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Article

Number of Sensors Needed to Achieve Reliable Aeration Cooling During the Fall Harvest and Monitoring of Grain Quality During the Non-Aerated Storage Period Based on Predicted Temperatures in a Grain Mass Using Cable-Based Sensors Versus Wireless Sensors as a Function of Sensor Distribution in Three Silo Sizes

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Abstract: Monitoring the quality of stored bulk grain is generally done using temperature cables hung from silo roofs. Little investigation has been done into the effects of number of sensors and their placement in terms of reliability of the monitoring system with regard to making stored grain quality management decisions. A previously developed 3D finite element simulation model was verified and used to investigate these aspects. In the first study, a silo was loaded with about 228.6 Mg (9000 bushels) of maize and six temperature cables were placed in the grain mass. The maize was aerated continuously for a period of two weeks, and the cable sensor temperatures were compared to the predicted temperatures which were in close agreement with the observed readings. The standard error of prediction ranged from 2.0 to 3.7°C. In the second study, 15 and 30 sensors were placed at manufacturer recommended depths and horizontal locations in the grain mass of three silo sizes (i.e., 11x11, 14.6x14.6 and 14.6x18.3 m diameter by eave height). The average grain temperatures predicted by the 15 and 30 sensors over a one-year simulation period were compared to the average grain temperatures predicted for the entire grain mass (1968, 3052, and 3204 mesh nodes). The number of sensors needed to monitor stored grain temperatures reliably in the three silo sizes investigated heavily depended on whether the aeration control strategy achieved a sufficiently low temperature by the time the aeration fans were turned off and sealed ahead of the non-aerated storage period. Fifteen or 30 sensors were sufficient to monitor grain temperatures during the aeration cooling period but for the two larger silo sizes more than 30 sensors would be needed during the storage period. As silo size increased, and surface-to-volume ratio decreased, grain temperatures remained lower during the storage period. Results support the best management practice recommendation of leaving cooled grain cold and not warming it up in the spring ahead of storage into the summer.

Keywords: sensors; aeration; cool-down; storage; silo

1. Introduction

The efficient and reliable management of grain storage is crucial for maintaining grain quality and minimizing post-harvest losses. Aeration cooling and temperature monitoring play vital roles in preserving grain quality during the fall harvest and non-aerated storage periods. Accurate temperature predictions within a grain mass are essential for determining the optimal number and distribution of sensors needed to achieve reliable aeration cooling and effective monitoring.

In recent years, advancements in sensor technology have provided grain storage operators with two primary options for temperature monitoring: cable-based sensors and wireless sensors [1]. Cable-based sensors utilize physical cables that traverse through the grain mass with sensors located at some predetermined location, while wireless sensors (cableless) offer options for sensors to be randomly distributed within the stored grain mass [2–4]. Understanding the comparative effectiveness of these sensor types and their relationship with the number and distribution of sensors in different silo sizes is a critical aspect of optimizing grain storage operations.

A novel three-dimensional finite element model coded in Fortran was developed and validated by Dr. Maier and one of his former Ph.D. students as part of his dissertation research [5]. The 3D finite element (FE) model was expanded by another Ph.D. student [6] and has been successfully used to investigate various scenarios of stored grain ecosystem management [7,8]. The 3D MLP-FE model has the capability to predict temperature and moisture content at specific locations within a stored grain mass, for example representing number of sensors and their distribution, during aerated and non-aerated periods as a function of grain conditions, silo sizes, and historic weather data.

The objectives of this study were to (1) verify the accuracy of the 3D MLP-FE ecosystem model in terms of temperature prediction in a stored grain mass during aerated periods and (2) apply the 3D MLP-FE ecosystem model to investigate the number of sensors required to achieve reliable aeration cooling during the fall harvest and accurate monitoring of grain quality during the non-aerated storage period. Additionally, it examines the predicted temperatures within a grain mass using both cable-based and wireless sensors. The focus is on assessing the influence of sensor distribution in three different silo sizes, allowing for a comprehensive analysis of sensor performance across varying storage capacities.

The findings of this research will contribute to the advancement of grain storage management practices by providing valuable insights into the optimal use of sensors for aeration cooling and temperature monitoring. By evaluating the effectiveness of cable-based and wireless sensors and their relationship with sensor distribution, storage operators can make informed decisions to ensure the preservation of grain quality and minimize losses.

2. Materials and Methods

Verification of the accuracy of the 3d MLP-FE ecosystem model in terms of temperature prediction in a stored grain mass during aerated periods

Data collection for verification of the 3D MLP-FE ecosystem model was carried out in a silo filled with about 228.6 Mg (9000 bushels) of maize at the ISU Agricultural Engineering and Agronomy Research Farm on November 1, 2018, for long-term storage into the summer of 2019. Six cables equipped with temperature and RH sensors were installed, probed, and left in the grain mass after in-bin stir-drying had been completed. The custom-made cables had digital thermistor and RH sensors installed every 1.2 m (4 ft) that measure temperature and RH of the interstitial air inside the grain mass. The monitoring system collected data hourly, sent data to a gateway, and from there via cellphone modem to a cloud-based server. A total of 18 cable sensors were located in the grain mass at three grain depths (1.3, 2.5, and 3.7 m) with 6 sensors per layer, respectively. The vertical and horizontal locations of the sensors were determined and recorded. The drying fan was turned on April 10, 2019, and operated continuously until April 25, 2019. The airflow rate through the grain mass was determined based on measuring a static pressure drop in the plenum of 30 cm (2.7 inches) of water and the known performance curve of the fan, i.e., 1.4 m3/min/Mg (1.4 cfm/bu). This resulted in a calculated air velocity of 0.215 m/s through the stored maize assuming 40% porosity in the grain mass.

The simulation model requires a total of seven input files. One of these is the mesh which depicts the grain mass inside the silo to be modeled (Figure 1). The silo specifications enclosing the grain mass of 4.87 m diameter and 4.30 m grain depth were used to create a mesh of elements for a level stored grain mass using the Abaqus software which resulted in 1062 nodes and 785 elements. Hourly weather data from April 10 to April 25, 2019 consisting of hourly solar radiation, temperature, RH, and wind speed was downloaded from the Iowa State University Mesonet system (https://mesonet.agron.iastate.edu), representing the aerated grain storage period in Ames, Iowa, USA. The 18 nodes out of 1062 nodes that matched the location of the 18 cable-based sensors were

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used to verify the observed versus predicted temperature results of the 3D MLP-FE model by statistical means (i.e., the temperature of the output of the 18 nodes versus the temperatures recorded by the 18 cable-based sensors) from April 10 to April 25, 2019.

The most common method of model verification is to quantify the error, or difference, between measured and predicted values by calculating the standard error of prediction [9,10]. In this study, the standard error of prediction was used to verify the previously developed 3D stored grain ecosystem model, i.e., the standard error of the estimate (SE) between each pair of predicted values (node outputs) and observed values (cable-based temperature values) was calculated and evaluated (Eq .1). The standard error of the estimate gives a measure of the accuracy of predictions (i.e., the mean standard deviation between the observed and predicted values).

$$SE=\sqrt{(\Sigma(y^{\wedge}{}'-y)2/n)} \quad (1)$$

where
RWL = recommended weight limit
SE = standard error of estimate
Σ = Sum
y = measured values
y' = predicted values
n = number of values

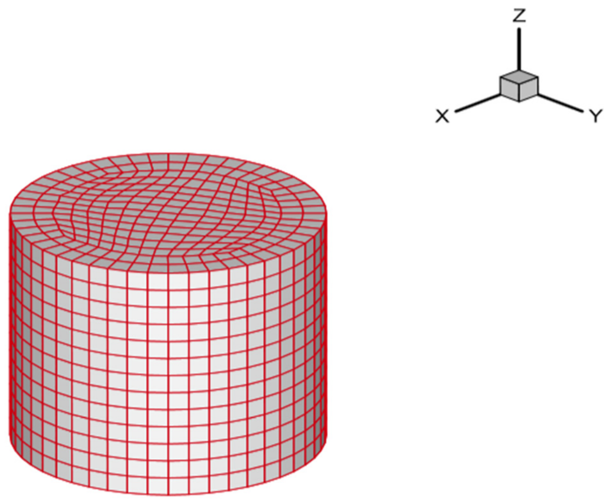

Figure 1. Discretized grain mass within the silo domain (mesh) used to verify the grain temperature predictions by the 3D MLP-FE simulation model.

Application of the 3d MLP-FE ecosystem model to determine the number of wireless sensors needed to achieve reliable aeration cooling and monitoring stored grain quality

To determine the number of sensors needed to achieve sufficient reliability for stored grain quality monitoring based on predicted temperatures, three different silo dimensions were evaluated. The silo sizes were 11 m in diameter by 11 m eave height (and level grain depth), 14.6 m in diameter and 14.6 m eave height (and level grain depth), and 14.6 m in diameter and 18.3 m eave height (and level grain depth). The three silo specifications were used to create three mesh sets of elements (1968, 3052 and 3204 nodes) for 3D simulation of a cylindrical stored grain mass using the Abaqus software. For each silo dimension, a set of 30 nodes was initially used to simulate the placement of cable-based or wireless temperature sensors to monitor the grain mass, and then the number of nodes/sensors was decreased by half (i.e., 15). The placement of the nodes/sensors within the grain mass were adapted based on the configurations of a commercial temperature and moisture cable supplier, i.e., OPI Blue Advanced Grain Storage Management (Calgary, Canada) for the silo sizes investigated.

For the first silo with a capacity of 745 Mg (29,315 bushels), the recommendation is to place three temperature cables evenly spaced radially and 2/3 of the distance between the center and the wall of the silo (7.3 m from the center) with sensors spaced 1.83 m vertically on each cable. For the simulated silo, the same pattern for three temperature cables was followed. However, the spacing between nodes on each cable was reduced to about 1 m in the case of 30 nodes and increased to about 2 m in the case of 15 nodes. The bottom node of each cable was 0 m above the perforated plenum floor, and the top node of each cable was 0.01 m below the grain surface for 30 nodes and 2.4 m for 15 nodes.

For the second silo with a capacity of 1765 Mg (69,487 bushels), the manufacturer recommendation is to place six temperature cables in the grain mass with five cables evenly spaced radially and 2/3 of the distance between the center and the wall of the silo (i.e., 9.7 m from the center) plus one cable in the center. For the simulated silo, the same pattern for six temperature cables was followed. However, the spacing between nodes on each cable was increased to about 2.3 m in the case of 30 nodes and about 4.5 m in the case of 15 nodes. The locations of the bottom and top nodes were respectively 0 m above the perforated floor and 0.1 m below the grain mass surface.

For the third silo with a capacity of 2206 Mg (86,589 bushels), the recommendation is the same as for the second silo given the same diameter. Given the greater depth, the spacing between nodes on each cable was increased to about 3.2 m in the case of 30 nodes and about 6.5 m in the case of 15 nodes. The locations of the bottom and top nodes were respectively 0 m above the perforated floor and 0 m below the grain mass surface.

To determine whether 15 or 30 nodes are sufficient to monitor grain temperatures during aerated versus non-aerated storage, the average grain temperatures were calculated based on 15 and 30 nodes during the two distinct periods and then compared to the respective average grain temperatures calculated based on the total number of mesh nodes of each silo size simulated for both periods. A difference of 5°C or less between the average temperatures (i.e., 15 versus 30 nodes, or 15 versus total nodes, or 30 versus total nodes) was considered sufficiently reliable to make grain quality management decisions based on monitoring stored grain temperatures during the critical fall harvest cool-down period, or the non-aerated storage period.

3. Results

Verification of the accuracy of the 3d MLP-FE ecosystem model in terms of temperature prediction in a stored grain mass during aerated periods

The results in Table 1 show that the model predicted grain temperatures with standard errors of 2.8-3.7°C for the six sensor pairs located in the grain mass 3.7 m above the perforated plenum floor. The standard errors were lowest for the sensor pair in the center (2.8°C), 3.1-3.3°C for the pairs at 2/3 radial distance from the center, and highest for the sensor pair located 0.3 m from the silo wall (3.7°C).

The model predicted grain temperatures with standard errors of 2.7-3.7°C for the six sensor pairs located in the grain mass 2.5 m above the floor. The standard errors were lowest for the sensor pair in the center (2.7°C), 2.8-3.1°C for the pairs at 2/3 radial distance, and highest for the sensor pair located 0.3 m from the silo wall.

The model predicted grain temperatures with standard errors of 2.0-3.3°C for the six sensor pairs located in the grain mass 1.3 m above the floor. Interestingly, the sensor pair located at a 2/3 distance from the center on the south side had the lowest standard error (2°C) instead of the center (3.0°C). The sensor pair located 0.3 m from the silo wall still had the highest standard error (3.3°C).

In general, the model predicted grain temperatures with an average standard error of 3.1°C. This result compares well with a previous much more extensive validation of the model that resulted in standard errors of prediction in the range of 1.0°C to 3.1°C for maize [11]. Thus, for the purpose of this study, the model was considered sufficiently accurate in terms of predicting stored grain temperatures.

It is not surprising that the accuracy of the temperature prediction is better at the center of the grain mass than in the periphery where the effects of varying ambient conditions and especially solar radiation are the greatest. A recent analysis by [12] indicates that grain temperatures in a 1 m thick periphery layer fluctuate according to a daily pattern during non-aerated periods and that pattern is established soon after aeration fans are turned off. This implies that the periphery layer essentially cannot be controlled by a stored grain manager.

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Similarly, the accuracy of the temperature prediction is better at a distance close to the perforated plenum floor especially during aerated periods as a result of exposure to the ambient air temperature being pushed into the plenum by an aeration fan. As the cooling front moves upward through the grain mass accuracy tends to decrease. Several parameters could affect the accuracy of model prediction including variations in thermal conductivity coefficients of different maize hybrids, and presence of broken maize and the fines portion of foreign material that accumulate in the bottom layer of a grain mass that was dried with stirring machines in the case of the silo used for this validation experiment. The presence of accumulated broken maize and the fines portion of foreign material decreases porosity in the bottom layer which could increase cooling time relative to upper layers with a higher porosity which was recently documented by [13].

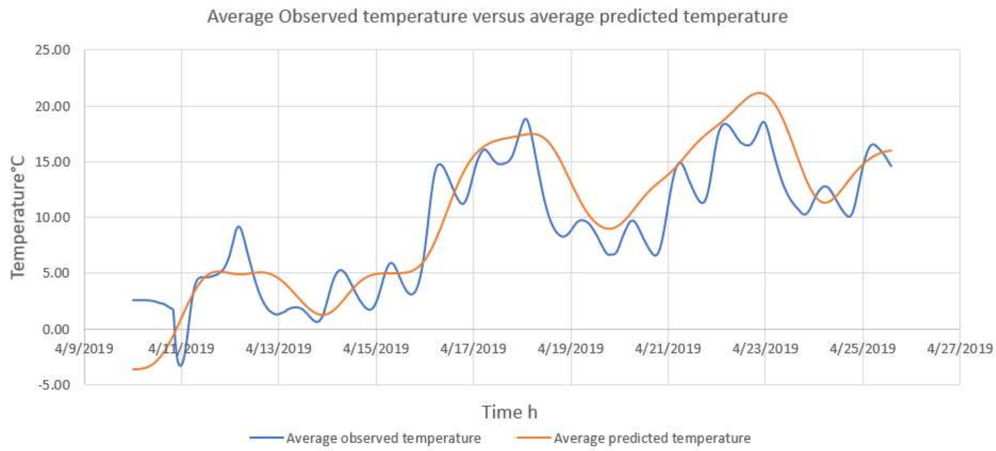

Figure 2. Average observed temperature versus average predicted temperature of the sensor pair located in the grain mass 3.7 m above the floor between April 10 to 25, 2019.

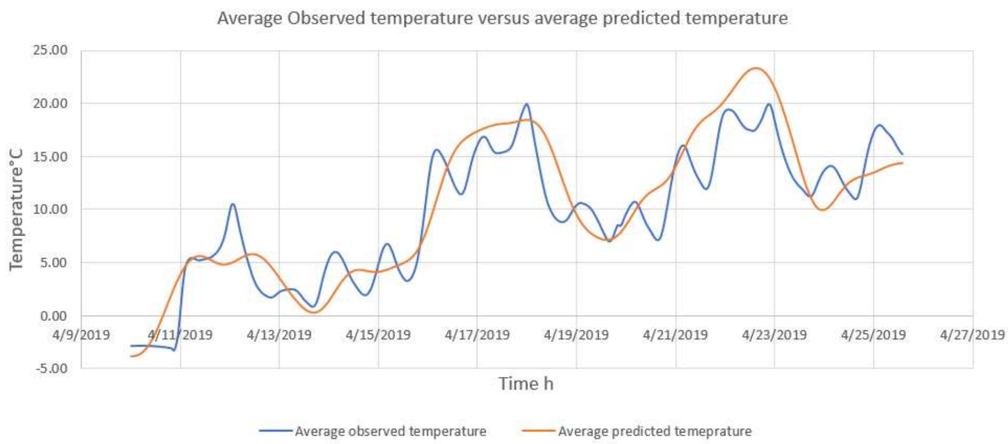

Figure 3. Average observed temperature versus average predicted temperature of the sensor pair located in the grain mass 2.5 m above the floor between April 10 to 25, 2019.

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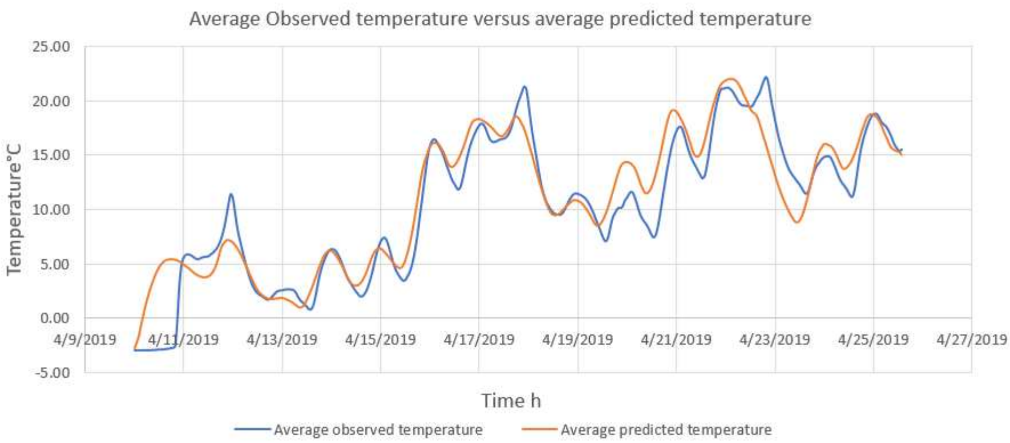

Figure 4. Average observed temperature versus average predicted temperature of the sensor pair located in the grain mass 1.3 m above the floor between April 10 to 25, 2019.

Table 1. Error analysis of observed versus predicted grain temperatures of the cable-based sensor and silo mesh node pairs located at different depths within the grain mass above the perforated plenum floor and different cardinal locations.

Cable Sensor vs Node ID	Standard Error of Estimate	Sensor Pair Located 3.7 m above the Floor and Respective Cardinal Point:
	data	data
M1S3 vs 1033	2.8	Center
M2S3 vs 814	3.1	North: 2/3 distance from center
M3S3 vs 795	3.3	East: 2/3 distance from center
M4S3 vs 815	3.2	South: 2/3 distance from center
M5S3 vs 797	3.1	West: 2/3 distance from center
M6S3 vs 956	3.7	South: 0.3 m distance from silo wall
		Sensor pair located 2.5 m above the floor and respective cardinal point:
M1S2 vs 679	2.7	Center
M2S2 vs 618	2.9	North: 2/3 distance from center
M3S2 vs 637	3.0	East: 2/3 distance from center
M4S2 vs 619	2.8	South: 2/3 distance from center
M5S2 vs 620	3.1	West: 2/3 distance from center
M6S2 vs 602	3.7	South: 0.3 m distance from silo wall
		Sensor pair located 1.3 m above the floor and respective cardinal point:
M1S1 vs 491	3.0	Center
M2S1 vs 283	3.1	North: 2/3 distance from center
M3S1 vs 346	3.2	East: 2/3 distance from center
M4S1 vs 338	2.0	South: 2/3 distance from center
M5S1 vs 344	2.9	West: 2/3 distance from center
M6S1 vs 425	3.3	South: 0.3 m distance from silo wall

Application of the 3d MLP-FE ecosystem model to determine the number of wire-less sensors needed to achieve reliable aeration cooling and monitoring stored grain quality.

3.1. Experiments: Four Different Simulation Sets

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3.1.1. Simulation Set 1: Continuous Aeration during the Fall Harvest period

In this set of simulations, the aeration strategy ran continuously from October 1 to December 31, 2013 (a total of 2,208 h vs the typically recommended three cycles of 150-200 h per cycle, or 450-600 h, i.e., 20-27% fan run time). The fan was turned off from January 1, 2014 to September 31, 2014 (274 d x 24 h/d = 6,576 h).

3.1.2. Simulation Set 2: Controlled Aeration until Top Grain Layer Temperature reached 0°C

In this set of simulations, the aeration strategy turned the fan on whenever the current ambient temperature was lower than the average temperature of all sensor nodes (except those on the center cable) and ran the fan until the average temperature dropped below the current ambient temperature and, as an additional constraint, the average temperature of the top layer nodes reached 0°C. The fan was then turned off and sealed for the rest of the simulation period. The 11x11 m silo size did not have any node in the center of the grain mass while the 14.6x14.6 and 14.6x18.3 m silo sizes had 3 nodes in the case of 15 nodes and 6 nodes in the case of 30 nodes in the center of the grain mass.

3.1.3. Simulation Set 3: Controlled Aeration until Top Grain Layer Temperature Reached -3°C

In this set of simulations, the aeration strategy turned the fan on whenever the current ambient temperature was lower than the average temperature of all sensor nodes (except those on the center cable) and ran the fan until the average temperature dropped below the current ambient temperature and, as an additional constraint, the average temperature of the top layer nodes reached -3°C. The fan was then turned off and sealed for the rest of the simulation period. The nodes that controlled the fan were located at a two-thirds distance from the center to the bin wall. The 11x11 m silo size did not have any node in the center of the grain mass while the 14.6x14.6 and 14.6x18.3 m silo sizes had 3 nodes in the case of 15 nodes and 6 nodes in the case of 30 nodes in the grain mass.

3.1.4. Simulation Set 4: Controlled Aeration Whenever Ambient Temperature Was Lower than Grain Temperature

In this set of simulations, the aeration strategy turned the fan on whenever the current ambient temperature was lower than the average temperature of all sensor nodes (except those on the center cable) and ran the fan until the average temperature dropped below the current ambient temperature. The nodes that controlled the fan were located at a two-thirds distance from the center to the silo wall. The 11x11 m silo size did not have any nodes in the center of the grain mass while the 14.6x14.6 and 14.6x18.3 m silo sizes each had 3 nodes in the case of 15 nodes and 6 nodes in the case of 30 nodes located in the center of the grain mass.

3.2. Results: Simulations Set 1: Continuous Aeration during the Fall Harvest Period

In this set of simulations, the aeration strategy ran continuously from October The results shown in Figures 5–7 represent the average grain temperature values observed by monitoring the grain at positions reflective of the 15 and 30 sensor locations along with one labeled total that represents the temperature values reflected by averaging all mesh nodes of the numerical solution for each of the three silo dimensions.

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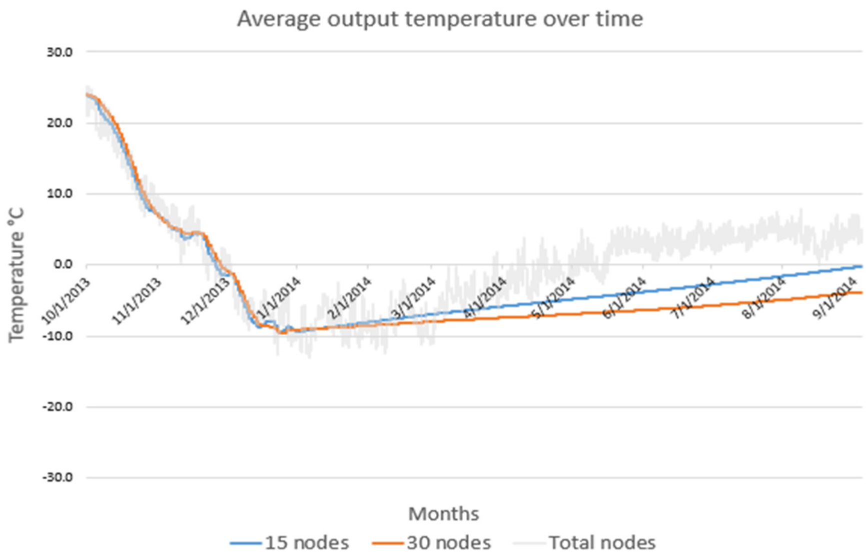

Figure 5. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013. The fan was on only from October 1 to December 31, 2013.

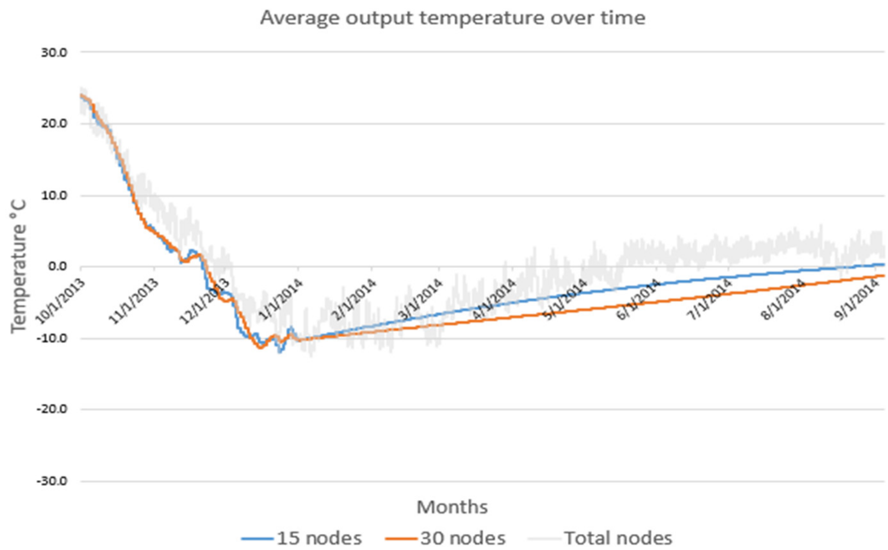

Figure 6. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning October 1, 2013. The fan was on only from October1 to December 31, 2013.

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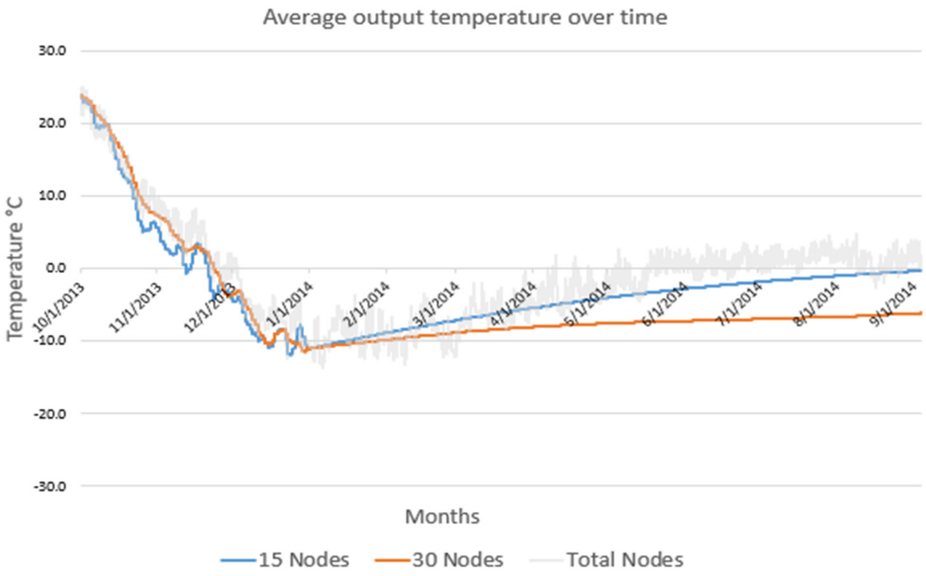

Figure 7. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013. The fan was on only from October1to December 31, 2013.

Cool Down Period (October 1 to December 31, 2013)

In the case of the 11x11 m silo, the average temperatures of the 15 and 30 nodes were 0.07°C and 0.55°C, respectively, higher than the average temperature of the total nodes from the numerical solution (Table 2). In the case of the 14.6x14.6 m silo, the average temperatures of the 15 and 30 nodes were 2.50°C and 2.28°C, respectively, lower than the average temperature of the total nodes from the numerical solution. And, for the 14.6x18.3 m silo, the average temperatures of the 15 and 30 nodes were 2.1°C and 0.8°C, respectively, lower than the average temperature of the total nodes from the numerical solution. The differences between the average temperatures of the 15 and 30 nodes were 0.48°C, 0.22°C, and 1.3°C for the three silo sizes, respectively. The standard deviations were similar across silo sizes and node numbers. These small differences in results imply that during the cool-down period, a minimum number of 15 sensors (perhaps even fewer) placed in different layers of the grain mass would suffice to monitor progress of the aeration cooling front assuming uniform airflow through a cored and leveled grain mass.

Table 2. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperature and standard deviations calculated for the numerical solution (total) for a three-month controlled aeration simulation of maize in a 11x11, 14.6x14.6 and 14.6x18.3 m silo beginning October 1, 2013. The fan was on during the entire period.

		15 Nodes	**30 Nodes**	**Total Nodes**
	Average (°C)	4.3	4.8	4.2
11x11 m silo	s.d. (°C)	10.2	10.4	9.8
	Average (°C)	2.2	2.4	4.7
14.6x14.6 m silo	s.d. (°C)	10.7	10.8	9.8
	Average (°C)	2.2	3.5	4.3
14.6x18.3 m silo	s.d. (°C)	10.4	10.8	9.8

Storage Period (January 1 to September 30, 2014)

In the case of the 11x11 m silo, the average temperatures of the 15 and 30 nodes were 3.89°C and 5.89°C lower, respectively, than the average temperature of the total nodes from the numerical solution (Table 3). In the case of the 14.6x14.6 m silo, the average temperatures of the 15 and 30 nodes were 2.2°C and 4.02°C lower, respectively, than the average temperature of the total nodes from the numerical solution. And, for the 14.6x18.3 m silo, the average temperatures of the 15 and 30 nodes were 1.7°C and 5.1°C lower, respectively, than the average temperature of the total nodes from the numerical solution. The differences between the average temperatures of the 15 and 30 nodes were 2.0°C, 1.8°C, and 3.4°C for the three silo sizes, respectively.

Across the three silo sizes, the average temperature of the total nodes was higher than the average temperatures of either the 15 or 30 nodes. Additionally, the standard deviations of the total nodes were two to three times greater. This is not surprising because the grain temperatures in the periphery layer are highest during spring and summer due to solar radiation which is captured by the nodes placed near the silo wall. In comparison, the 15 and 30 nodes are only located in the center and two-thirds distance from the center preventing them from capturing these externally caused temperature fluctuations. In the case of the average temperature of the total nodes from the numerical solution there are a number of nodes in the periphery layer weighting the average temperature as a function of the warmer periphery temperatures.

Interestingly, the average grain temperature of the total nodes from the numerical solution for the 11x11 m silo was only 1.0°C warmer than the one for the 14.6x14.6 m silo which was also only 1.0°C warmer than the one of the 14.6x18.3 m silo. In general, as silo size increased, and external silo surface to stored grain volume ratio decreased, the average grain temperature remained lower during the non-aerated period. The surface to volume ratio of the 11x11, 14.6x14.6, and 14.6x18.3 m silos are respectively 0.20 m-1, 0.05 m-1, 0.04 m-1. This implies that smaller silo sizes have a greater amount of surface area for heat transfer due to ambient temperature and solar radiation per volume of stored grain, and thus are less desirable for storing grain into the warmer summer months (Montross, 1999). Solar radiation and convective heat transfer from the wind are responsible for heat transfer into the silo. By increasing the surface area, the net heat flux into the silo is increased. However, a difference of 2°C between the smallest and largest silo evaluated in this study is not enough to conclude that a different number of cable-based or wireless sensors and their respective placement within the grain mass should differ among these silos.

Table 3. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperature and standard deviations calculated for the numerical solution (total) for a nine -month controlled aeration simulation of maize in a 11x11, 14.6x14.6 and 14.6x18.3 m silo beginning January 1, 2014. The fan was off during the entire period.

		15 Nodes	30 Nodes	Total Nodes
	Average (°C)	-4.7	-6.7	-0.8
11x11 m silo	s.d. (°C)	2.5	1.4	5.2
	Average (°C)	-4.0	-5.9	-1.8
14.6x14.6 m silo	s.d. (°C)	3.0	2.6	4.5
	Average (°C)	-4.5	-7.9	-2.8
14.6x18.3 m silo	s.d. (°C)	3.1	1.3	4.5

The results also show that during the aeration cool-down period, the average temperatures of the 15 and 30 nodes were closer to the average temperature of the numerical solution than in the case of the storage period. This implies that the grain temperatures in the grain mass were more uniform during the cool-down period than during the non-aerated storage period. Therefore, more than 30 sensors might be required during the storage period for the silo sizes investigated even though the differences between the average temperatures of the 15 and 30 nodes were only 2.00°C, 1.82°C, and 3.40°C for the 11x11, 14.6x14.6, and 14.6x18.3 m silos, respectively.

Analysis after removing the temperature values of the center cable for the 14.6x14.6 m and 14.6x18.3 m silos

Cool Down Period (October 1 to December 31, 2013)

Given the influence of the relatively low temperatures in the core of the grain mass on the average grain temperatures, the simulations results were reanalyzed by removing the three center cable sensors for the 15 node case and the six center cable sensors for the 30 node case of the two larger silos (Table 4). For the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.02°C higher and 0.38°C lower than the average temperature of the total nodes from the numerical solution compared to 2.50°C and 2.28°C lower for the average temperatures of the 15 and 30 nodes, respectively, before removing the temperature values of the center cable. In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.0°C and 0.4°C lower than the average temperature of the total nodes from the numerical solution compared to 2.1°C and 0.8°C lower for the average temperatures of the 15 and 30 nodes, respectively.

Table 4. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperature and standard deviations calculated for the numerical solution (total) for a three-month controlled aeration simulation of maize in a 14.6x14.6 and 14.6x18.3 m silo beginning October 1, 2013. The fan was on during the entire period.

		12 Nodes	**24 Nodes**	**Total nodes**
14.6x14.6 m silo	Average (°C)	4.3	4.7	-0.07
	s.d. (°C)	9.9	9.9	7.01
14.6x18.3 m silo	Average (°C)	3.9	4.3	-0.89
	s.d. (°C)	9.9	10.1	7.12

Storage Period (January 1 to September 30, 2014)

In terms of the storage period, for the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 2.16°C higher and 3.86°C lower than the average temperature of the total nodes from the numerical solution (Table 5). In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 2.2°C and 4.02°C lower than the average temperature of the total nodes from the numerical solution. For the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 1.6°C and 4.9°C lower than the average temperature of the total nodes from the numerical solution. In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 1.7°C and 5.1°C lower than the average temperature of the total nodes from the numerical solution.

In general, the results show that removing the center cable results in warmer average grain temperatures that were closer to the average temperature of the total nodes from the numerical solution. This was primarily caused by the core of the grain mass remaining cool after the October through December cool-down period and not being further affected by the rewarming of the periphery layer and bulk portion of the grain mass during the subsequent non-aerated storage period.

Table 5. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperature and standard deviations calculated for the numerical solution (total) for a nine-month storage period simulation of maize in 14.6x14.6 and 14.6x18.3 m silos beginning January 1, 2014. The fan was off during the entire period.

		12 Nodes	24 Nodes	Total nodes
14.6x14.6 m silo	Average (°C)	-4.0	-5.7	-1.8
	s.d. (°C)	3.1	2.7	4.5
14.6x18.3 m silo	Average (°C)	-4.4	-7.7	-2.8
	s.d. (°C)	3.1	1.4	4.5

3.3. Results: Simulations Set 2: Controlled Aeration until top Grain Layer Temperature Reached 0°C

The results shown in Figures 8–10 represent the average grain temperature values observed by monitoring the grain at positions reflective of the 15 and 30 sensor locations along with one labeled that represents the temperature values reflected by averaging all nodes of the numerical solution for each of the three silo dimensions.

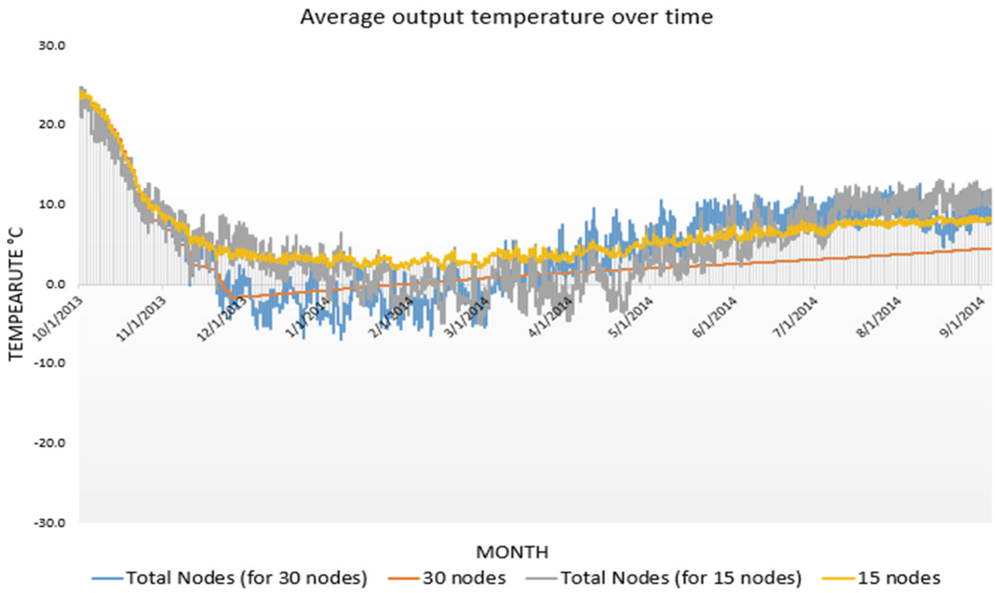

Figure 8. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 15 or 30 nodes for a one-year controlled aeration and storage simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off and sealed for the rest of the simulation period. The aeration cool-down period ended on November 21, 2013.

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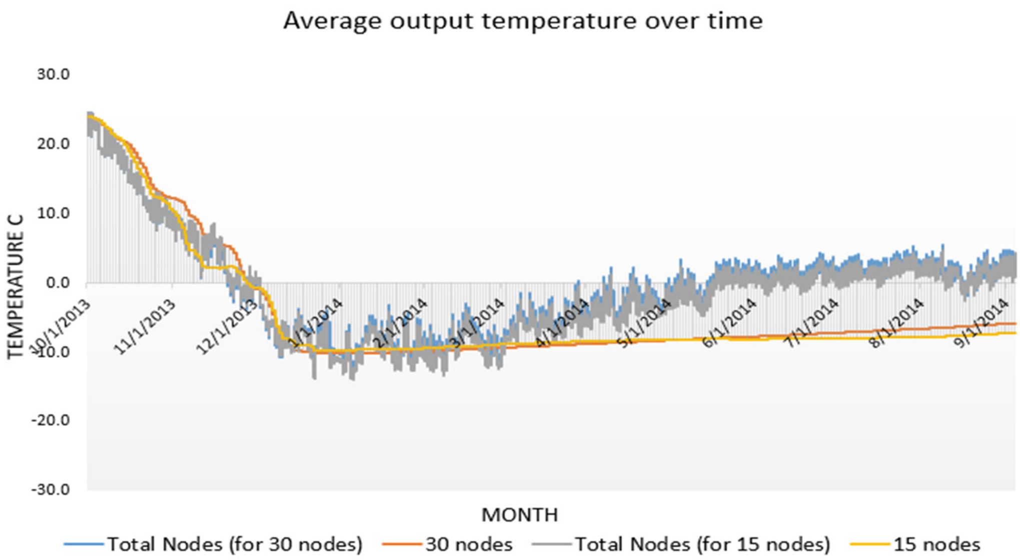

Figure 9. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off and sealed for the rest of the simulation period. The aeration cool-down period ended on December 23, 2013.

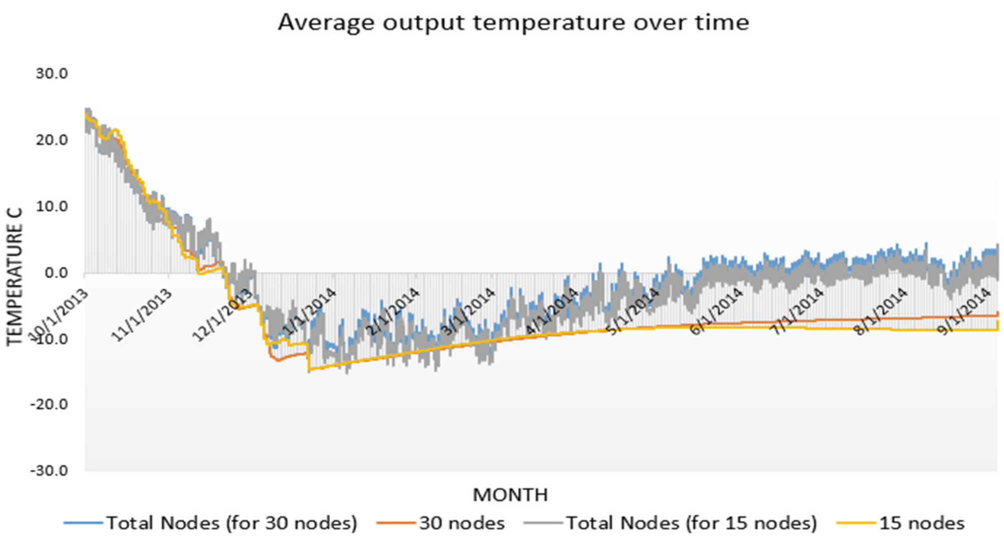

Figure 10. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off and sealed for the rest of the simulation periods. The aeration cool-down period ended on December 23, 2013.

Cool Down Period

In the case of the 11x11 m silo size, the average temperatures reported by the 15 and 30 nodes were 1.2°C and 0.5°C higher, respectively, than the average temperatures of the total nodes from the numerical solution (Table 6). In the case of the 14.6x14.6 m silo size, the average temperatures

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reported by the 15 and 30 nodes were 1.4°C and 2.2°C higher, respectively, than the average temperatures of the total nodes from the numerical solution (Table 7). For the 14.6x18.3 m silo size, the average temperatures reported by the 15 and 30 nodes were 2.2°Cand 1.5°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 8).

Across all silo sizes, the differences between the average grain temperature reported by 15 nodes and the average temperature of the total nodes from the numerical solution were 1.2°C, 1.4°C, and 2.2°C, respectively, and for the 30 nodes 0.5°C, 2.2°C, and 1.5°C, respectively. These results imply that 15 or 30 sensors are sufficiently reliable to monitor progress of aeration cooling in these three silo sizes.

Table 6. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 15 or 30 nodes for a two-month (October 1 to November 21, 2013) controlled aeration simulation of 745 MT of maize in a 11x11 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	12.6	6.6
30 nodes	10.4	8.0
Total nodes (15 nodes controlled the fan)	11.4	6.4
Total nodes (30 nodes controlled the fan)	9.9	7.4

Table 7. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for a three-month (October 1 to December 23, 2013) controlled aeration simulation of 1765 Mg of maize in a 14.6x14.6 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	6.5	10.4
30 nodes	7.5	10.8
Total nodes (12 nodes controlled the fan)	5.6	9.8
Total nodes (24 nodes controlled the fan)	5.3	9.8

Table 8. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for a three-months (October 1 to December 23, 2013) controlled aeration simulation of 2206 Mg of maize in a 14.6x18.3 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	3.9	11.4
30 nodes	3.4	11.6

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Total nodes (12 nodes controlled the fan)	5.1	9.7
Total nodes (24 nodes controlled the fan)	4.9	9.8

Storage Period

In the case of the 11x11 m silo, the average temperatures of the 15 and 30 nodes were 0.6°C higher and 2.1°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 9). In the case of the 14.6x14.6 m silo, the average temperature of the 15 and 30 nodes were 5.2°C and 5.9°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 10). And, for the 14.6x18.3 m silo, the average temperatures of the 15 and 30 nodes were 5.1°C and 5.7°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 11). The differences between the average temperatures of the 15 and 30 nodes were 3.7°C, 0.2°C, and 0.5°C for the three silo sizes, respectively.

Table 9. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for a three-months (October 1 to December 23, 2013) controlled aeration simulation of 2206 Mg of maize in a 14.6x18.3 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	**Average s.d. (°C)**
15 nodes	5.3	2.1
30 nodes	1.6	1.7
Total nodes (15 nodes controlled the fan)	4.7	4.7
Total nodes (30 nodes controlled the fan)	3.7	5.0

Table 10. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for a three-months (October 1 to December 23, 2013) controlled aeration simulation of 2206 Mg of maize in a 14.6x18.3 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	**Average s.d. (°C)**
15 nodes	-8.4	0.7
30 nodes	-8.2	1.3
Total nodes (12 nodes controlled the fan)	-3.2	4.7
Total nodes (24 nodes controlled the fan)	-2.3	4.6

Table 11. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for a three-months (October 1 to December 23, 2013) controlled aeration simulation of 2206 Mg of maize in a 14.6x18.3 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	-9.5	1.8
30 nodes	-9.0	2.3
Total nodes (12 nodes controlled the fan)	-4.4	4.7
Total nodes (24 nodes controlled the fan)	-3.3	4.6

Analysis after removing the temperature values of the center cable for the 14.6x14.6 m and 14.6x18.3 m silos

Cool Down Period

In the case of the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 1.0°C higher and 2.3°C lower than the average temperatures of the total nodes from the numerical solution (Table 12). In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 1.4°C and 2.2°C lower than the average temperatures of the total nodes from the numerical solution. In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.5°C and 0.2°C lower than the average temperatures of the total nodes from the numerical solution. In comparison, before removing the temperature values of the center cable, the average temperature of the 15 and 30 nodes were 2.2°C and 1.5°C lower than the average temperatures of the total nodes from the numerical solution.

Table 12. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes in the case of 14.6x14.6 and 14.6x18.3 m silos beginning October 1, 2013. The period from October 1, 2013 to December 23, 2013 was considered the cool down period. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached 0°C, the fan was turned off and sealed for the rest of the simulation periods.

	14.6x14.6 m silo		**14.6x18.3 m silo**	
	Average Temperature (°C)	**Average s.d. (°C)**	**Average Temperature (°C)**	**Average s.d. (°C)**
12 nodes	6.5	10.1	4.6	10.6
24 nodes	7.6	10.5	4.7	11.2
Total nodes (12 nodes controlled the fan)	5.6	9.8	5.1	9.7
Total nodes (24 nodes controlled the fan)	5.3	9.8	4.9	9.8

Table 13. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was turned off and sealed from December 23, 2013 to September 30, 2014 of maize in the 14.6x14.6 and 14.6 x 18.3 m silos.

	14.6x14.6 m silo		**14.6x18.3 m silo**	
	Average Temperature (°C)	**Average s.d. (°C)**	**Average Temperature (°C)**	**Average s.d. (°C)**
12 nodes	-8.4	0.7	-9.5	1.8
24 nodes	-9.3	0.4	-11.4	1.1
Total nodes (12 nodes controlled the fan)	-3.2	4.7	-4.4	4.7

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Total nodes (24 nodes controlled the fan)	-2.3	4.6	-3.3	4.6

3.4. Results: Simulations Set 3: Controlled Aeration until Top Grain Layer Temperature Reached -3°C

The results shown in Figures 11–13 represent the average grain temperature values observed by monitoring the grain at positions reflective of the 15 and 30 sensor locations along with one labeled total that represents the temperature values reflected by averaging all nodes of the numerical solution for each of the three silo dimensions.

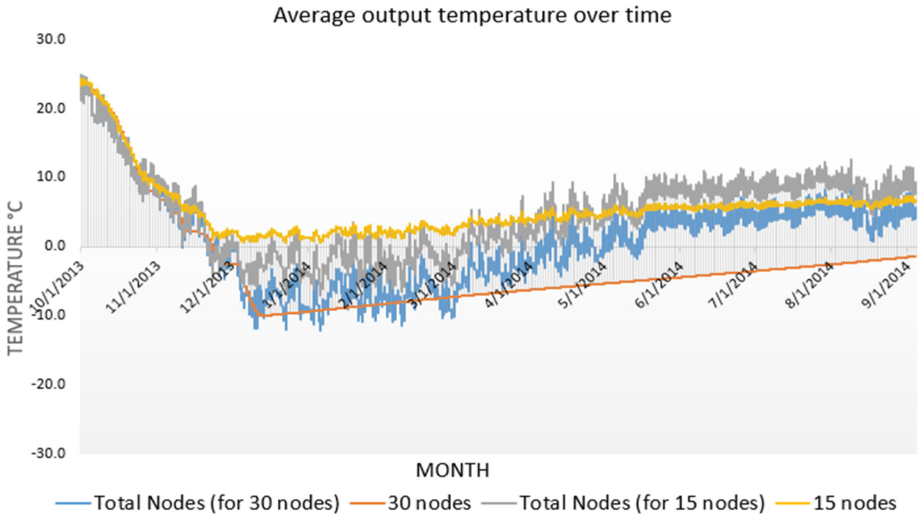

Figure 11. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 15 or 30 nodes for a one-year controlled aeration and storage simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off and sealed for the rest of the simulation period. The aeration cool-down period ended on December 14, 2013.

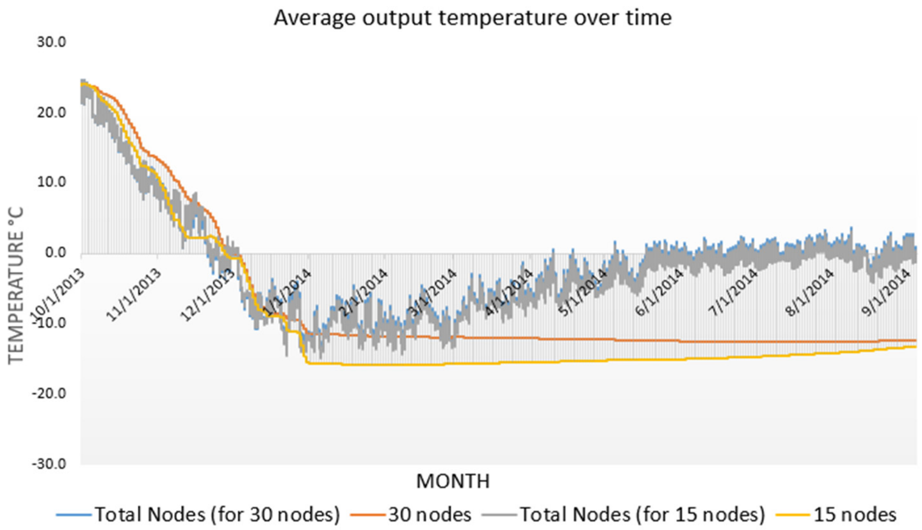

Figure 12. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning

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October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off and sealed for the rest of the simulation period. The aeration cool-down period ended on December 24, 2013.

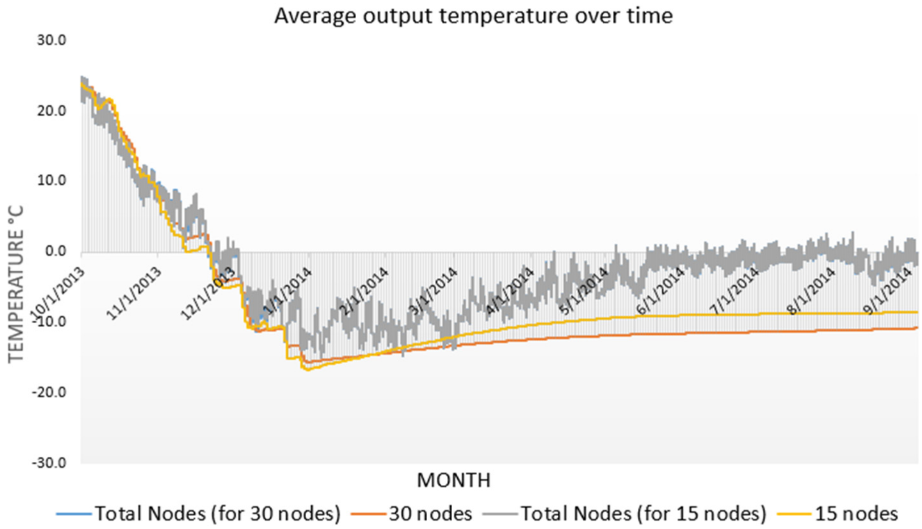

Figure 13. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 30 or 15 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off and sealed for the rest of the simulation periods. The aeration cool-down period ended on January 3, 2014.

Cool Down Period

In the case of the 11x11 m silo size, the average temperatures reported by the 15 and 30 nodes were 0.3°C and 0.3°C higher, respectively, than the average temperatures of the total nodes from the numerical solution (Table 14). In the case of the 14.6x14.6 m silo size, the average temperatures reported by the 15 and 30 nodes were 1.0°C and 1.9°C higher, respectively, than the average temperatures of the total nodes from the numerical solution (Table 15). For the 14.6x18.3 m silo size, the average temperatures reported by the 15 and 30 nodes were 1.6°Cand 1.9°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 16).

Across all silo sizes, the differences between the average grain temperature reported by 15 nodes and the average temperature of the total nodes from the numerical solution were 0.3°C, 1.0°C, and 1.6°C, respectively, and for the 30 nodes 0.3°C, 1.8°C, and 1.9°C, respectively. These results imply that 15 or 30 sensors are sufficiently reliable to monitor progress of aeration cooling in these three silo sizes.

Table 14. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 15 or 30 nodes for an aeration simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off.

	Average Temperature (°C)	**Average s.d. (°C)**
15 nodes	12.3	6.8

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30 nodes	6.8	9.8
Total nodes (15 nodes controlled the fan)	11.0	6.7
Total nodes (30 nodes controlled the fan)	6.5	9.2

Table 15. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for an aeration simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	6.3	10.5
30 nodes	6.1	11.4
Total nodes (12 nodes controlled the fan)	5.3	9.9
Total nodes (24 nodes controlled the fan)	4.2	10.2

Table 16. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes for an aeration simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	1.9	12.3
30 nodes	1.2	12.5
Total nodes (12 nodes controlled the fan)	3.5	10.3
Total nodes (24 nodes controlled the fan)	3.1	10.6

Storage Period

In the case of the 11x11 m silo, the average temperatures of the 15 and 30 nodes were 0.6°C higher and 5.1°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 17). In the case of the 14.6x14.6 m silo, the average temperature of the 15 and 30 nodes were 10.4°C and 8.2°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 18). And, for the 14.6x18.3 m silo, the average temperatures of the 15 and 30 nodes were 5.9°C and 7.7°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 19). The differences between the average temperatures of the 15 and 30 nodes were 9.8°C, 2.8°C, and 1.8°C for the three silo sizes, respectively.

Table 17. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was turned off and sealed from December 14, 2013 to September 30, 2014 for 745 Mg of maize stored in a 11x11 m silo.

	Average Temperature (°C)	Average s.d. (°C)
15 nodes	4.2	1.9

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30 nodes	-5.6	2.4
Total nodes (15 nodes controlled the fan)	3.6	5.1
Total nodes (30 nodes controlled the fan)	-0.5	5.4

Table 18. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was turned off and sealed from December 24, 2013 to September 30, 2014 for 1765 Mg of maize stored in a 14.6x14.6 m silo.

	Average Temperature (°C)	**Average s.d. (°C)**
15 nodes	-14.9	0.9
30 nodes	-12.1	0.5
Total nodes (12 nodes controlled the fan)	-4.5	4.5
Total nodes (24 nodes controlled the fan)	-3.9	4.4

Table 19. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was turned off and sealed from December 24, 2013 to September 30, 2014 for 1765 Mg of maize stored in a 14.6x14.6 m silo.

	Average Temperature (°C)	**Average s.d. (°C)**
15 nodes	-10.5	2.3
30 nodes	-12.3	1.3
Total nodes (12 nodes controlled the fan)	-4.6	4.3
Total nodes (24 nodes controlled the fan)	-4.6	4.3

Analysis after removing the temperature values of the center cable for the 14.6x14.6 m and 14.6x18.3 m silos

Cool Down Period

In the case of the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 1.0°C and 2.1°C higher than their respective average temperature values of the total nodes from the numerical solution (Table 20). However, before removing the temperature values of the center cable, the average temperatures of both 15 and 30 nodes were respectively 1.0°C and 1.9°C lower than their respective average temperature values of the total nodes from the numerical solution.

In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.7°C and 0.5°C lower than their respective average temperature values of the total nodes from the numerical solution. However, before removing the temperature values of the center cable, the average temperatures of both 15 and 30 nodes were respectively 1.6°C and 1.9°C lower than their respective average temperature values of the total nodes from the numerical solution.

Table 20. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes in the case of 14.6x14.6 and 14.6x18.3 m silos beginning October 1, 2013. The period from October 1 to December 24, 2013 was considered the cool down period in the case of the 14.6x14.6 m and from October 1, 2013 to January 3, 2014 in the case of the 14.6x18.3 m silo. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. Additionally, when the average temperature of the top layer nodes reached -3°C, the fan was turned off.

	14.6x14.6 m silo		14.6x18.3 m silo	
	Average Temperature (°C)	Average s.d. (°C)	Average Temperature (°C)	Average s.d. (°C)
12 nodes	6.3	10.2	2.8	11.4
24 nodes	6.3	11.0	2.6	12.0
Total nodes (12 nodes controlled the fan)	5.3	9.9	3.5	10.3
Total nodes (24 nodes controlled the fan)	4.2	10.2	3.1	10.6

Storage Period

In the case of the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 9.0°C lower and 7.7°C lower than the average temperatures of the total nodes from the numerical solution (Table 21). In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 1.4°C and 8.2°C lower than the average temperatures of the total nodes from the numerical solution. In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 3.8°C and 6.6°C lower than the average temperature of the total nodes from the numerical solution. In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 5.9°C and 7.7°C lower than the average temperature of the total nodes from the numerical solution.

Table 21. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was turned off and sealed from December 24, 2013 to September 30, 2014 in the case of the 14.6x14.6 silo m and from January 3, 2013 to September 30, 2014 in the case of the 14.6 x 18.3 m silo.

	14.6x14.6 m silo		14.6x18.3 m silo	
	Average Temperature (°C)	Average s.d. (°C)	Average Temperature (°C)	Average s.d. (°C)
12 nodes	-13.5	0.8	-8.4	2.1
24 nodes	-11.6	0.3	-11.2	1.3
Total nodes (12 nodes controlled the fan)	-4.5	4.5	-4.6	4.3
Total nodes (24 nodes controlled the fan)	-3.9	4.4	-4.6	4.3

3.5. Results: Simulations Set 4: Controlled Aeration Whenever Ambient Temperature Was Lower Than Grain Temperature

In this set of simulations, the aeration strategy turned the fan on whenever the current ambient temperature was lower than the average temperature of all sensor nodes (except those on the center cable) and ran the fan until the average temperature dropped below the current ambient temperature. The nodes that controlled the fan were located at a two-thirds distance from the center to the silo wall. The 11x11 m silo size did not have any nodes in the center of the grain mass while the 14.6x14.6 and 14.6x18.3 m silo sizes each had 3 nodes in the case of 15 nodes and 6 nodes in the case of 30 nodes located in the center of the grain mass. The results shown in Figures 14–16 represent the average grain temperature values observed by monitoring the grain at positions reflective of the 15 and 30 sensor locations along with one labeled total that represents the temperature values reflected by averaging all nodes of the numerical solution for each of the three silo dimensions. In terms of the two larger silos, the two averages of the numerical solution reflect control of the aeration fan based on 12 versus 24 nodes.

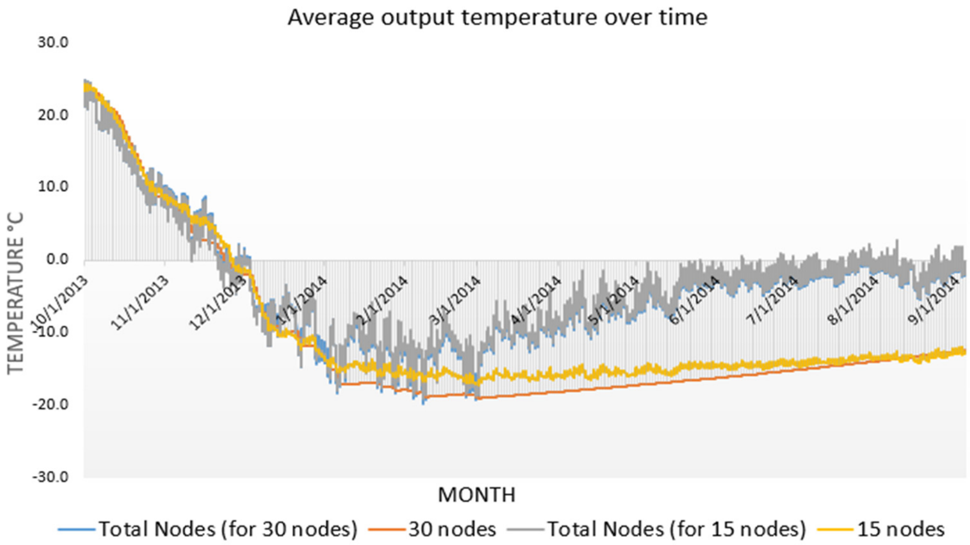

Figure 14. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 15 or 30 nodes for a one-year controlled aeration and storage simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 15 or 30 nodes in the grain mass. The aeration cool-down period ended on March 3, 2014.

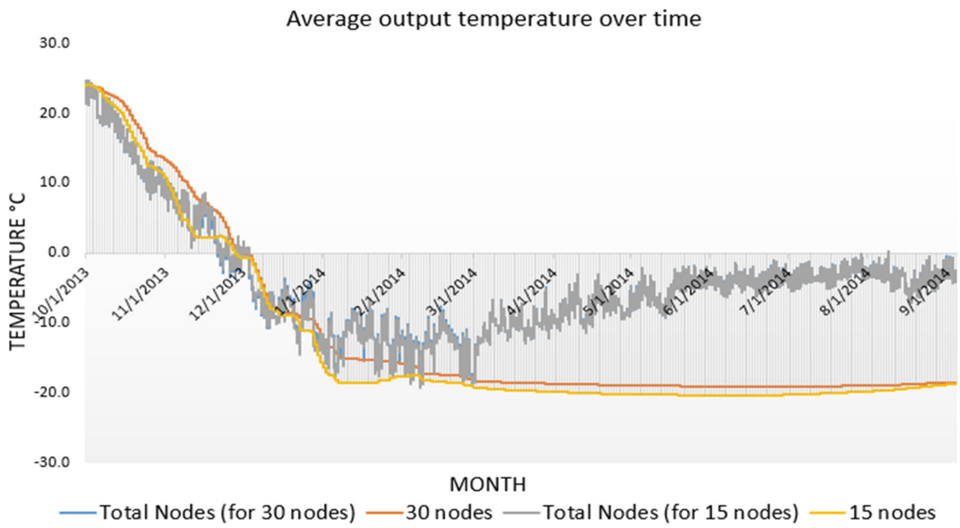

Figure 15. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. The aeration cool-down period ended on March 2, 2014.

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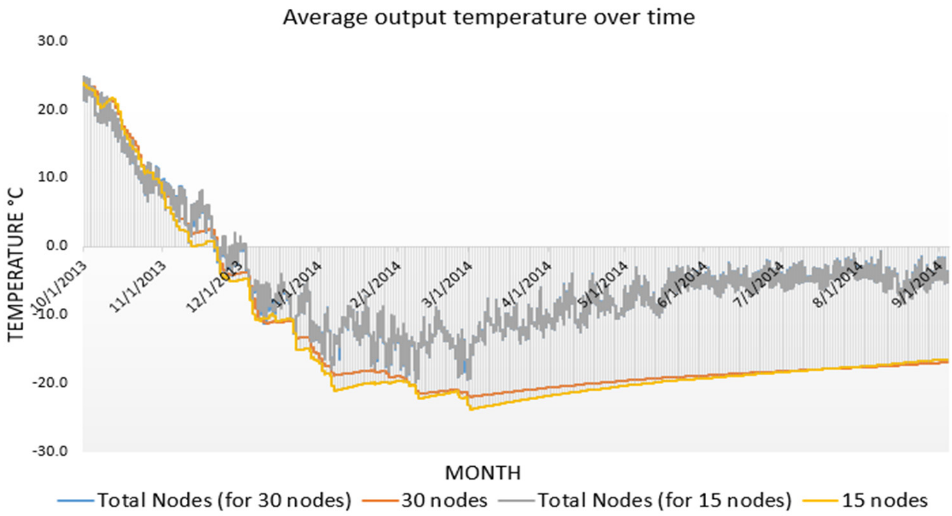

Figure 16. Average temperature values for 15 and 30 nodes versus the average temperature calculated for the numerical solution (total) when the fan was controlled by either 12 or 24 nodes for a one-year controlled aeration and storage simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013. The fan was turned on whenever the ambient air temperature was cooler than the average temperature of either the 12 or 24 nodes in the grain mass. The aeration cool-down period ended on March 2, 2014.

Cool Down Period

In the case of the 11x11 m silo size, the average temperatures reported by the 15 nodes was 0.6°C higher and for the 30 nodes it was the same as the average temperatures of the total nodes from the numerical solution (Table 22). In the case of the 14.6x14.6 m silo size, the average temperatures reported by the 15 and 30 nodes were 0.3°C and 2.8°C higher, respectively, than the average temperatures of the total nodes from the numerical solution. For the 14.6x18.3 m silo size, the average temperatures reported by the 15 and 30 nodes were 1.7°C and 0.7°C lower, respectively, than the average temperatures of the total nodes from the numerical solution.

Across all silo sizes, the differences between the average grain temperature reported by 15 nodes and the average temperature of the total nodes from the numerical solution were 0.6°C, 0.3°C, and 1.7°C, respectively, and for the 30 nodes 0.0°C, 2.8°C, and 0.7°C, respectively. These results imply that 15 or 30 sensors would be sufficiently reliable to monitor progress of aeration cooling in these three silo sizes.

Table 22. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 15 or 30 nodes in the case of 11x11 m silo and 12 or 24 in the case of 14.6x14.6 and 14.6x18.3 silo beginning October 1, 2013. The period from October 1, 2013 to March 3, 2014 was considered the cool down period in the case of the 11x11 m silo and from October 1, 2013 to March 2, 2014 in the case of the 14.6x14.6 and 14.6x18.3 silos.

	11x11 m silo	
	Average Temperature (°C)	Average s.d. (°C)
15 nodes	4.2	11.2
30 nodes	3.8	11.3
Total nodes (15 nodes controlled the fan)	3.6	10.3

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Total nodes (30 nodes controlled the fan)	3.8	10.3
	14.6x14.6 m silo	
15 nodes	4.3	11.3
30 nodes	6.8	11.5
Total nodes (12 nodes controlled the fan)	4.0	10.4
Total nodes (24 nodes controlled the fan)	4.0	10.3
	14.6x18.3 m silo	
15 nodes	2.1	12.2
30 nodes	2.9	12.1
Total nodes (12 nodes controlled the fan)	3.8	10.2
Total nodes (24 nodes controlled the fan)	3.6	10.3

Storage Period

In the case of the 11x11 m silo, the average temperatures of the 15 and 30 nodes were 8.8°C and 10.1°C lower, respectively, than the average temperatures of the total nodes from the numerical solution (Table 23). In the case of the 14.6x14.6 m silo, the average temperatures of the 15 and 30 nodes were 12.2°C and 10.8°C lower, respectively, than the average temperatures of the total nodes from the numerical solution. And, for the 14.6x18.3 m silo, the average temperatures of the 15 and 30 nodes were 11.5°C and 10.8°C lower, respectively, than the average temperatures of the total nodes from the numerical solution. The differences between the average temperatures of the 15 and 30 nodes were 2.2°C, 1.4°C, and 1.4°C for the three silo sizes, respectively.

Table 23. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 15 or 30 nodes in the case of 11x11 m silo and 12 or 24 in the case of 14.6x14.6 and 14.6x18.3 silo beginning October 1, 2013. The period from March 3, 2014 to September 30, 2014 was considered the storage period in the case of the 11x11 m silo and from March 2, 2014 to September 30, 2014 in the case of the 14.6x14.6 and 14.6x18.3 silos.

	11x11 m silo	
	Average Temperature (°C)	Average s.d. (°C)
15 nodes	-14.8	1.1
30 nodes	-16.4	1.1
Total nodes (15 nodes controlled the fan)	-6.0	5.1
Total nodes (30 nodes controlled the fan)	-6.3	5.1
	14.6x14.6 m silo	
15 nodes	-19.5	0.9
30 nodes	-18.1	1.4

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Total nodes (12 nodes controlled the fan)	-7.3	4.4
Total nodes (24 nodes controlled the fan)	-7.3	4.4
	14.6x18.3 m silo	
15 nodes	-19.5	0.9
30 nodes	-18.1	1.4
Total nodes (12 nodes controlled the fan)	-7.3	4.4
Total nodes (24 nodes controlled the fan)	-7.3	4.4

Analysis after removing the temperature values of the center cable for the 14.6x14.6 m and 14.6x18.3 m silos

Cool Down Period

In the case of the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.9°C higher and 2.2°C lower than the average temperatures of the total nodes from the numerical solution (Table 24). In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 0.3°C and 2.8°C lower than the average temperatures of the total nodes from the numerical solution. In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 0.8°C and 0.5°C lower than the average temperatures of the total nodes from the numerical solution. In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 1.7°C and 0.7°C lower than the average temperatures of the total nodes from the numerical solution.

Table 24. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by either 12 or 24 nodes in the case of 14.6x14.6 and 14.6x18.3 silos beginning October 1, 2013. The period from October 1, 2013 to March 2, 2014 was considered the cool down period.

	14.6x14.6 m silo		**14.6x18.3 m silo**	
	Average Temperature (°C)	Average s.d. (°C)	Average Temperature (°C)	Average s.d. (°C)
12 nodes	4.9	10.8	3.0	11.3
24 nodes	6.2	11.1	3.1	11.8
Total nodes (12 nodes controlled the fan)	4.0	10.4	3.8	10.2
Total nodes (24 nodes controlled the fan)	4.0	10.3	3.6	10.3

Storage Period

In the case of the 14.6x14.6 m silo, the results show that the average temperatures of the 12 and 24 nodes were 11.2°C higher and 9.7°C lower than the average temperatures of the total nodes from the numerical solution (Table 25). In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and 30 nodes were 12.2°C and 10.8°C lower than the average temperatures of the total nodes from the numerical solution. In the case of the 14.6x18.3 m silo, the results show that the average temperatures of the 12 and 24 nodes were 9.4°C and 10.2°C lower than the average temperatures of the total nodes from the numerical solution. In comparison, before removing the temperature values of the center cable, the average temperatures of the 15 and

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30 nodes were 11.5°C and 10.8°C lower than the average temperatures of the total nodes from the numerical solution.

In general, the results show that removing the center cable results in warmer average temperatures (and closer to the average temperature of the total nodes from the numerical solution) which was primarily caused by the core of the grain mass cooling relatively quickly in October through March and not being further affected by the rewarming of the periphery grain during the non-fan operating periods.

Table 25. Average temperatures and standard deviations for 12 and 24 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total). The fan was controlled by 12 or 24 nodes in 14.6x14.6 and 14.6x18.3 silos beginning October 1, 2013. The period from March 2, 2014 to September 30, 2014 was considered the storage period.

	14.6x14.6 m silo		**14.6x18.3 m silo**	
	Average Temperature (°C)	Average s.d. (°C)	Average Temperature (°C)	Average s.d. (°C)
12 nodes	-18.5	1.1	-17.7	1.6
24 nodes	-17.0	1.2	-18.5	1.4
Total nodes (12 nodes controlled the fan)	-7.3	4.4	-8.3	4.3
Total nodes (24 nodes controlled the fan)	-7.3	4.4	-8.3	4.3

3.6. Results: Comparison between Simulation Results

4. Discussion

For all simulation runs and silo sizes, the average grain temperatures reported by either 15 or 30 nodes were consistently lower than the respective average temperatures of the total nodes from the numerical solution (Tables 26–28). This is primarily due to the grain temperatures in the periphery layer of the grain mass being heavily influenced by solar radiation which is highest during the spring and summer. None of the sensors in either the 15 or 30 node cases were located within the periphery layer. Instead, they were all located either in the center or at two-thirds distance from the center and one-third distance from the silo wall. In comparison, there were quite a few nodes among the total number of mesh nodes that were located in the periphery layer and weighted the numerical solution as a function of warmer temperatures due to the effect of solar radiation on the silo wall. As a result, the average temperature of the numerical solution is consistently warmer than the average temperature predicted by the 15 and 30 nodes.

Table 26. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 745 Mg of maize in a 11x11 m silo beginning October 1, 2013 for four sets of simulation runs. The number of hours the fan operated are included in the last column.

	Average Temperature (°C)	**Average s.d. (°C)**	**Fan run hours**
	Simulation Set 1		
15 nodes	-2.27	7.01	
30 nodes	-3.59	7.58	
Total Nodes (1968)	0.54	7.12	2208

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	Simulation Set 2		
15 nodes	6.2	4.2	
30 nodes	3.1	4.9	
Total nodes (15 nodes controlled the fan)	5.2	5.4	977
Total nodes (30 nodes controlled the fan)	4.8	6.0	974
	Simulation Set 3		
15 nodes	5.5	4.4	
30 nodes	-2.9	7.2	
Total nodes (15 nodes controlled the fan)	4.7	6.0	1016
Total nodes (30 nodes controlled the fan)	1.0	7.0	1192
	Simulation Set 4		
15 nodes	-9.6	10.3	
30 nodes	-10.9	10.9	
Total nodes (15 nodes controlled the fan)	-3.4	8.1	1952
Total nodes (30 nodes controlled the fan)	-3.5	8.2	1596

Table 27. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 1765 Mg of maize in a 14.6x14.6 m silo beginning October 1, 2013 for four sets of simulation runs. The number of hours the fan operated are included in the last column.

	Average Temperature (^{o}C)	**Average s.d. (^{o}C)**	**Fan run hours**
	Simulation Set 1		
15 nodes	-2.4	6.8	
30 nodes	-3.6	7.1	
Total Nodes (1968)	-0.07	7.0	2208
	Simulation Set 2		
15 nodes	-4.7	8.3	
30 nodes	-4.3	8.7	
Total nodes (12 nodes controlled the fan)	-1.1	7.4	1411
Total nodes (24 nodes controlled the fan)	-0.4	7.1	1478
	Simulation Set 3		
15 nodes	-9.6	10.6	
30 nodes	-7.0	10.4	
Total nodes (12 nodes controlled the fan)	-2.1	7.6	1543

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Total nodes (24 nodes controlled the fan)	-1.7	7.4	1590
	Simulation Set 4		
15 nodes	-12.9	12.3	
30 nodes	-11.4	12.7	
Total nodes (12 nodes controlled the fan)	-4.2	8.3	1909
Total nodes (24 nodes controlled the fan)	-4.2	8.2	2058

Table 28. Average temperatures and standard deviations for 15 and 30 nodes versus the average temperatures and standard deviations calculated for the numerical solution (total) for a one-year controlled aeration and storage simulation of 2206 Mg of maize in a 14.6x18.3 m silo beginning October 1, 2013 for four sets of simulation runs. The number of hours the fan operated are included in the last column.

	Average Temperature (°C)	**Average s.d. (°C)**	**Fan run hours**
	Simulation Set 1		
15 nodes	-2.7	6.7	
30 nodes	-4.8	7.6	
Total Nodes (1968)	-0.89	7.1	2208
	Simulation Set 2		
15 nodes	-6.2	8.2	
30 nodes	-5.9	8.1	
Total nodes (12 nodes controlled the fan)	-2.1	7.5	1217
Total nodes (24 nodes controlled the fan)	-1.2	7.3	1250
	Simulation Set 3		
15 nodes	-7.1	8.7	
30 nodes	-8.2	9.3	
Total nodes (12 nodes controlled the fan)	-2.3	7.5	1295
Total nodes (24 nodes controlled the fan)	-2.4	7.5	1322
	Simulation Set 4		
15 nodes	-13.8	11.7	
30 nodes	-13.1	11.7	
Total nodes (12 nodes controlled the fan)	-5.0	8.4	1588
Total nodes (24 nodes controlled the fan)	-5.0	8.4	1620

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In general, across all silo sizes, the average grain temperature of the total nodes from the numerical solution were the lowest in Simulation Set 4, followed by Simulation Set 3, then Simulation Set 2, and lastly Simulation Set 1. This was not surprising because Simulation Set 4 had an aeration control strategy that turned the fan on whenever the ambient temperature was cooler. As a result, the grain was cooled whenever possible throughout the one-year storage period. Interestingly, in this scenario intermittent fan operation continued into March which is a much longer operating window than typically needed and resulted in much colder grain temperatures than generally recommended. The second coldest average grain temperatures were achieved in Simulation Sets 3 and 2 because in addition to turning on the fan whenever the ambient temperature was cooler than the average grain temperature, the fan was not turned off for the season and sealed until the average grain temperature of the grain mass top layer reached -3°C and 0°C, respectively. Finally, the average grain temperature in Simulation Set 1 was the warmest because the fan ran continuously no matter the grain or ambient temperatures from October 1 through December 31, 2013. Due to the cyclical weather pattern of increasing and decreasing temperatures during the fall harvest period, the grain was cooled and rewarmed multiple times. Once the fan was turned off (and sealed), the average grain temperature was higher going into the storage season compared to the other simulation sets, and continued to increase during the spring and summer resulting in the warmest average grain temperature by the end of the storage period.

Across all simulation runs and silo sizes, the average grain temperature of the total nodes from the numerical solution remained sufficiently low (below 5°C for the two larger silos, below 10°C for the smaller silo) to support the best management practice recommendation that grain cooled during the fall harvest and maintained cool during the winter can be kept cold into the spring and summer storage period without the need to warm grain up in the spring. This assumes that other best management practices have been implemented including maize is stored at recommended safe moisture content levels, the grain mass has been cored and the grain peak inverted, headspace ventilation is utilized to prevent condensation conditions, and there are no signs of spoilage or insect activity as confirmed by carbon dioxide readings below 600-800 ppm. One concern with the simulation runs undertaken in this study is the high number of fan operating hours (about double) compared to what is typically expected. Simulation Set 2 had the lowest fan run hours for the three silo sizes investigated. This indicates that a better fan control strategy should have been utilized in this study. However, minimizing fan run hours was not a goal in this study. Nevertheless, minimizing fan run hours (and associated shrink loss and electricity costs) while maintaining grain in good condition is important to every stored grain manager. Among the four scenarios evaluated Simulation Set 2 resulted in the most cost-effective aeration strategy for cooling grain during the critical fall harvest period and keeping the grain in safe condition during the non-aerated storage period.

The results of Simulation Set 1 showed that 15 or 30 sensors were enough to monitor grain temperature during the aeration cooling and non-aerated storage periods with sufficient reliability in the 11x11, 14.6x14.6 and 14.6x18.3 m silos. The results of Simulation Set 4 and 3 showed that 15 or 30 sensors were enough to keep track of grain temperature during the aeration cooling period but not during the storage period for the three silo sizes because the average temperatures of the 15 and 30 nodes were much lower than the average temperature of the numerical solution. During the aeration cooling period, the average grain temperatures of the 15 and 30 nodes were within ±5°C of the average temperature of the numerical solution whereas during the storage period, the average grain temperatures of the 15 and 30 nodes were more than 5°C different from the average temperature of the numerical solution. The results of Simulation Set 2 showed that 15 or 30 sensors were enough to keep track of grain temperature during the aeration cooling period in the three silo sizes but only during the storage period in the 11x11 m silo. These results imply that the number of sensors whether cable-based or wireless required to monitor stored grain with sufficient reliability is a function of silo size and heavily depends on whether the aeration control strategy achieved a sufficiently low temperature by the time the aeration fans are turned off for the season and sealed to prevent grain from warming up too quickly in the spring and summer.

5. Conclusions

The accuracy of a previously developed 3D ecosystem model was verified and then applied to determine the number of sensors needed to reliably monitor stored grain quality based on predicted grain temperatures in three different silo sizes. The key results are:

1. The predicted grain temperatures closely followed the observed grain temperatures during the aeration period. The standard error of prediction was in the range of 2.0-3.7°C.
2. The number of sensors needed to monitor stored grain temperatures with sufficient accuracy in 11x11, 14.6x14.6 and 14.6x18.3 m silos heavily depends on whether the aeration control strategy achieved a sufficiently low temperature by the time the aeration fans were turned off ahead of the non-aerated storage period.
3. For the three silo sizes investigated, 15 or 30 sensors were sufficient to monitor grain temperatures during the aeration cooling period but for the two larger silo sizes more than 30 sensors would be needed to monitor reliably during the storage period.
4. As silo size increased, and surface-to-volume ratio decreased, grain temperatures remained lower during the storage period. Results support the best management practice recommendation of leaving cooled grain cold and not warming it up in the spring ahead of storage into the summer.

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