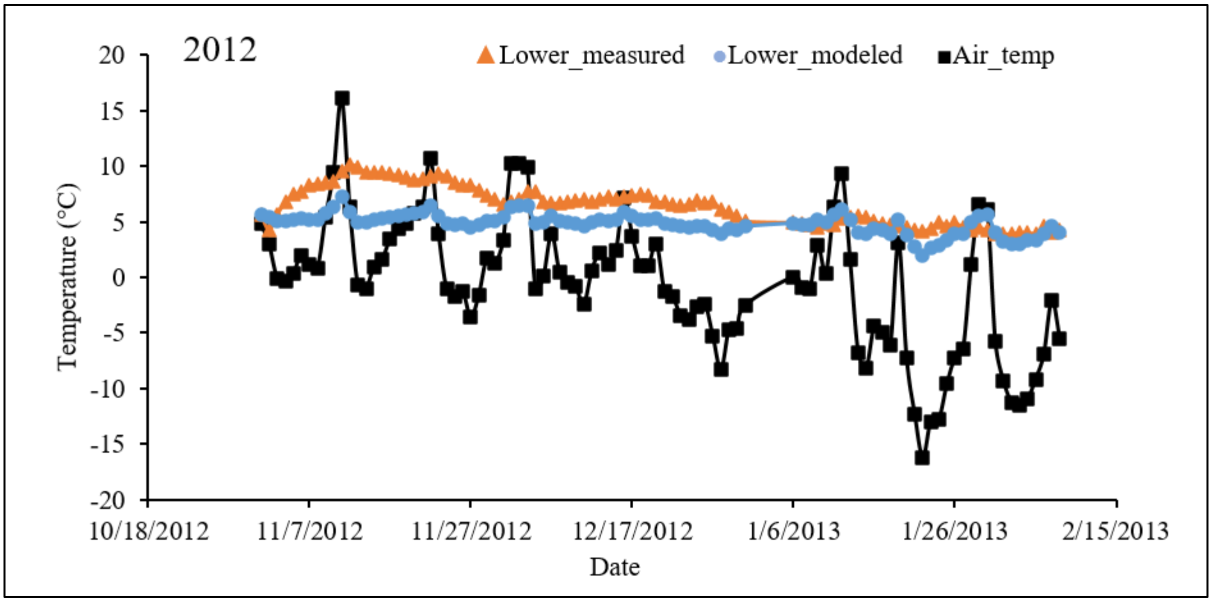

Figure 35: Graph: Shows the measured (▲) and modeled (●) temperatures (°C) of the lower zone of the sugar beet pile for the 2012 season in relation to air temperature (■).

Table 11: Significance level, resulting from ANOVA analysis, assessing whether predicted and measured pile temperatures differed in the upper, middle and lower zones over two storage seasons.

Pile zone	2011	2012
Upper	0.34	< 0.0001
Middle	0.06	< 0.0001
Lower	< 0.0001	< 0.0001

EVALUATION OF PILE GEOMETRIES AND VENTILATION ON SUGAR LOSS

1. Daily Sugar Loss Comparison Between Pile Geometries and Ventilation

Further analysis was conducted to study the effect of pile height (decreased, increased and commercial) and the effect of ventilation using the model developed above. Pile shape was predicted to affect temperature gradients and subsequently sugar loss. These models were developed one time under actual air temperature according to the air temperature records from 1 November 2012 to 8 February 2013, and the second time with 3°C increase in the air temperature relative to 2012 data every day to evaluate different designs in the case of warmer winters. The ventilated pile yielded significantly ($P \leq 0.05$) lower daily sugar loss (kg/metric ton/day) while the other designs did not vary significantly according to mean difference analysis under 2012 or increased air temperatures (Table 12 for 2012 air temperature and Table 13 for 3°C increase in the air temperature relative to 2012 data) and (Fig. 36 for 2012 air temperature and Fig. 37 for 3°C increase in the air temperature relative to 2012 data).

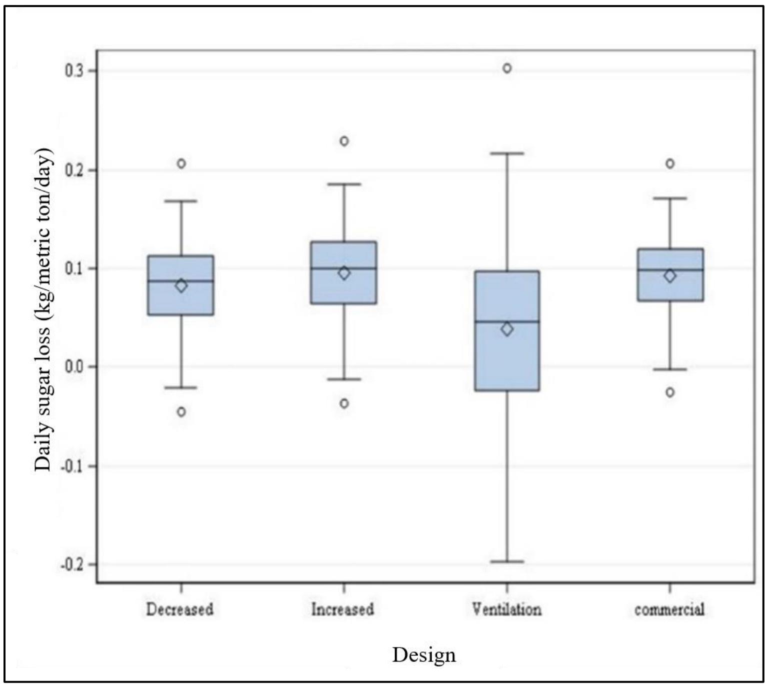

Figure 36: Boxplot: Displays the distribution of the values for daily sugar loss rate (kg/metric ton/day) of different designs of sugar beet storage piles based on 2012 air temperatures. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

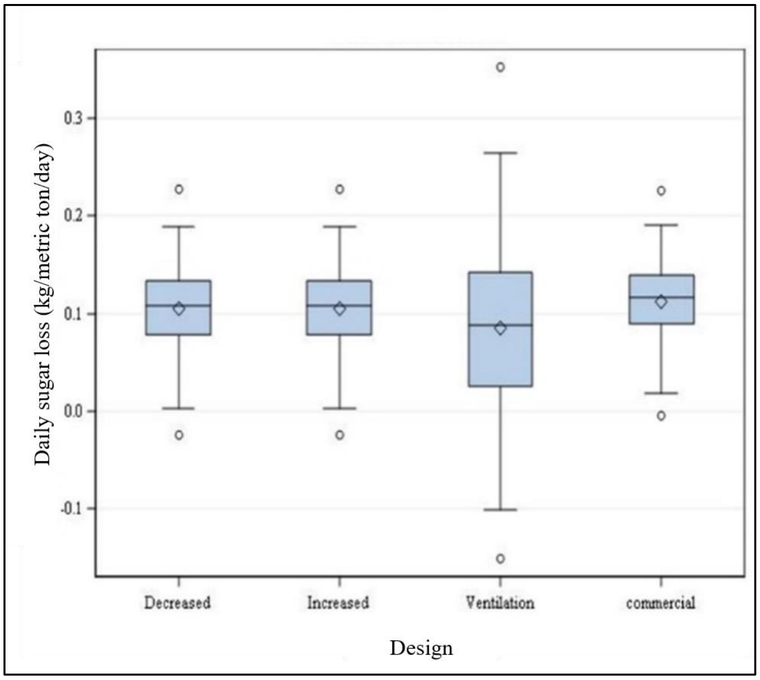

Figure 37: Boxplot: Displays the distribution of the values for daily sugar loss rate (kg/metric ton/day) of different designs of sugar beet storage piles based on predicted 3°C increase in air temperatures relative to 2012 data. Diamonds (◊) represent the mean values; circles (○) represent the outlier values.

Table 12: Modeled prediction of the daily rate of sugar loss (kg/metric ton/day) for beet piles having different heights or ventilation in a sugar beet pile based on the 2012 air temperature.

Treatment	**Pile height (m)**	**Rate of sugar loss (kg/metric ton/day)[a]**
Decreased height pile	2.4	0.083 A
Commercial pile	4.9	0.093 A
Increased height pile	7.3	0.096 A
Ventilated pile	4.9	0.04 B

*Values followed by different letters within a column differ based on the LSD test ($\alpha \leq 0.05$).
[a]LSD value = 0.0171

Table 13: Daily rate of sugar loss (kg/metric ton/day) for beet piles having different heights or ventilation in a sugar beet pile based on 3°C increase in air temperature relative to 2012 data.

Treatment	**Pile height (m)**	**Rate of sugar loss (kg/metric ton/day)[a]**
Decreased height pile	2.4	0.105 A

Table 13 (cont'd)

Commercial pile	4.9	0.113 A
Increased height pile	7.3	0.105 A
Ventilated pile	4.9	0.085 B

*Values followed by different letters within a column differ based on the LSD test ($\alpha \leq 0.05$).
[a]LSD value = 0.0167

2. Cumulative Sugar Loss Comparison Between Pile Geometries and Ventilation

Table 14 represents the predicted amount of Cumulative sugar loss (kg/metric ton) following 100 days of field storage in piles modeled with varying height or ventilated pile designs under the 2012 actual air temperatures and 3°C higher air temperatures relative to 2012 data. The amount of sugar loss was lower in the ventilated pile design than the other designs under both the 2012 and the increased pile temperatures according to the model.

Table 14: Predicted total sugar loss (kg/metric ton) after 100 days of field storage based on the temperatures obtained from models varying pile height, ventilation and average temperature (+3 °C) for beet piles under the 2012 season.

Pile modification	**Pile height (m)**	**Cumulative sugar loss over 100 days (kg/metric ton)**
Decreased height pile	2.4	8.37
Commercial pile	4.9	9.62
Increased height pile	7.3	9.33
Ventilated pile	4.9	6.03
Decreased height pile with 3°C increase in air temperature relative to 2012 data	2.4	10.49
Commercial pile with 3°C increase in air temperature relative to 2012 data.	4.9	11.29

Table 14 (cont'd)

Increased height pile with 3°C increase in air temperature relative to 2012 data.	7.3	12.09
Ventilated pile with 3°C increase in air temperature relative to 2012 data.	4.9	9.49

DISCUSSION

The model developed in the current study generally underestimated the measured temperature as well as sugar loss in sugar beet pile during storage. The lack of fit between the measured temperatures and modeled temperatures was possibly due to the steady-state heat transfer condition of the model that was assumed for simplicity for model development instead of accurately reflecting dynamic conditions. The steady-state condition refers to the situation when the change of the internal energy does not vary with time (Datta, 2002), which we decided to be a day. A steady-state condition may occur in a controlled system where the inputs (i.e., air temperature and wind speed) do not change during the time. This was not the case in the studied beet pile as the environmental conditions changed frequently. On the other hand, developing a dynamic model for outdoor sugar beet pile storage would be highly challenging, because in the most available transient models of storage systems, they have controlled environment with limited variables, whereas in the case of this study we have the air temperature, wind speed, relative humidity, precipitation, solar radiation, root temperature, respiration, desiccation, soil temperature, soil moisture content, water evaporation, and condensation as variables that give the model so much complexity. So that we found that considering the most important factors in a simple model as a primary step, then modify that simple model in future studies working toward some complexity.

Also employing a day to be the time for a steady-state was a relatively long time as we found that the pile temperature was responsive to the air temperature that changes as much as 15 °C in one day. Also, neglecting the effect of moisture transfer and the change in the water content inside the pile may have contributed to an inaccurate estimate of the thermal conductivity of the pile material (beet, water and air). Results obtained by Xu and Burfoot (1999) confirm the importance of accurately measuring or calculating the moisture content to develop heat transfer models for biological materials. Although their model had a good fit in most parts of the pile, a lack of fit occurred when the moisture content was incorrectly calculated. Hoang et al. (2003), also attributed the underestimation of their model to desiccation on the surface of chicory roots during storage, because the water heat transfer coefficient is 50 to 100 times higher than the air heat transfer coefficient (Datta, 2002). Something similar could be a possible reason in the current study, especially for the error found at the surface of the pile. Although lack of fit due to moisture content miscalculations was expected, we adapted the idea of a simple, more easily applied and less intensive model. For instance, moisture sensors to cover every part in a huge body like the beet pile is very costly and time-consuming. Also, understanding the limitations of the current model can help future researchers decide the important aspects to monitor or model to develop a better model.

Non-uniform root size of the beet pile during storage, leading to varied sizes of voids between roots, can also lead to inexact estimates of in thermal conductivity, water content and air movement calculations (Hoang et al., 2003). In addition to the above, using the average of the daily temperatures resulted in losing some model sensitivity to the change of temperature during the day. As mentioned before, we used the daily average air temperature and wind speed as inputs when we developed the model. At any time, these inputs change significantly during the day, using the average of such inputs may have reduced the model's sensitivity to changes in the environmental condition. This likely affected accuracy, as the pile temperature was sensitive to the changes in ambient conditions.

Lack of fit between measured and predicted temperatures often is found in models of biological materials. For example, Zou et al. (2006b) explained the inaccuracy in their model by errors in the position of thermocouples, model input values and/or model assumptions. Similarly, Hoang et al. (2003) found underestimation of chicory temperature due to water loss and condensation on the surface of the roots from evaporation due to low relative humidity in the storage room as well as non-uniform porous, variation in the product sizes and the relatively small voids compared to the size of the roots. On the other hand, Markarian et al. (2006) developed a mathematical model with high accuracy, due to the controlled storage system, the model included mass and heat transfer in three dimensions and for a limited storage time (1 hour). Their success is likely a function of their control of conditions and highlights the difficulties in a complex, uncontrolled system that contribute to lack of fit as in the case of our model.

The cumulative sugar loss depending on measured and modeled temperatures were highly correlated. This means that the Cumulative sugar loss based on the modeled temperatures can be helpful to roughly predict the cumulative sugar loss based on the measured temperatures. This can be a helpful technique for storage managers to evaluate new pile designs.

According to the pile zone comparison, differences of measured temperatures between the three pile zones described the existence of temperature variations inside the pile and show that the upper zone was always colder than the middle and lower zones and the lower zone is always warmer than the middle and the upper zone. The results for sugar loss are in good agreement with the results for temperature. The results are expected because the upper zone is exposed to the relatively cold air and removes the heat of the upper zone by convection. On the other hand, the lowest zone gained heat from the ground by conduction, thereby increasing the temperature in that zone.

Estimated daily sugar losses were higher early in the storage campaign. These results were similar to the findings of Fox (1973) and Wyse (1975) that 50% of sugar loss in sugar beets occur during the first two weeks of storage, and the majority of the sugar loss occurs during the first 40 days of storage.

Cumulative sugar loss calculations in different zones highlight an elevated sugar loss in the lower zone compared with the middle and the upper zones. This indicates the importance of reducing the temperature of this zone (Yang and Rao, 2006).

In the case of the effect of pile zones on modeled temperature accuracy, the modeled and measured temperatures showed good agreement in the upper and middle zones during the 2011 season for these zones. This may be a function of the model making better predictions at higher temperatures, this means that the model is accurate for predicting the pile temperatures in these zones. However, the model underestimated the temperature of the lower zone for both storage seasons.

It should be noted that the lower zone is mainly affected by the ground temperature and in the model, as we used the semiannual average temperature of the ground obtained from Reese, MI (Schaetzl et al., 2005) which resulted in losing part of the model sensitivity to the changes of temperature in that zone. Moreover, in the pile base, the beet weight is relatively high and that possibly caused damage to the roots and consequently increased respiration rate and thereby increase temperature (Cole, 1977). The compressed damaged roots may have also caused blocking of the voids which happened to potatoes (Pringle et al., 2009), which may have changed the thermal conductivity of the pile material. Furthermore, beet roots in a field pile are often mixed with topsoil and stones. (Flegenheimer, 2015) noted there were an estimated 136,000 metric tons of topsoil and other debris are added to beet storage piles each year. The non-beet materials are mainly accumulated at the base of the pile, filling the voids and altering the physical and thermal properties of the pile material.

In the middle zone, differences between modeled and measured temperatures are possibly from condensation in that zone. An increase in moisture content can subsequently affect porosity, thermal conductivity and air movement. The middle zone is also likely to be warmer than anticipated because of the heat gained from the lower zone. The warmer air stream that moves from the lower zone to the middle zone holds moisture and can cause a condensation layer as happened in a potato storage study by (Pringle et al., 2009). Consequently, an increase of the moisture in the middle zone could lead to partially blocking the voids with water that change the thermal conductivity of that zone and cause a decline in respiration (Lafta and Fugate, 2009). That could be an explanation of the model agreement with measured temperature in 2011 with the increase in air temperature and possibly increase in evaporation from the lower zone that causes the formation of a condensation zone and reduces the respiration rate of the beets in that zone.

The upper pile zone is the most susceptible part of any changes in environmental conditions, as it has the largest surface interacts with ambient conditions (e.g., sunlight, wind, rain, snow, temperature, humidity). Fluctuations in air temperatures lead to an increase in respiration rate and sucrose loss even if occur of storage temperatures of -1 °C or below (Wyse, 1978), which was the case in the commercial pile especially in the upper zone. Therefore, evaluating the respiration rate under a constant storage temperature and using that value in the model as a source of heat possibly led to underestimation in temperature in this zone. Fluctuation can significantly increase sucrose loss due to the accumulation of reducing sugars after respiration. Additionally, the possibility of root dehydration in this zone is much higher than the other zones (Campbell and Klotz, 2006; List, 2015). Dehydration damages the cells and can result in loss of permeability control and electrolyte leakage, which significantly increase respiration (Lafta and Fugate, 2009; Yang and Rao, 2006). Dehydration also occurs due to cell freezing, cells start to freeze (or damage) at -2 °C and they are completely frozen at -5 °C (Campbell and Klotz, 2006; Wyse, 1978). Freezing followed by thawing causes the cells to lose metabolic control and permeability, which causes increased cell respiration, desiccation and root deterioration (Lafta and Fugate, 2009; Wyse, 1978). Lafta and Fugate (2009); Wyse (1978) noted a temperature fluctuation and dehydration within 60 cm from the pile surface, which likely increases respiration, as dehydration causes more than 82% increase in the respiration rate compared with the initial respiration rate

In the 2011 season, the air temperature was relatively higher than in the 2012 season and that contributed to less freezing damage. The temperatures in that year were closer to those used to calculate the respiration rate in the laboratory experiment, and may account for the increase in the model accuracy (i.e., lack of significant difference between model and measured temperatures) in the upper zone found that season.

The model predicted that pile height and ventilation at the base of the pile could make a significant contribution to sugar loss. Through ventilation, the increase in the surface exposed to cold air convection lead to a significant decrease in the rate of daily sugar loss compared to other pile designs. The ventilated pile yielded lower daily and Cumulative sugar loss comparing with the commercial, increased height and decreased height designs applying the 2012 air temperature and 3°C increase in 2012 air temperature. The result is consistent with the results of the zone comparison, which emphasized the significant increase in sugar loss found in the lower zone, where heat is gained directly from the ground. Reducing the heat in the base of the pile, the sugar loss significantly decreased from 9.3 kg/metric ton in the commercial pile to 3.95 kg/metric ton in the ventilated pile, which is 68% decrease in sugar loss compared with the commercial pile. Thus, after 100 days in the storage, a higher rate of sugar loss was found for the commercial pile (11.29 kg per metric ton per 100 days) compared to the ventilated pile (8.55 kg per metric ton per 100 days); a 3°C increase in air temperature would yield a 24% increase in sugar loss. On the other hand, the change in the pile height (either increase or decrease) does not affect the sugar loss significantly in comparison with the commercial beet pile based on the air temperature of 2012 or 3°C increase in 2012 air temperature. The results are similar to those for a study by Michigan Sugar Company (List, 2015) in which they found that they needed to reduce the pile width by 83.9% and the pile height by 38.7% to reach 1% of the sugar loss from harvesting to December. In addition to these findings, we recommend insertion of natural ventilation at the base of the pile during the storage period.

SUMMARY AND CONCLUSIONS

The enormous production of sugar beet prevents the immediate processing of harvested roots and is responsible for the need for vast storage facilities until processing. In Michigan, beets are stored in huge piles exposed to the fluctuations in the surrounding environmental condition. Approximately half of the storage piles are unventilated, thus, natural convection is the only cooling technique for the top and sides of each of such piles. Fluctuating air temperatures enhance respiration rate and microbial activity in the exposed piles, which results in a reduction in root quality and increased sugar loss. In the current study, mathematical simulation methodology was applied to solve for pile temperatures. Such simulation is intended to help storage managers not only for predicting temperatures but also to improve management decisions regarding pile structure (dimensions and shape), handling stored beet and installation of appropriate ventilation systems.

A two-dimensional mathematical model was developed as a function of environmental parameters (air temperature, air velocity, RH and an average ground temperature) to simulate the heat transfer process during the storage period and to predict the temperature profile of an unventilated sugar beet pile. The model was developed based on the finite element approach. Model validation was obtained by comparing the modeled temperatures with measured temperatures collected from a commercial beet pile using embedded thermocouples for two seasons, 2011 and 2012, for 37 and 95 days, respectively.

The model that was developed generally underpredicted pile temperatures. This underprediction is attributed to several factors including the assumption by the model of steady-state conditions, meaning that pile temperature is assumed to be in equilibrium with its environment, which is likely rarely true. Additionally, the model excluding moisture mass transfer taking place in the pile, which can affect the heat loss and thermal conductivity and subsequently alter heat transfer calculations.

The model accuracy was evaluated by comparing the modeled and measured temperatures for three spatial zones in the pile upper, middle and lower zones. The modeled and measured temperatures showed fair agreement in the upper and middle zones. However, the model underestimated the temperature of the lower zone during the two storage seasons.

The measured and modeled temperatures were used to calculate the Cumulative sugar loss (kg/metric ton). A strong relationship was obtained between modeled and calculated values with a correlation coefficient of higher than 99%. As expected, based on differences in model and actual temperatures, the Cumulative sugar loss calculated based on model temperature was lower than the Cumulative sugar loss calculated based on the measured temperature. The effect of pile height or use of ventilation compared to commercial piles was also tested by assessing two different pile geometries, a 50% reduction of the height of the commercial pile or a 50% increase of the height of the commercial pile, in addition to taking into account the ventilation at the base of the commercial pile. The three models were evaluated relative to a commercial pile design under normal and increased air temperature to examine the effects of the designs in the case of warmer winters. The results showed that the ventilated pile yielded significantly lower sugar loss compared with the commercial pile under actual (2012) and increased temperature scenarios. The increased and decreased height-piles did not vary significantly from the commercial pile for sugar loss.

In future work, we recommend developing a model for a transient heat transfer condition, including moisture mass transfer states and using hourly data instead of daily average values as the air temperature for instant can change 15°C in one day during the storage period. The change also occurs continuously in air velocity, RH and precipitation. A dynamic model (unsteady-state conditions) will take into consideration the fluctuation in the environmental conditions which will increase the model accuracy as a consequence. There is a need to include beet respiration rate values for a wider range of temperatures and use various root sizes as it significantly affects respiration (Wyse, 1978). Further, non-uniform root size can lead to varied sizes of voids between roots which causes an inexact result in thermal conductivity, water content and air movement calculations (Hoang et al., 2003). We can improve our model if we provide more precise parameters for the designed model such as ground temperature measurements, porosity and airflow inside the pile.

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LITERATURE CITED

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