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Final Report

Research Report

Defining Best Management Practices for Using Supplemental Heating with Natural Air Drying

For:
Saskatchewan Canola Development Commission (SaskCanola)
Saskatchewan Wheat Development Commission (SWDC)

PAMI
Innovative Solutions for Agriculture and Beyond

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Defining Best Management Practices for Using Supplemental Heating with Natural Air Drying

Roy Maki, P.Eng., M.Sc.
Project Leader

Charley Sprenger, BE, M.Sc.,
Project Leader

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1. Executive Summary

Drying grain on-farm is a common practice in Saskatchewan to minimize the risk of spoilage during storage. Many producers use natural air drying (NAD) systems to minimize the capital and operating costs of grain drying. However, very little practical information or best management practices are available to help producers make management and operational decisions related to using supplemental heating.

The objective of this project was to conduct bench-scale drying trials to determine how the use of supplemental heat affects the drying rate and storage conditions of wheat and canola. Year 1 (2018) trials were conducted to evaluate the effect of air flow rate on supplemental heating with NAD compared to NAD without the addition of heat. Year 2 (2019) trials examined the rate of drying with supplemental heat at three different temperature increases. An economic assessment of using supplemental heating systems was also completed to summarize the capital and operating costs related to supplemental heating systems.

Results from the Year 1 experimental trials indicate that adding heat when ambient conditions are cool and damp will increase the drying rate of wet wheat in the bin; however, sufficient airflow (>13.5 L/s per m^3 [1 cfm/bu]) is required to remove the extracted moisture from the bin. No treatments achieved safe storage conditions during the three-week trial; however, the wheat was very damp having a moisture content (MC) of 17.4% when the trial started. In the second trial, damp canola (13% MC) was dried down to a safe-for-storage 10% MC within four days with an applied airflow rate of 27.0 L/s per m^3 (2 cfm/bu) and a 10°C increase in inlet air temperature, or dried down within five days without heat. It took eight days to dry canola at 13.5 L/s per m^3 (1 cfm/bu) with heat. Both trials suggest that over-drying at the bottom of the bin may not be avoidable, and that an average dry moisture should be targeted, and then the grain should be mixed.

In Year 2 (2019) it was observed that a 10°C increase in temperature is adequate if that results in a plenum temperature of greater than 5°C. Greater energy requirements (higher temperature increases) would be required if sub-zero ambient conditions are being experienced for prolonged periods of time. The efficiency of this scenario is unknown based on the experimental approach in this project. The drying rate of wheat in the 2019 trial was 0.5% and 0.75% per week for the 5°C and 10°C increase treatments; it is to be noted that the ambient conditions were <0°C for almost the entire two-week trial, which would likely have reduced the potential drying rate. For the canola drying trial, the rate of drying for both heated treatments were 1% per week. The relative humidity (RH) reduction as a result of a 10°C temperature increase was calculated to be 57% and 67% for the wheat and canola trials, respectively, compared to the theoretical 50%; this difference could be attributed to heat losses in the ducting. Based on these

observed rates of drying for both canola and wheat, supplemental heating with a NAD system may not be suitable for starting grain moisture contents >3% above dry (i.e., damp rather than tough); increased risk of spoilage is possible in those situations. Careful monitoring or reduced grain bed depths can help to mitigate this if a heated-air dryer is not available.

A technical review indicated that there are numerous manufacturers of equipment that are suitable for supplemental heating systems, but the efficiencies of these systems are not all known. There are options to implement direct or indirect systems either upstream or downstream of the aeration fan; all alternatives come with advantages and disadvantages unique to individual operations. Fuel type has the greatest impact on operating costs; natural gas (NG) is the most inexpensive fuel; however, access to NG can be capitally hindering in certain regions. Estimated efficiencies range from 50% to 75% compared to dedicated heated-air drying system efficiencies of 40% to 55%. Supplemental heating for NAD systems does have the potential to be a lower capital alternative to heated air drying to extend the drying season; however, based on currently available knowledge (including this research) careful management of this practice is required to keep operating costs comparable to that of a dedicated dryer system.

Overall, this project has generated useful baseline information on the effect of using NAD with supplemental heat on drying rate and grain storage conditions for wheat and canola. General recommendations for implementing supplemental heating were developed and are included in this full report.

2. Introduction

Supplemental heating systems allow producers to use existing natural air drying (NAD) systems by adding heat to the air with a heater fueled by oil, natural gas, diesel, or propane. Increasing the temperature of the air dramatically increases the air's capacity to dry and can turn a bad drying day in November into a good drying day, similar to those experienced in August or September. Several types of heating systems are commercially available, and new systems are introduced on the market every year. However, there has been little to no scientific or independent evaluation of the efficiency of these systems. In addition, best management practices for utilizing supplemental heating systems are limited or based on outdated research and observations. There was considerable research conducted on using solar systems for supplemental heating in the late 1970s and early 1980s in the United States, but there is very little information on supplemental heating that is publicly available and recent. In some cases, the only available information is from bin, heater, or fan manufacturers, which, while informative, may not be as robust or independent as producers need to make sound storage management decisions.

In some cases, using biomass, such as flax straw, oat hull pellets, or wood chips as a heating fuel, may be more economical and environmentally conscious than burning diesel or propane for grain drying. However, the cost of the combustion appliance, as well as storage and handling of the biomass (in addition to the cost of the biomass if it is not available on-farm) will impact the economic viability of using biomass for grain drying.

One of the existing technology gaps is the lack of control over the amount of heat added to the air. Most heating systems for grain bins are either on or off, so the temperature of the air entering the bin (after the heater) will fluctuate with the ambient air temperature. It is well known that fluctuations in air and grain temperature will have a negative impact on drying efficiency. A simple thermostat may be used to control the heating element and ensure a consistent and controlled inlet temperature. The Prairie Agricultural Machinery Institute (PAMI) has worked with equipment suppliers (such as Grain Guard) and innovators (such as Wilde AgVentures) to explore and evaluate cost-effective control systems for smaller bins (approximately 176 m^3 [5,000 bu] capacity).

2.1 Research Objectives

The objectives of this project were to

1. scientifically determine how the use of supplemental heat affects the drying rate and storage conditions of wheat and canola,
2. determine the economic benefits of using supplemental heating with NAD (with various fuel types) including fixed and variable costs in comparison to managing

damp grain with NAD only (no heat) and heated air drying in a dedicated drying system, and

3. compile and disseminate best management practices for use of supplemental heat with NAD.

3. Methodology

The following subsections detail the methodology used to determine the effects of supplemental heat on wheat and canola during Year 1 (2018).

3.1 Grain Drying

Grain drying trials were conducted at PAMI in Humboldt, Saskatchewan, using its bench-scale test bins.

3.1.1 Experimental Design

In Year 1 (2018), the two trials focused on the effect of airflow rate on drying rate with and without heat addition. One trial was conducted with wheat and the other with canola. For each trial, three of the bins had no heat addition, and three of the bins were controlled to provide a 10°C temperature increase to the fan inlet. Within each heat addition treatment, three airflow rates were used (**Table 3-1**); canola requires a higher airflow rate due to the higher resistance caused by low porosity throughout the grain bulk.

Table 3-1. Airflow rates used in Year 1 (2018) grain drying trials.

Commodity	Airflow rates L/s per m^3 (cfm/bu)		
	Low	Mid	High
Wheat	3.4 (0.25)	6.8 (0.5)	13.5 (1.0)
Canola	6.8 (0.5)	13.5 (1.0)	27.0 (2.0)

Although it is recommended to use higher airflow rates (13.5 L/s per m^3 [1 cfm/bu]) when using supplemental heating, large bin manufacturers state that lower airflow rates (3.4 L/s per m^3 [0.25 cfm/bu]) are suitable for use with supplemental heating. Although some drying has been observed with NAD at 1.3 L/s per m^3 (0.1 cfm/bu), it has been hypothesized that low airflow rates in combination with additional heat can result in high grain temperatures with little moisture removal, greatly increasing the risk of spoilage. This trial allowed PAMI to collect data to better understand the importance of airflow rate recommendations when the air is heated.

In Year 2 (2019), the effect of temperature increase on drying rate in wheat and canola was assessed. Airflow rate remained fixed at 13.5 L/s per m^3 (1 cfm/bu) for all treatments. A 10°C increase in air temperature will effectively reduce the relative humidity (RH) of the inlet air by half, at which point the air's capacity to dry is increased significantly. The purpose of this trial set was to understand if 10°C is a good target recommendation for heat addition to facilitate NAD and to assess the heat transfer efficiency of NAD systems (and thus, the economic viability of using supplemental heating).

All trials were planned to occur in mid-late fall to ensure the ambient conditions were representative of conditions where supplemental heating is typically used. Unfortunately, environmental conditions in the fall of Year 2 (2019) were unseasonably cold and humid; available grain was damp rather than tough (>3% above dry) and temperatures were sub-zero. Protocols remained the same; therefore, discussion points will address the effect of these conditions on the results if they varied from the hypotheses.

3.1.2 Bin Set-up

Grain drying trials were performed using PAMI's NAD research facility (**Figure 3-1**). The NAD facility consists of six 530-L (15-bushel) grain bins. The bins have a 46 cm (18 in) diameter. Each bin is equipped with

- one variable speed centrifugal aeration fan (**Figure 3-2**),
- one plenum forming the bottom of the bin to simulate full floor aeration (**Figure 3-3**),
- one tension load cell attached to the top of the bin used for continual weight (moisture loss or gain) analysis (**Figure 3-4**),
- six temperature sensors at various locations (**Figure 3-5**),
- six RH sensors at the same locations as the temperature sensors (**Figure 3-5**), and
- four sampling ports allowing grain samples to be taken from the bottom of the bin (7.6 cm [3 in] above plenum), at quarter-height (76.2 cm [30 in] above plenum), at half-height (152 cm [60 in] above plenum) and at three-quarter height (229 cm [90 in] above plenum; **Figure 3-6**).

The test bin set-up is housed inside a large round shed equipped with an overhead door. This door remained open and was covered by a mesh screen throughout the entire test period.

One of the main benefits of using PAMI's NAD test bins is the ability to continually monitor the weight of the bins via the load cells. Estimating the amount of drying or wetting based on sampling is challenging due to the inconsistency of collecting representative samples from the entire bin. Knowing that the weight loss or gain in the bins is affected only by variations in the quantity of water contained in the bin, the amount of drying or wetting can be continually assessed.

Figure 3-1. PAMI bench-scale test bin set-up.

Figure 3-2. Centrifugal fan on each bin.

Figure 3-3. Plenum at bottom of bin.

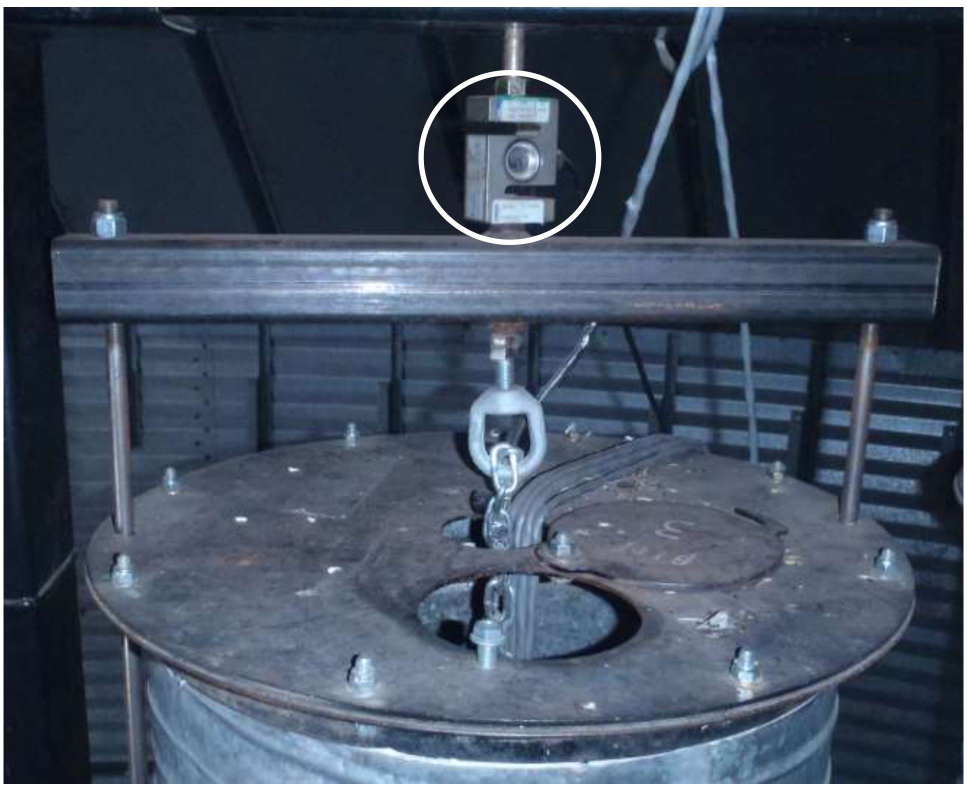

Figure 3-4. Tension load cell (one on each bin).

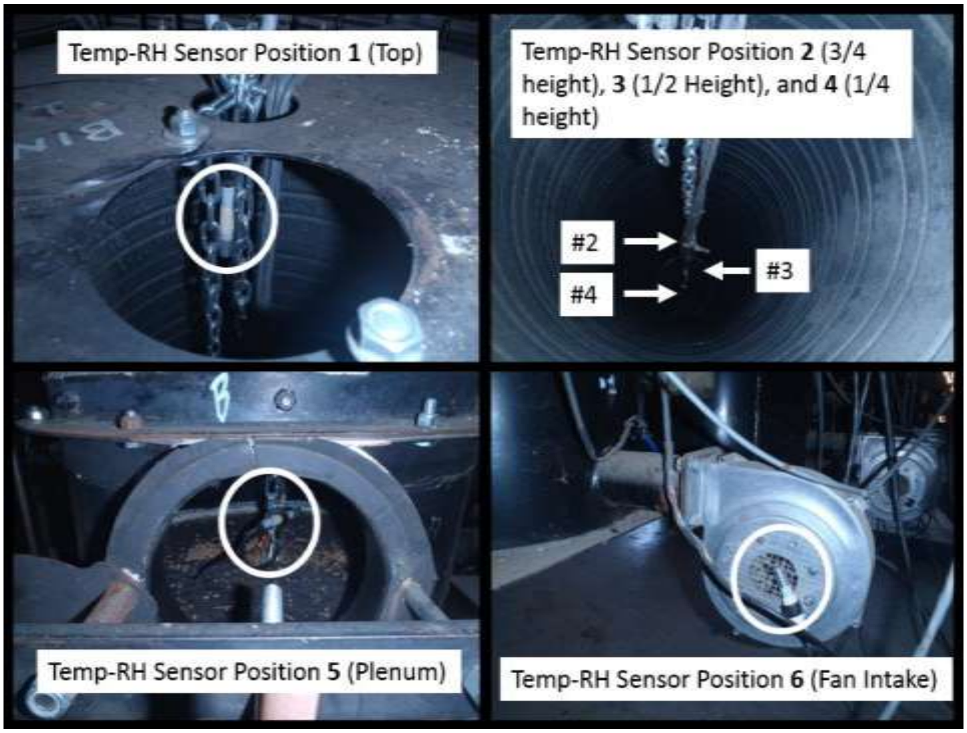

Figure 3-5. Position of six temperature and RH sensors.

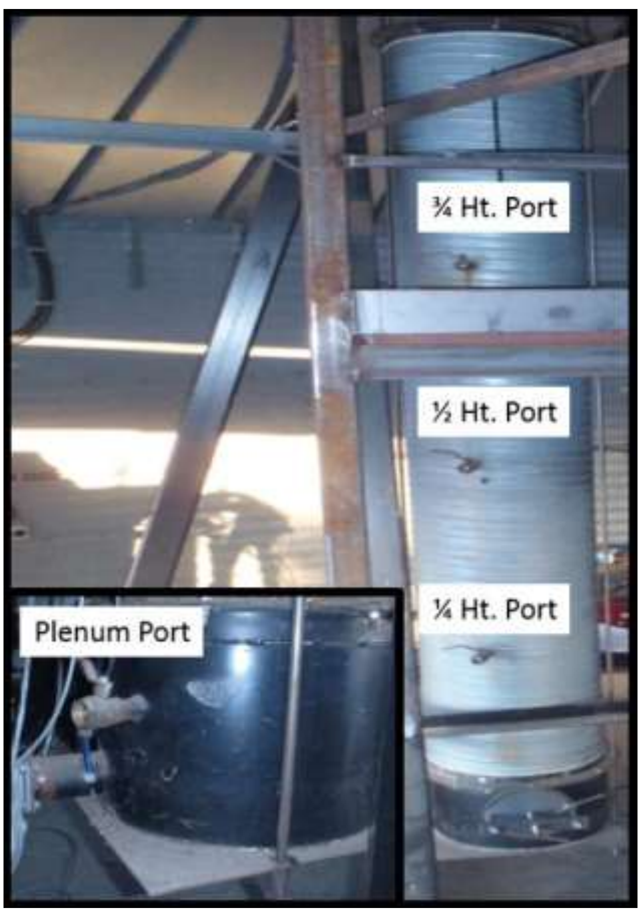

Figure 3-6. Location of four sampling ports.

3.1.3 Supplemental Heat Supply

To accommodate supplemental heat addition to the existing grain drying facility, a heating and ducting system was designed and built to allow controlled addition of heat to the fans.

In Year 1 (2018), three of the six 530-L (15-bushel) grain bins required supplemental heat for the trial runs. Heated air was added to the intake of three of the variable-speed centrifugal aeration fans while ambient air entered the intake of the other three aeration fans. The intake of the three aeration fans that were coupled to the bins requiring supplemental heat was connected to the outlet of a 10.2-cm (4-in) diameter 366-cm (144-in) length of insulated ducting (**Figure 3-7**). Heated air was supplied to the inlet of the three insulated ducts by connecting the ducting to a preheated chamber (**Figure 3-8**).

Figure 3-7. Insulated duct outlet connected to aeration fan inlet.

Figure 3-8. Insulated duct inlet connected to preheated chamber.

The chamber (**Figure 3-9** consisted of a 2,662-L (94-cu ft) insulated enclosure with an electric heater (**Figure 3-10**) contained within the cavity. Ambient air was drawn into the cavity through intake vent holes located on the side of the preheat chamber (**Figure 3-11**) as the three aeration fans drew the heated air out of the cavity through the insulated ducts. A temperature control unit (**Figure 3-12**) was used to control the cavity temperateness at a settable offset above ambient temperature. The control unit incorporated two negative temperature coefficient (NTC) thermistor temperature sensors, one placed outside the chamber measuring the ambient air temperature and one placed inside the chamber to measure the heated air temperature within the cavity. To maintain a pre-set temperature differential between the ambient air and the air within the chamber, the controller activated the electric heater located within the chamber. This heater then added sensible heat to the chamber as required to maintain the pre-programmed temperature differential setpoint.

Figure 3-9. Preheated chamber used to supply heated air to bins.

Figure 3-10. Electric heater located inside preheated chamber.

Figure 3-11. Intake vent holes located on the side of the preheat chamber.

Figure 3-12. Temperature control unit.

The differential temperature setpoint was adjusted to provide the required air temperature at the inlet of the aeration fans. This compensated for heat losses occurring from the insulated ducts, which resulted in temperature differentials between the inlet and outlet of the ducting system. The temperature-RH sensor located at the aeration fan intake (**Figure 3-5**, position 6) measured the supplemental heat quality of the air entering the bin.

3.1.4 Verification of Sensors

All load cells and sensors (temperature and RH) were verified prior to loading the wheat. Airflow rates were set and verified after each loading of the wheat and canola.

Tension Load Cell Verification: Verification of the load cells was performed when the bins were empty prior to loading the wheat. Reference weights were placed on top of the bins so that calibration could be performed when the data acquisition equipment was coupled to the load cells.

Temperature and RH Verification: Temperature and RH was verified with a reference temperature/RH instrument (TSI 7545 Indoor Air Quality Meter) when the bins were empty prior to loading the wheat. A heat source was placed down the center of each bin to verify the response of each temperature and RH sensor inside the bin.

Fan Flow Rate Verification: Airflow rates were measured at each fan inlet after the bins were filled with grain. A calibrated, handheld rotating vane anemometer (Omega HHF143 with 2.75 in. diameter probe) was used to measure the velocity of air passing through the inlet opening of the fan. With the probe sealed against the fan opening, the cross-sectional area of the probe was used to determine the airflow rate. The fan rotational speed was adjusted until the desired flow rate was achieved. The desired air flow rate (in L/s per m^3 or cfm/bu) was calculated using the actual weight of the grain (converted to volume in bushels) and the assigned airflow rate target for each bin.

3.1.5 Rewetting of Grain Samples

Tough grain samples are required for the drying trials to simulate the storage and drying of damp grain. Due to dry fall conditions during the local (Humboldt, Saskatchewan, area) wheat harvest in 2018, tough wheat was not available for the trial; therefore, dry wheat was rewetted prior to loading the bins. The moisture content (MC) of the wheat was rewetted from 14.6% to 17.4% over the course of five days.

3.1.6 Loading of Grain and Initial Weights

Prior to loading grain, the data acquisition system was used to log the loads over a ten-minute period. The load data of the empty bins was then averaged and used as the bin tare weight. The MC of grain samples was measured using a Labtronics Model 919 grain moisture meter, Fluke 54 II Thermometer, and a Mettler Toledo MS6002S scale. The test bins are equipped with a bucket elevator that transferred the grain into each bin (**Figure 3-13**.

Figure 3-13. Loading grain into test bins.

In Year 1, Hard Red Spring Wheat (HRSW) was loaded on September 26, 2018, with an initial MC of 17.4%. The mass in each bin was measured, and the starting mass and volume of the grain was calculated by subtracting the tare weight and dividing by the bulk density of the grain (747 kg/m^3 or 60 lb/bu; **Table A-1**). In Year 2, HRSW was loaded into the test bins on November 19, 2019 at 17.7% average moisture content.

In Year 1, Canola was loaded on October 15, 2018, with an initial MC of 13.2%. The mass in each bin was measured, and the starting mass and volume of the grain was calculated by subtracting the tare weight and dividing by the measured bulk density of the grain (664 kg/m^3 or 53 lb/bu). In Year 2, canola was loaded into the test bins on October 26, 2019, at 14.8% average MC.

3.1.7 Assignment of Airflow Rates and Heat to the Bins

To assess the effect of airflow rate on drying efficiency with and without supplemental heat (10°C of added heat), three different target airflow rates were assigned to duplicate bins depending on the grain type in Year 1 (2018). The measured air velocity at the fan inlet was used to calculate actual airflow rates (**Table 3-2** and **Table 3-3**). For the Year 1 wheat trial, fans were set on September 26, 2018. Once the airflow rates were set and verified, the fans ran continuously until October 15, 2018.

Table 3-2. Summary of airflow rates and for Year 1 (2018) stored wheat trial.

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
Inlet Air Conditions	Heated	Ambient	Heated	Heated	Ambient	Ambient
Target airflow rate, L/s per m^3 (cfm/bu)	13.5 (1)	6.8 (0.5)	6.8 (0.5)	3.4 (0.25)	3.4 (0.25)	13.5 (1)
Actual airflow rate at fan[1], L/s per m^3 (cfm/bu)	13.13 (0.97)	6.69 (0.50)	6.62 (0.49)	20.2 (1.50)	20.16 (1.50)	13.37 (0.99)

1 Actual airflow rate measured when fan speeds were set.

As there was no drying occurring in the low-airflow-rate bins during the first two weeks of the trial, the original rate was adjusted to 20.2 L/s per m^3 (1.5 cfm/bu) on October 10, 2018, (day 14) to examine the drying rate of a higher airflow. Hence, the actual airflow rate at the fan reported in **Table 3-2** corresponds to the corrected airflow rate.

For the Year 1 canola trial, fans were set on October 15, 2018. Once the airflow rates were set and verified, the fans ran continuously until October 29, 2018.

Table 3-3. Summary of airflow rates for Year 1 (2018) stored canola trial.

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
Inlet Air Conditions	Heated	Ambient	Heated	Heated	Ambient	Ambient
Target airflow rate, L/s per m^3 (cfm/bu)	13.5 (1)	6.8 (0.5)	6.8 (0.5)	27.0 (2)	27.0 (2)	13.5 (1)
Actual airflow rate at fan, L/s per m^3 (cfm/bu)	12.28 (0.91)	6.90 (0.51)	6.78 (0.50)	28.54 (2.12)	32.00 (2.37)	12.91 (0.96)

For the first 24 hours of the canola trial, the high-airflow-rate bins were closer to 13.5 L/s per m^3 (1 cfm/bu) due to an error in verifying the fan speeds. The fans were adjusted to 27.0 L/s per m^3 (2 cfm/bu) for the remainder of the trial.

For the second year of trials in 2019, the goal was to assess the effect of different temperature increases at a constant airflow rate of 13.5 L/s per m^3 (1 cfm/bu). The target temperature increases were 5°C and 10°C above ambient; ambient air conditions were used as the control treatment. The average actual temperature increase, ΔT, for each treatment is displayed in **Figure 3-14.** The average ΔT for each treatment was 1°C to 2°C higher than the target increase; this is due to the fact the heater was programmed to turn on any time the temperature of the inlet air mass dropped below the target temperature and to compensate for heat loses in the ducting. There were two replicate bins of each treatment for the trial.

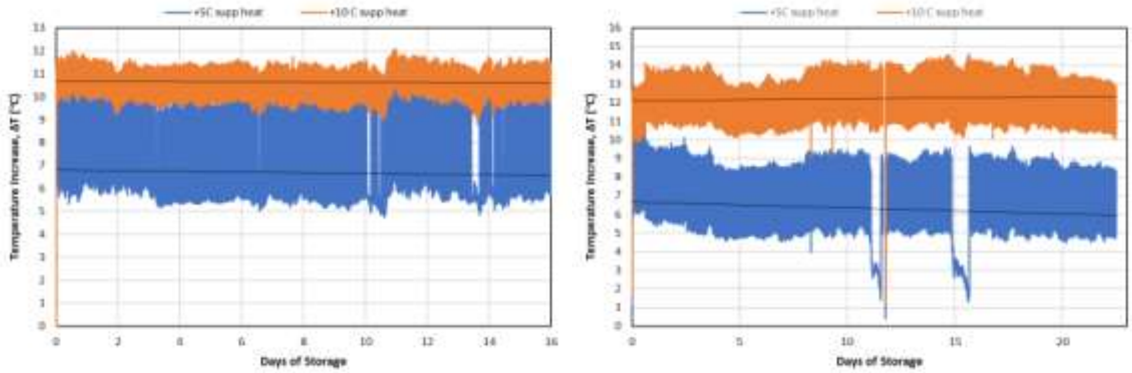

Figure 3-14. Actual average (trendline) temperature increases due to supplemental heat added to ambient air at the plenum inlet for the wheat (left) and canola (right) trials.

3.1.1 Data Acquisition

A Somat eDAQ data acquisition system was used to record data for both grain types over a period of 14 and 19 days for the canola trial and wheat trial, respectively. Data was recorded at one-minute intervals. **Table 3-4** outlines the number and type of sensors used during the monitoring process. The reference temperature and RH sensors were monitoring the conditions inside the heater box to assess the thermal efficiency of the supplemental heat system. A screenshot of the data acquisition interface is shown in **Figure 3-15**.

Table 3-4. Sensors monitored by the data acquisition system.

Parameter	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Total
Load	1	1	1	1	1	1	6
Temperature	6	6	6	6	6	6	36
RH	6	6	6	6	6	6	36
Fan Speed	1	1	1	1	1	1	1
Ref Temperature	0	0	0	0	0	0	1
Ref RH	0	0	0	0	0	0	1
Total recorded data channels							**86**

Figure 3-15. Screenshot of data acquisition interface.

3.1.2 General Observations

For all trials, observations were recorded regarding condensation in the headspace in addition to the number of heater hours over the course of the trial. Heating system efficiency was calculated based on the heat loss between the heat system box and the fan inlet.

3.2 Economic Assessment

An economic assessment of NAD systems with supplemental heating was completed in Year 2 (2019) of this project. Data and information were collected from literature, discussions with producers and technology providers, and the research trials using PAMI's test bins.

A review of technologies included different heating systems and temperature control/feedback systems. The economic analysis included the cost of various heating systems and fuels, as well as the viability of using supplemental heating earlier in the season to expand the harvest window. Another PAMI project, in collaboration with Team Alberta, is currently gathering information on existing on-farm grain drying activities, including supplemental heat systems; unofficial results are discussed in this report. Instructions for how to select and size an appropriate heater were compiled.

4. Results and Discussions

The project results are separated into grain drying sections outlining MC and temperature analysis.

4.1 Grain Drying

Moisture content, grain weights, and grain temperature data from each bin were recorded for the six treatments (three airflow rates and two temperatures). Ambient temperature and humidity data were averaged for the three standard bins at the fan intake as well as for the three bins with supplemental heat.

4.1.1 Moisture Content

Moisture content of the grain was assessed in two ways: continually based on the actual weight of the grain in the bin, and using a moisture meter to intermittently measure the MC of grain samples. Using the temperature and RH data of the grain, the equilibrium moisture content (EMC) was also calculated, which correlates to grain MC. The following discussions are focused on the weight of the grain (based on load cell data), while **Table B-1** through **Table B-8** in **Appendix B** compare the results from each method of MC estimation for each trial in Year 1 to verify the EMC equations.

Based on the average MC of the grain measured at the start of the trial and the initial mass of grain recorded in each bin, the mass of water in each bin at the start of the trial was estimated. Assuming that any change in mass is due to water removal or addition, the average MC in the bin was estimated from the total mass in each bin that was logged throughout the trial. **Figure 4-1** through **Figure 4-4** display the drying rate for each trial completed for this project. The calculated MC for each airflow rate setting is compared to the average EMC of the ambient air through the trial. The moisture of the bin should theoretically trend towards the ambient EMC.

Effect of Airflow Rate on Wheat Moisture Content

Safe storage moisture for all classes of wheat is <14.5%. The rewetted Hard Red Spring Wheat was loaded into the test bins at 17.4% MC in Year 1 (2018).

The grain that received the high airflow rate with added heat treatment was almost dry (14.7%MC) after 19 days (**Figure 4-1**). Drying slowed or ceased entirely (in the case of the low airflow rate applications) in all other bins after two days. The low airflow rate was adjusted from 3.4 L/s per m^3 (0.25 cfm/bu) to 20.3 L/s per m^3(1.5 cfm/bu) on day 14 (October 10, 2018) to observe the drying rate at this level for several days; the MC dropped 0.3% and 1.4% over five days in the nonheated and heated bins, respectively. The final calculated MC was within 5% of the measured sample moisture.

All treatments trended towards the ambient air EMC, with the 13.5 L/s per m^3 (1 cfm/bu) rate with heat reaching the ambient EMC by the end of the trial. While the EMC of the heated air being blown into the bins was much lower than the ambient air, the air conditions in the head space and the temperatures surrounding the bin may have been enough to slow the average drying rate within the bin.

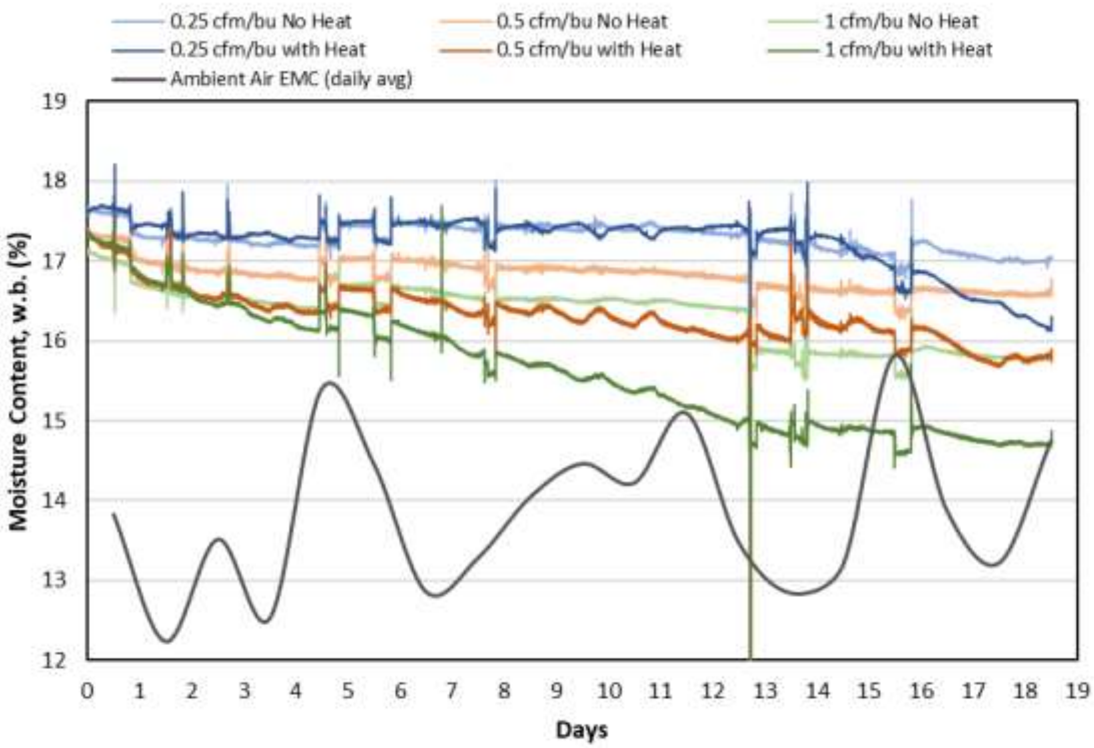

Figure 4-1. Calculated MC (average of entire bin) relative to average daily EMC of ambient air throughout the wheat drying trial in Year 1 (2018).

Red Hard Spring Wheat EMC values were validated for the modified Chung-Pfost model using the bench-scale bin temperature and RH sensor readings, along with the actual MC readings from the Labtronics moisture meter. Four sets of MC samples were taken and compared to corresponding EMC values and the average MC of the bin based on the load cell data. This data is summarized in **Appendix B**, **Table B-1** through **Table B-4**. The modified Chung-Pfost model underestimated all MC when compared to both measured and calculated MC values. In general, the largest deviations between samples and the EMC model occurred when the grain RH was >60%. This was not unexpected since the EMC models assume equilibration between the air and the grain; the grain temperature and RH data were recorded with the fans operating, so the grain MC did not have time to equilibrate to the fluctuating air MC.

Samples were taken at four levels within the bins; **Table 4-1** summarizes the vertical moisture profile in each bin at the end of the wheat drying trial. Over-drying at the bottom of the bin was observed in each bin where heat was added to the inlet airstream.

Table 4-1. Vertical MC profile of wheat in the bins at the end of the drying trial (Year 1).

		Airflow rates, L/s per m^3 (cfm/bu)					
		13.5 (1)		6.8 (0.5)		3.4 (0.25)	
		No heat	Heat	No heat	Heat	No heat	Heat
MC %	Top	16.8	17.5	17.5	18	17.5	18.5
	Middle	17.1	17.1	17.5	18.5	17.3	17.5
	Bottom	16.6	13.8	17.3	18.5	17.1	15.2
	Plenum	16.6	11	15.9	11.3	16.4	12.2
	Average	16.8	14.9	17.1	16.6	17.1	15.9

Effect of Airflow Rate on Canola Moisture Content

Canola is considered dry and safe for storage at a MC <10%. In the Year 1 (2018) trial, the canola was loaded at an MC of 13.2%, which is considered damp (**Table 4-2**).

Table 4-2. Average bin MC (measured and calculated) and days-to-dry for Year 1 (2018) canola drying trial.

			Airflow rates, L/s per m^3 (cfm/bu)					
			27.0 (2)		13.5 (1)		6.8 (0.5)	
			No heat	Heat	No heat	Heat	No heat	Heat
MC (%)	Oct. 15	Measured	13.0	13.1	13.3	13.2	13.2	13.2
	Oct. 29	Calculated	7.6	6.1	10.9	9.2	11.7	11.3
		Measured	7.7	6.4	10.1	9.3	11.4	11.5
	Min.	Calculated	7.6 (Oct 29)	4.6 (Oct 25)	10.9 (Oct 29)	9.2 (Oct 29)	11.7 (Oct 29)	11.3 (Oct 29)
Days to Dry			4.3	3.5	-	7.5	-	-

The bin that was subject to the high airflow rate dried to safe storage conditions almost one day earlier when 10°C of additional heat was used. The 13.5 L/s per m^3 (1 cfm/bu) rate treatment only reached dry conditions when heat was added. The low airflow rate treatments were unable to dry the grain to less than 11% over the course of the trial. This confirms that the airflow rate must be sufficient enough to remove moisture from the bin at the same rate that the moisture is removed from the grain.

All bin moisture measurements trended towards the inlet air EMC for their respective treatments. The heater was turned off after nine days as the high rate treatment was over-dried, and the drying rate for the low airflow treatments had plateaued; rewetting of the over-dried grain was observed once the heaters were turned off and the ambient EMC increased.

Note that days-to-dry is dependant on ambient conditions and cannot be used to estimate the required drying time for all conditions.

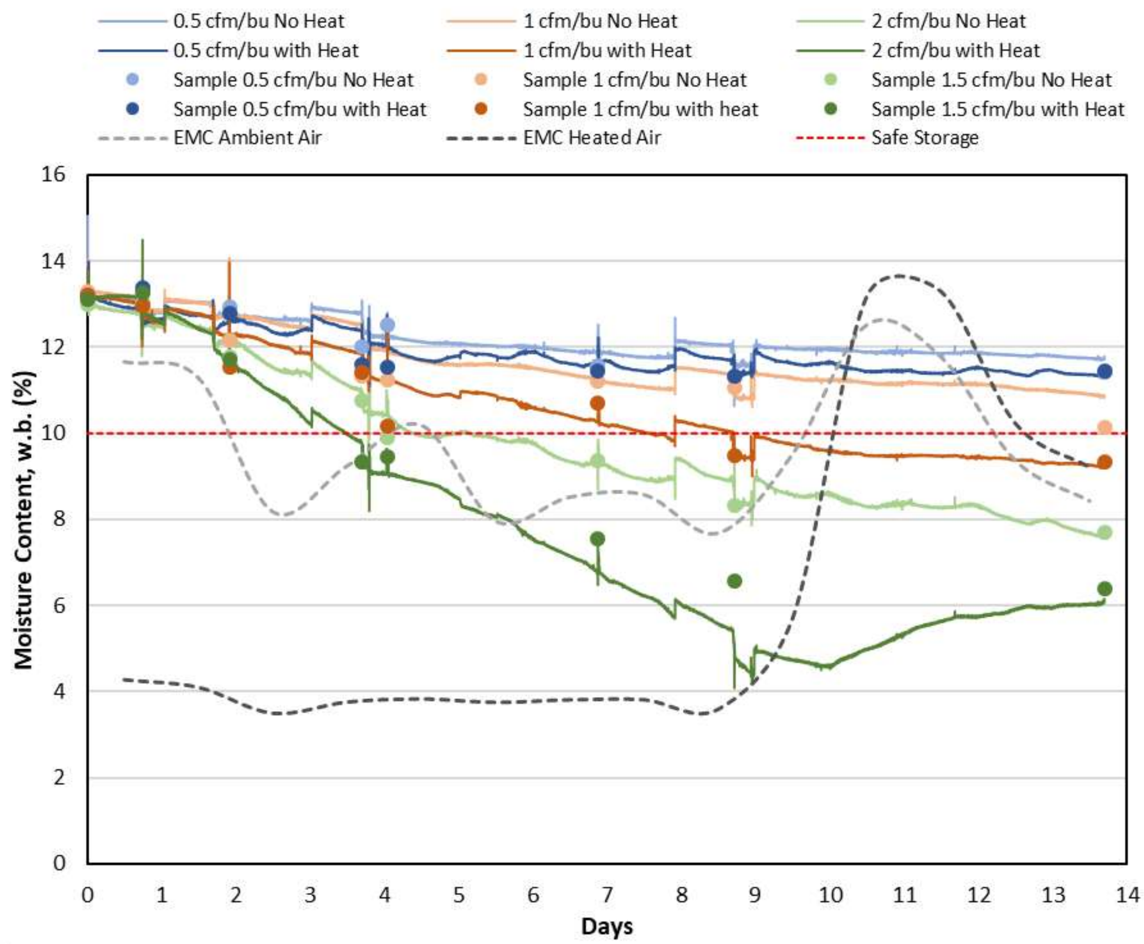

Figure 4-2. Calculated MC (average of entire bin) relative to average daily EMC of ambient air throughout the canola drying trial in Year 1 (2018).

Canola EMC values were validated for the modified Henderson model using the sensor readings and sample measurements. Four sets of MCs were compared in each trial year. This data is summarized in **Table B-5** through **Table B-8**. In general, lower measured grain RH values appeared to correspond with the largest deviations between the predicted EMC values and the measured/calculated grain MC. This was not unexpected since the EMC models assume equilibration between the air and the grain; the grain temperature and RH data were recorded with the fans operating, so the grain MC would not necessarily have had time to equilibrate to the fluctuating air MC.

Samples were taken at four levels within the bins; **Table 4-3** summarizes the vertical moisture profile in each bin at the end of the canola drying trial. Over-drying at the bottom of the bin was observed in all bins; while over-dry throughout, the 27.0 L/s per m^3 (2.0 cfm/bu) achieved a relatively uniform MC. The low- and mid-airflow rates were not sufficient to transport moisture through the grain mass and out of the bin.

Table 4-3. Vertical MC profile of canola in the bins at the end of the drying trial (Year 1).

		Airflow rates, L/s per m^3 (cfm/bu)					
		27.0 (2)		13.5 (1)		6.8 (0.5)	
		No heat	Heat	No heat	Heat	No heat	Heat
MC %	Top	8.3	6.3	12.1	11.3	12.6	12.8
	Middle	7.8	6.3	12.0	11.9	12.5	12.9
	Bottom	7.8	6.3	8.6	6.8	12.4	12.6
	Plenum	6.9	6.7	7.8	7.3	8.2	7.5
	Average	7.7	6.4	10.1	9.3	11.4	11.5

Effect of Temperature Increase on Wheat Moisture Content

The Year 2 (2019) wheat drying trial assessed the effect of temperature increase on drying. The wheat was loaded at an average moisture content of 17.6%; the trial ran for 16 days before being terminated due to very low ambient temperatures. The control (unheated) treatment saw less than half a percent of moisture reduction over the trial, while the 5°C and 10°C treatments saw reductions of 1% and 1.5%, respectively (**Figure 4-3**). None of the treatments saw the grain dried to safe storage conditions (<14.5%) over the two-week trial. Early and prolonged cold climate in the fall of 2019 resulted in slow rates of drying, even with supplemental heat added.

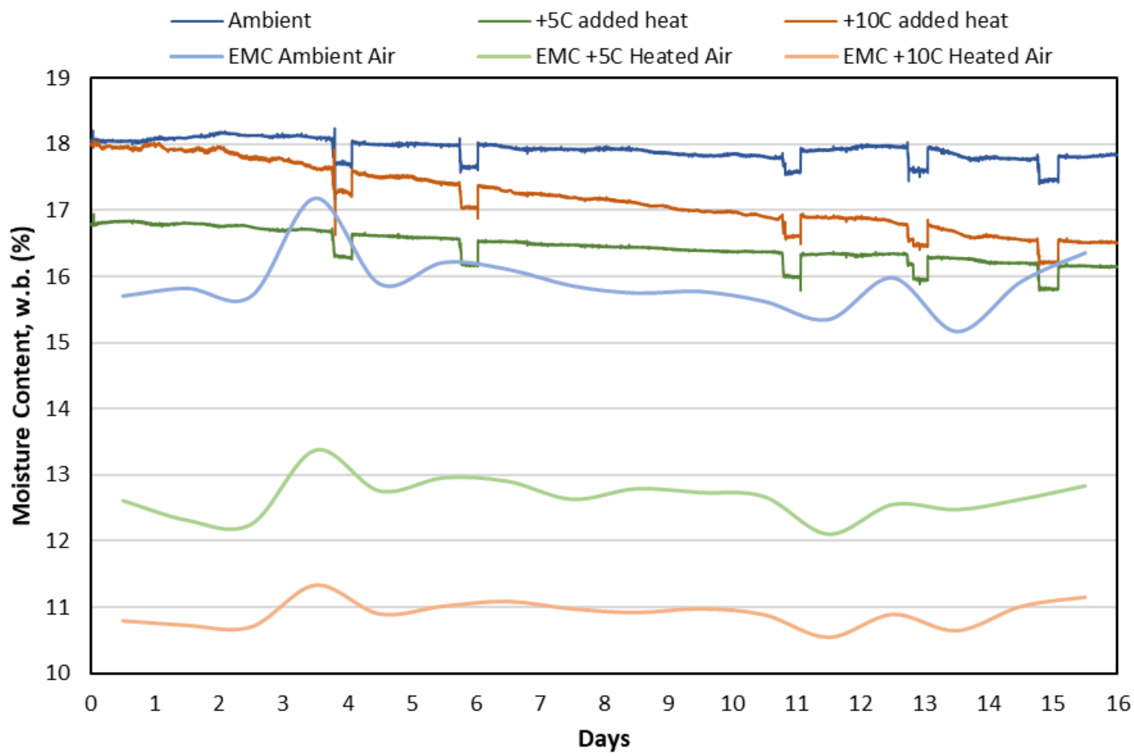

Figure 4-3. Calculated MC (average of entire bin) relative to average daily EMC of inlet airstreams throughout the wheat drying trial in Year 2 (2019).

Samples were taken at four levels within the bins; **Table 4-4**summarizes the vertical moisture profile in each bin at the end of the wheat drying trial in Year 2. Through this, it can be seen that the bottom half of the 10°C heat treatment was actually dry and that the dry front had just not progressed through the entire grain bulk. The trial was stopped at this point due to the limitations of the experiment, but the grain would not be safe to store in this condition; the grain should be turned, mixed, or drying continued until entire grain mass is dried.

Table 4-4. Vertical MC profile of canola in the bins at the end of the drying trial (Year 2).

	No Added Heat	5°C Added Heat	10°C Added Heat
Top	17.1	16.9	19.1
Middle	17.7	16.1	17.0
Bottom	17.6	15.7	14.6
Plenum	17.3	14.9	12.9
Average	17.4	15.9	15.9

A common rule of thumb for NAD with supplemental heat is that for every 10°C increase in temperature, the RH of the inlet air will be halved. When comparing the inlet conditions during the wheat trial in Year 2 (**Figure 4-4**) it was found that the actual change in RH for a 10°C increase is around 57% of the ambient RH which is close to half. A slight deviation from the theoretical relationship is expected due to anticipated efficiency losses in the ducting to the plenum.

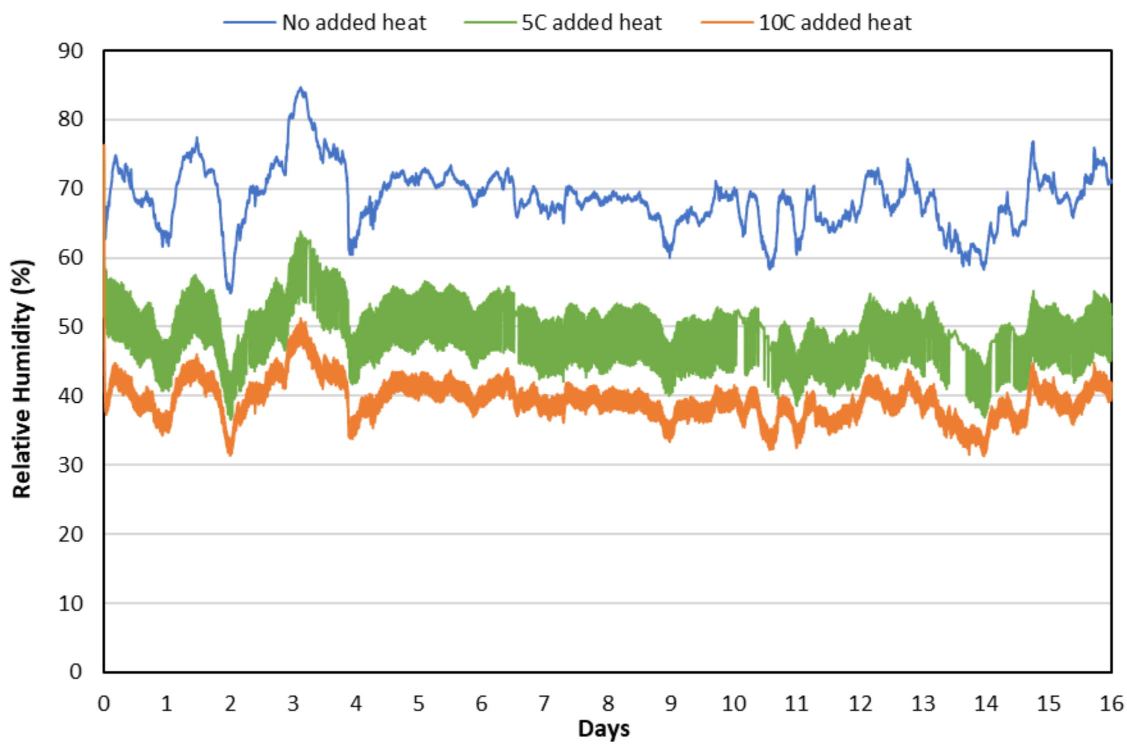

Figure 4-4. Measured RH (replicate average) of inlet air conditions for each supplemental heat treatment for the wheat trial in Year 2.

Effect of Temperature Increase on Canola Moisture Content

In Year 2 (2019), the effect of a temperature increase on drying was assessed. The canola was loaded damp at around 14.5% moisture content. Both heat treatments reduced the moisture content by 3% over the three-week trial (**Figure 4-5**), whereas the control (ambient) treatment only achieved a 1.5% decrease. Safe storage moisture (10%) was not reached for any of the trials; however, based on a drying rate of 1% per week when 5°C to 10°C of heated is added, an additional two weeks of drying would be sufficient to achieve this. Low ambient temperatures over the course of the trial will have attributed to the low drying rate; further discussion in **Section 4.1.2**.

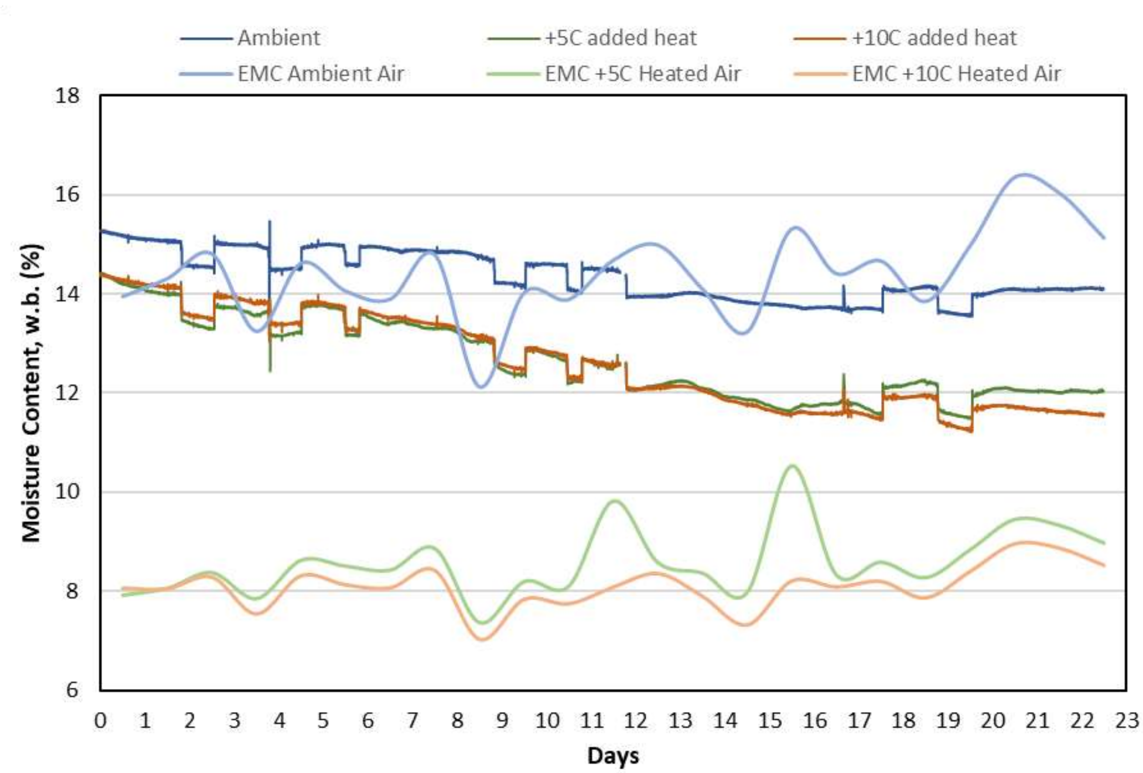

Figure 4-5. Calculated MC (average of entire bin) relative to average daily EMC of inlet airstreams throughout the canola drying trial in Year 2 (2019).

Samples were taken at four levels within the bins; **Table 4-5** summarizes the vertical moisture profile in each bin at the end of the canola drying trial in Year 2. Over-drying at the bottom of the bin was observed in the bins with heated inlet air treatments. In the heated bins, it is also seen that the moisture is being pushed through the grain bulk and had not reached the top by the end of the three-week trial.

Table 4-5. Vertical MC profile of canola in the bins at the end of the drying trial (Year 2).

	No Added Heat	5°C Added Heat	10°C Added Heat
Top	14.1	14.5	14.4
Middle	14.7	16.2	16.5
Bottom	14.7	10.8	10.9
Plenum	11.2	7.7	6.5
Average	13.6	12.3	12.1

When comparing the inlet conditions during the canola trial in Year 2 (**Figure 4-6**) it was found that the actual change in RH for a 10°C increase is around 67% (or two-thirds) of the ambient RH. This difference from the theoretical relationship of 50% is likely due to inefficiency losses in the ducting to the plenum.

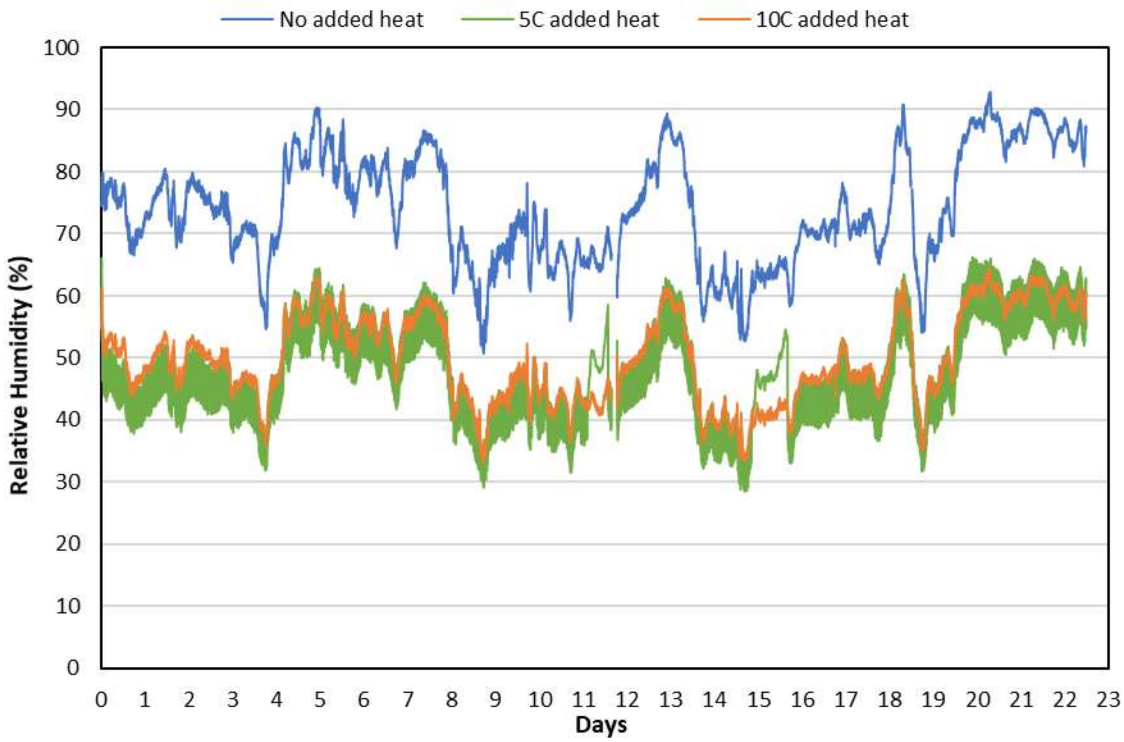

Figure 4-6. Measured RH (replicate average) of inlet air conditions for each supplemental heat treatment for the canola trial in Year 2.

4.1.2 Grain Temperature

Grain temperatures at the top and bottom of the bins were compared to the ambient temperatures outside the bins to determine if there was an effect of airflow rate and added heat on cooling rate. **Table 4-6** and

Table 4-7 summarize the initial and minimum temperatures reached during each trial for wheat and canola, respectively. Graphs of the temperature profiles can be found in the appendix and are discussed here.

Effect of Airflow Rate on Wheat Temperature Profile

Appendix A, Figure A-1 compares the bottom bin temperatures to the ambient temperature for the Year 1 (2018) wheat trial. It shows the treatments with no heat addition, regardless of airflow rate, nearly replicated the ambient inlet air temperature pattern. For the bins with added heat, the temperature trends for the high- and mid-airflow rate treatments followed the inlet air temperature fluctuations with minimal lag; however, the heated air introduced at 3.4 L/s per m^3 (0.25 cfm/bu) into the grain was unable to push the warm air into the grain bulk. Therefore, the temperature range at the bottom of this bin followed closer to the ambient conditions, but with a smoother profile and up to a one-day lag. When the 3.4 L/s per m^3 (0.25 cfm/bu) airflow rate was increased to 20.3 L/s per m^3 (1.5 cfm/bu), the temperature changes within the grain bulk matched the inlet conditions.

Conversely, **Figure A-2** in **Appendix A** compares the top grain temperature and the ambient temperature for the stored wheat. For treatments with no heat addition, decreases in airflow rate resulted in more moderate temperature fluctuations and an increase in lag behind ambient changes. As observed at the bottom of the bin, there was little difference between the temperature trends in the top of the grain bulk for the bins that had heated air added at rates of 6.8, 13.5, and 20.3 L/s per m^3 (0.5, 1.0, and 1.5 cfm/bu); however, the temperature profiles were approximately 5°C lower than the inlet conditions. There was no difference in temperature profile for the low airflow rate settings, regardless of heat addition.

Table 4-6. Summary of initial and final (24-hr average) grain temperatures for Year 1 (2018) wheat trials.

	Bottom of Bin			**Top of Bin**		
Airflow, L/s per m^3 (cfm/bu)	27.0 (2)	13.5 (1)	6.8 (0.5)	27.0 (2)	13.5 (1)	6.8 (0.5)
No Heat Added						
Initial Temperature (°C)	5.1	5.0	5.7	9.5	12.6	13.5
Final Temperature (°C)	-0.2	0.2	0.2	-1.0	0.4	2.3
Minimum Temperature (°C)	-5.2	-3.7	-3.2	-3.1	-0.4	-0.5
Heat Added (+10°C)						
Initial Temperature (°C)	15.1	10.3	11.4	12.0	11.8	13.0
Final Temperature (°C)	13.7	16.9	1.8	4.2	5.1	2.4
Minimum Temperature (°C)	8.7	6.4	-0.2	2.7	2.3	0.7

Effect of Airflow Rate on Canola Temperature Profile

The bottom grain temperatures are compared to the temperature of the inlet air for each treatment in **Appendix A**, **Figure A-3** for the Year 1 (2018) canola drying trial. The grain temperature at the bin for all treatments closely follow the respective inlet air temperature with negligible lag with the daily fluctuations. The daily maximum temperature observed in the low airflow rate bins was approximately 5°C and 10°C lower than the inlet temperature for the ambient and heated air treatments, respectively.

Figure A-4 in **Appendix A** presents the grain temperature at the top of the bin compared to the ambient temperature. The temperatures measured at the top of each bin fell within the daily ambient temperature range, regardless of whether heat was added or not. The lower airflow rates exhibited less severe daily temperature fluctuations. Lags of 0.25, 0.5, and 1 day behind the ambient temperature changes were observed in the bins with ambient temperature airflows at high, mid, and low rates. When heat was added to the inlet air, changes in temperature only lagged 0.25, 0.5, and 0.75 day behind ambient.

Table 4-7. Summary of initial and final (24-hr average) grain temperatures for Year 1 (2018) canola trials.

	Top of Bin			Bottom of Bin		
Airflow, L/s per m^3 (cfm/bu)	27.0 (2)	13.5 (1)	6.8 (0.5)	27.0 (2)	13.5 (1)	6.8 (0.5)
No Heat Added						
Initial Temperature (°C)	2.7	2.6	2.3	4.5	3.0	1.7
Final Temperature (°C)	8.2	3.9	3.6	9.6	7.3	5.6
Minimum Temperature (°C)	-3.3	-4.3	1.2	-1.8	-3.6	-2.9
Heat Added (+10°C)						
Initial Temperature (°C)	4.8	6.3	3.0	7.8	15.2	6.4
Final Temperature (°C)	9.2	3.3	2.9	8.5	6.5	6.5
Minimum Temperature (°C)	0.8	3.8	0.8	1.0	3.4	2.6

Effect of Temperature Increase on Wheat Temperature Profile

The temperature profile (bottom and top) of the grain bulks in Year 2 are displayed in **Figure 4-7**. The heated treatments follow the same temperature fluctuations as the ambient control conditions; however, the temperatures at the top of the bin are half of the treatment additions. Sub-zero temperatures at the top half of the bin during most of the two-week trial explains the slow drying rate described in the previous section.

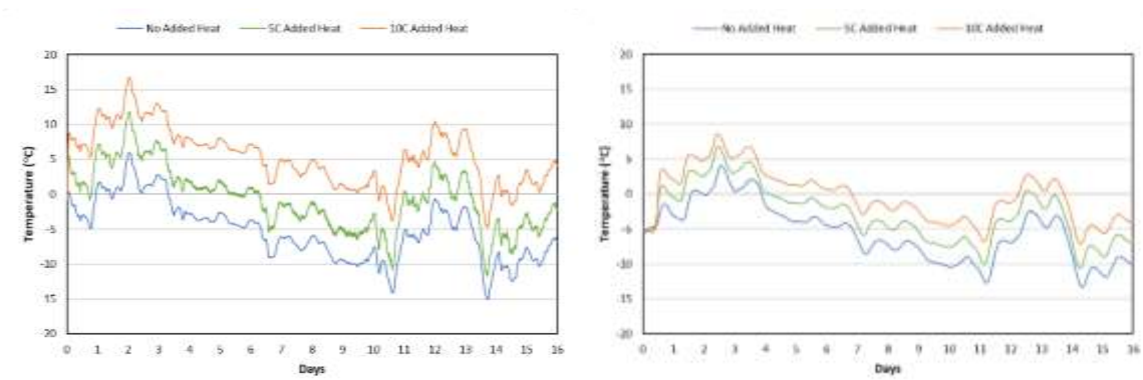

Figure 4-7. Average grain temperatures at bottom (left) and top (right) of the bins throughout the wheat drying trial in Year 2.

Effect of Temperature Increase on Canola Temperature Profile

The temperature profile (bottom and top) of the grain bulks in Year 2 are displayed in **Figure 4-8**. The temperature profile difference at the top of the bins follows the same trend as the bottom inlet temperatures; however, the difference between temperature treatments is approximately half of that at the inlet. Ambient temperatures for the majority of the trial were below 0°C; drying is almost non-existent at these conditions as the grain will freeze and moisture will not travel out of the kernels. By adding 5°C to 10°C of heat, the grain bulk will stay above freezing and allow NAD to continue; however, the temperatures were still below 10°C for most of the trial which would explain the slow drying rates observed in **Figure 4-5**. Risk of spoilage due to high grain temperatures was not a concern during this trial.

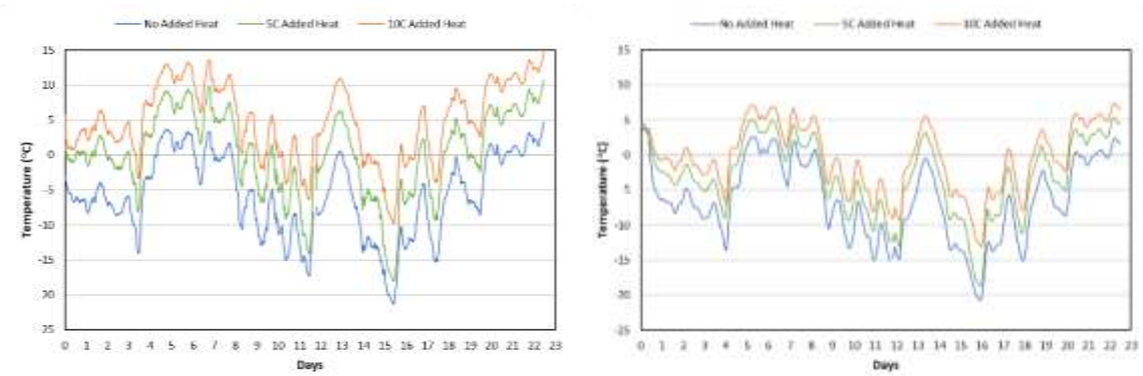

Figure 4-8. Average grain temperatures at bottom (left) and top (right) of the bins throughout the canola drying trial in Year 2.

4.2 Economics

The following section outlines the economic considerations for supplemental heating systems including a thorough technical review of currently available equipment and systems.

4.2.1 Technology Review

The use of supplemental heating with NAD systems is gaining popularity as a lower capital alternative for drying grain in years where the harvest season is late and ambient drying conditions are unfavourable. New technologies are being developed, but there are also a lot of innovative adaptations being implemented by farmers across the prairies. This technology review aims to differentiate different types of systems and highlight some pieces of equipment or systems that are being used (complete list in **Appendix C**).

Indirect vs. Direct-Fired Heating Systems

Indirect heating systems: Fuel is used to heat water then passed through heat exchanger(s).

Direct heating: flame is directly used to heat air.

Combustion of fuels like propane or natural gas does generate water, but the amount of water added to air is negligible compared to the amount of water being removed from the bin. For example, the amount of water added to the air using a propane heater (assuming 10°C increase for 5,000 cfm) is approximately 10 lb/hr. The amount of water being removed from the bin is approximately 120 to 200 lb/hr depending on the rate of drying.

Figure 4-9. Direct fired heater ducted to bin aeration inlet (upstream).
(source: https://saskproship.com/wp/wp-content/uploads/2018/06/Screen-Shot-2018-06-18-at-3.59.49-PM-300x257.png)

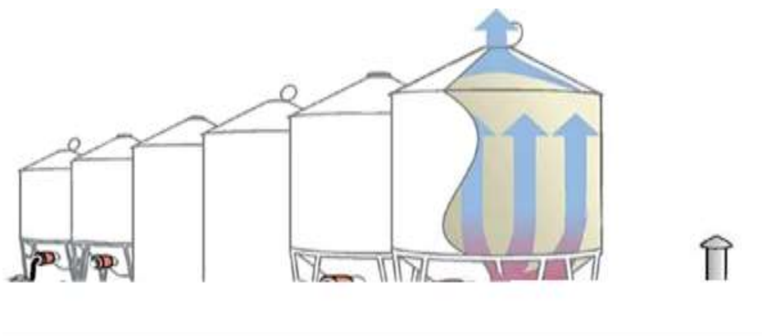

Figure 4-10. Indirect heating using centralized heater and heat transfer fluid.
(source: https://dryair.ca/wp-content/uploads/2014/07/Bin_art_3D_no_list_06050813KAO-592006-9755.jpg)

Upstream vs. Downstream Implementation

The location of the heater relative to the aeration fan differentiates between upstream and downstream heating.

Table 4-8. Pros and cons of upstream and downstream heater installations

Heater Location	Pros	Cons
Upstream	• Easier to implement • Suitable for retrofitting • Can be transferred between bins easily	• Flame can be "pulled in" to the fan/motor and cause damage (i.e., potential fire risk)
Downstream	• Theoretically more energy efficient • Does not expose the motor/blade of fan to increased temperatures	• Not easily transferred between bins

Figure 4-11. Downstream direct-fired heater.
(source: https://static.agcanada.com/wp-content/uploads/sites/4/2017/08/ChadBown_heater.jpg)

Fuel type

Electricity, propane, natural gas, and diesel are the primary fuel types used in existing supplemental heating systems. Propane and natural gas are considered "clean burning" fuels, so they can be used to directly heat the air entering the fan or bin. Diesel should only be used in indirect applications. There are a few novel solar-powered applications in development (**Appendix C**). Biomass-fired units also have the potential to provide a GHG friendly, renewable application for in-bin drying. A case-study of this potential is assessed in **Section 4.2.5**.

Figure 4-12. Diesel flameless (indirect) construction heater.
(source: https://www.hermannelson.com/wp-content/uploads/2016/03/BT375K_quarter.jpg)

Controls/Monitoring

The use of controls can increase the overall efficiency of supplemental heating systems.

4.2.2 Effect of Fuel Type on Cost

The total fuel cost for supplemental heating systems theoretically depends on the specific fuel cost ($/L) and its energy density (GJ/L). The commodity cost per unit will fluctuate from month to month and region to region, but the energy density is constant. If a carbon tax is applied, that will increase the cost per million BTU. The amount of that increase depends on the fuel since each fuel emits a different amount of carbon per L burned.

Table 4-9. Fuel cost scenarios.

Fuel	Fuel Cost* (variable)		Energy Density (fixed)		Fuel Cost (variable)		Fuel Cost (variable)
Diesel	$1.25/L	DIVIDED BY	38.6 MJ/L	EQUALS	$0.032/MJ	X 1056	$34.20 per million BTU
Natural Gas	$0.0998/m^3		37.0 MJ/m^3		$0.0027/MJ		$2.85 per million BTU
Propane	$ 0.60/L		25.3 MJ/L		$0.023 /MJ		$25.04 per million BTU

*SK rates as of January 2020

While natural gas (NG) is a more inexpensive fuel type, the capital cost of bringing in a NG service to a point of use can be significant.

4.2.3 Drying System Efficiencies

The theoretical amount of energy required to evaporate 1 lb of water is approximately 970 BTU (latent heat of vaporization). Past PAMI testing benchmarked the efficiency of heated-air drying systems to be 40% to 55%; this translates to an energy requirement of 1,800 to 2,400 BTU/lb of water removed. A general rule of thumb is that the faster you try and dry grain, the more energy is required to remove that water in the grain. Therefore, supplemental heating systems may be more efficient, up to 75% (1,300 BTU/lb water) under ideal conditions being hypothesized.

Data from PAMI's collaboration project with Team Alberta was still in progress at the completion of this research project. Preliminary results indicate that the observed efficiencies are in the range that was hypothesized. This information will be made publicly available as references for producers once the study is complete.

Based on educated assumptions, scenarios for fuel cost of heated air drying versus NAD with supplemental heat at various operational efficiencies (days to dry) are summarized in **Table 4-10**. The difference in days to dry represents how effectively the management practices are implemented (i.e. ensuring sufficient airflow rates, appropriately sizing heaters, etc…). All scenarios assume 5,000 bu of wheat being dried from 17.5 to 14.5% (removing approx. 2 lb water per bu) with propane costs of $0.65/L.

Table 4-10. Cost of fuel for grain drying scenarios (heated air drying vs. NAD with heat)

Dryer type	Approx. BTU/lb water removed	Theoretical required BTU	Capacity of heat added (BTU/hr)	Propane cost ($/hr)	Required days of operation	Realistic BTU (capacity* hr)	Realistic propane cost ($)
Heated air dryer	2,000	18 million	1.2 million	32	0.5	14.4 million	384
					1	28.8 million	768
NAD + supp heating	1,300	11.7 million	100,000	3	5	12 million	360
					7	16.8 million	504
					14	33.6 million	1,008
					21	50.4 million	1,512

Supplemental heated NAD systems could therefore be comparable in terms of operating fuel costs to that of heated air dryers if managed efficiently. More information for producers will continue to help improve these decision-making processes.

4.2.4 Case Study A: Sizing Heater Systems

Efficient implementation of supplemental heating in NAD systems requires proper sizing of heaters to ensure that the necessary drying rates are achieved.

The size of heater you need depends on two things:

1. The air flow rate (cfm) from your fan, and
2. Your desired temperature increase.

Heater capacity (BTU/hr) = temperature increase (degrees C) x air flow rate (cfm) x 2.05

Example 1: To raise the air temperature by 10°C for a bin/fan that is pushing 5,000 cfm, the required heater capacity is 10 x 5,000 x 2.05 = 102,500 BTU/hr.

Example 2: A 100,000 BTU/hr heater attached to a bin/fan that is pushing 7,500 cfm is expected to provide a temperature increase of 100,000/7,500/2.05 = 6.5°C.

Keep in mind these equations assume a highly efficient heat transfer set-up, meaning all heat generated by the heater ends up in the air. The overall efficiency of some systems may be as low as 50%, so it is important to estimate your required heater size accordingly.

4.2.5 Case Study B: Biomass Systems

A biomass heating system suitable for supplemental heating NAD would be an indirect system (boiler or stove); biomass heat generation is 75% to 80% efficient before losses due to ducting are considered (BERC, 2009). Wood pellets are the most common and most widely accepted biomass fuels as they are a more uniform fuel; off-spec grain could also be used as a fuel as well as other dedicated energy crops or residues. **Table 4-11** summarizes the fuel densities of various biomass fuels and the corresponding cost in $/million BTU; the cost per unit of energy is comparable to diesel and propane (**Table 4-10**). Handling requirements and capacity to house the biofuels will be required.

Table 4-11. Energy density of potential biomass fuels (Government of Manitoba, 2012).

Biomass Fuel	**Energy Density** (GJ/tonne)	**Energy Density** (BTU/lb)	**Cost** ($/million BTU)
Wood Pellets #1	19.1	8,200	17.28
Wheat	20.2	8,700	23.00
Corn	19.8	8,500	27.73
Willow Biomass	18.0	7,739	10.56
Wheat Straw Cubes	17.9	7,713	9.56

* Fuel unit costs are for 2012.

More research on the practicality of these types of systems is required, but the feasibility of biomass as an alternative fuel source for necessary drying may be promising if climate change agendas are increased.

5. Conclusions

This project has generated useful baseline information on the effect of using NAD with supplemental heat on drying rate and grain storage conditions for wheat and canola.

The results from Year 1 (2018) indicate that adding 10°C of heat when ambient conditions are cool and damp will increase the drying rate, as long as the airflow rate is sufficient to move the moisture all the way through the grain bulk. A minimum of 1 cfm/bu is recommended for NAD with supplemental heat. Airflow rate has an impact on drying rate, particularly for wetter grain. Preliminary validation of existing EMC models for wheat and canola indicate that the charts may need to be updated to include the temperature and RH conditions that are experienced when supplemental heat is added.

In Year 2 (2019), it was observed that a 10°C increase in temperature is adequate if that results in a plenum temperature of greater than 5°C. Greater energy requirements (higher temperature increases) would be required if sub-zero ambient conditions are being experienced for prolonged periods of time. The efficiency of this scenario is unknown based on the experimental approach in this project.

Drying rates of 0.5% to 1% per week can be achieved using supplemental heating if properly managed to extend the drying season or to operate in unfavourable conditions. Based on these observed rates of drying for both canola and wheat, supplemental heating with a NAD system may not be suitable for starting grain moisture contents >3% above drying (i.e., damp rather than tough), as increased risk of spoilage is possible. Careful monitoring or reduced grain bed depths can help to mitigate this if a heated-air dryer is not available. Over-drying at the bottom of the bin is expected to occur in almost all currently available bin configurations based on the mode of moisture removal. Development of novel ducting systems may help to overcome this.

Supplemental heating for NAD systems has the potential to be a lower capital alternative to heated air drying in order to extend the drying season; however, based on currently available knowledge (including this research) careful management of this practice is required to keep operating costs comparable to that of a dedicated dryer system.

5.1 General Management Practices

The following is a summary of recommended general management practices when using NAD systems with supplemental heat. These recommendations were compiled based on results of this research project and other expert judgement where specific information is still lacking.

1. For safety and grain quality reasons, only use a CSA-certified heater designed for use with grain storage fans. Follow manufacturer's instructions for installation and operation.
2. Unless an adequate airflow rate can be ensured (minimum 1 cfm/bu), there is a risk of overheating the grain.
   - Low airflow rates may not have enough energy to fully remove moisture from the bin.
3. A plenum temperature of 10°C to 20°C should be targeted; however, limit the air temperature increase to 15°C or less.
   - Higher temperature increases result in high fuel costs, reduced heat transfer efficiency, increased chance of over drying, and increased chance of condensing and freezing at edge of bin.
4. Do not exceed an inlet (after heater) temperature of 30°C.
   - Even though higher temp equals greater drying capacity, you do not want to overheat the grain.
   - Air flow rates of 0.75 to 1 cfm/bu can "keep up" with moderate drying rates, but not with high drying rates associated with high temperatures (>30°C).
5. As much as possible, maintain a **consistent** air temperature flowing to the bin.
   - Thermostatic controllers are becoming more common and will help achieve a consistent temperature being delivered to the bin. This will help minimize day-to-night temperature variations.
6. Since condensation on a cold bin roof can cause moisture problems in the stored grain, ensure adequate ventilation in the headspace.
   - A minimum of 1 sqft of vent space for every 1,000 cfm of airflow is required.
   - Consider the use of "active" ventilation in the headspace to expel moist air more effectively.
7. Consider turning the bottom grain once the average bin moisture is dry to distribute over-dry grain.
8. Ensure that the drying front is pushed through the bin before stopping aeration. As noted in the testing, stopping the NAD with an incomplete cycle can leave grain with localized moisture levels higher than what was originally present in the grain.
9. Grain **must be** cooled to less than 15°C after drying.
   - Cooling will also remove some moisture, so drying may be complete when moisture is within 1% of target.
10. Monitor grain conditions with in-bin cables and/or samples during drying.

5.2 Future Work

The conclusion of this project indicates that there would be value in completing an additional year of study in which the treatments are intended to apply a constant inlet temperature (5°C or 10°C) instead of a constant temperature increase. This could provide insight into the value of using a temperature control system. The efficiency of this approach may differ as the energy input could be higher, but the drying rate may also increase.

Further benchmarking of existing system efficiencies (continuation and dissemination of PAMI/Team Alberta initiatives) is also needed to provide producers with sufficient information to make good management decisions.

6. Extension and Communication Activities

PAMI has presented preliminary results of is project at the following events:

- AgPROVE, Meota, December 2018
- Farm Forum, December 2018
- FarmTech, Edmonton, January 2019
- Agri-Visions, Lloydminster, February 2019
- Crop Connect, Winnipeg, February 2019
- Crop Production Show, Saskatoon, January 2020
- Crop Connect, Winnipeg, February 2020
- Various producer group meetings in January through March 2020

PAMI will continue to present on the topic of NAD with supplemental heat as requested.

A Frequently Asked Questions (FAQ) factsheet was developed on the topic of supplemental heating for NAD systems in 2019 and was updated in 2020. This factsheet is available on PAMI's website and is included as **Appendix D**.

A collaboration between PAMI and Team Alberta is aimed at assessing the techno-economics of grain drying on the Prairies; additional extension documents (factsheets and tools) for producers will be developed through this collaboration for dissemination of best managed practices (BMP)s for supplemental heating that are updated within this research project.

7. References

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Appendix A

Data

Table A-1. Summary of trial starting bin weights and grain volumes.

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
Wheat – Year 1 (2018)						
Empty weight, kg (lb)	77 (170)	77 (169)	76 (168)	76 (167)	77 (171)	77 (169)
Loaded weight, kg (lb)	491 (1083)	499 (1101)	495 (1091)	506 (1116)	490 (1081)	495 (1092)
Weight of grain, kg (lb)	414 (913)	423 (932)	419 (923)	431 (950)	413 (910)	419 (924)
Volume of grain, m^3 (bu)	0.53 (15.2)	0.54 (15.5)	0.54 (15.4)	0.55 (15.8)	0.53 (15.2)	0.54 (15.4)
Wheat – Year 2 (2019)						
Empty weight, kg (lb)	78 (171)	78 (172)	77 (170)	77 (170)	78 (172)	76 (168)
Loaded weight, kg (lb)	489 (1078)	502 (1106)	502 (1107)	500 (1103)	493 (1086)	502 (1106)
Weight of grain, kg (lb)	411 (906)	424 (934)	425 (937)	423 (933)	414 (914)	425 (938)
Volume of grain, m^3 (bu)	0.53 (15.1)	0.54 (15.6)	0.55 (15.6)	0.54 (15.6)	0.53 (15.2)	0.55 (15.6)
Canola – Year 1 (2018)						
Empty weight, kg (lb)	77 (170)	77 (169)	76 (168)	76 (167)	77 (171)	77 (169)
Loaded weight, kg (lb)	416 (917)	421 (927)	425 (937)	425 (936)	419 (923)	425 (937)
Weight of grain, kg (lb)	339 (748)	344 (759)	349 (769)	349 (769)	341 (752)	349 (769)
Volume of grain, m^3 (bu)	0.49 (14.1)	0.50 (14.3)	0.51 (14.4)	0.51 (14.5)	0.49 (14.1)	0.51 (14.4)
Canola – Year 2 (2019)						
Empty weight, kg (lb)	77 (170)	78 (172)	77 (169)	77 (170)	78 (172)	76 (168)
Loaded weight, kg (lb)	422 (931)	420 (926)	419 (924)	428 (944)	416 (917)	418 (922)
Weight of grain, kg (lb)	345 (761)	342 (754)	342 (755)	351 (773)	338 (746)	342 (755)
Volume of grain, m^3 (bu)	0.50 (14.3)	0.50 (14.2)	0.50 (14.2)	0.51 (14.5)	0.49 (14.0	0.50 (14.2)

Table A-2. Average bin MC (measured and calculated) for Year 1 (2018) wheat drying trial (September 26 to October 15, 2018).

			Airflow rates, L/s per m³ (cfm/bu)							
			20.3 (1.5)*		13.5 (1)		6.8 (0.5)		3.4 (0.25)	
			No heat	Heat	No heat	Heat	No heat	Heat	No heat	Heat
MC (%)	Sept. 26	Measured	-	-	17.1	17.3	17.3	17.3	17.6	17.6
	Oct. 10	Calculated	17.3	17.3	15.7	14.8	16.6	16.1	17.3	17.3
		Measured	17.1	17.2	16.4	15.4	16.9	16.4	17.1	17.2
	Oct. 15	Calculated	17.0	16.1	15.7	14.7	16.6	15.8	-	-
		Measured	17.1	15.9	16.8	14.9	17.1	16.6	-	-
	Min.	Calculated	17.0 (Oct 15)	16.1 (Oct 15)	15.7 (Oct 15)	14.7 (Oct 10)	16.6 (Oct 15)	15.7 (Oct 14)	17.3 (Oct 10)	17.3 (Oct 10)

* The low airflow rate (0.25 cfm/bu) was adjusted to 1.5 cfm/bu on October 10, 2018 (day 14).

Table A-3. Average bin MC (measured and calculated) and days-to-dry for Year 1 (2018) canola drying trial.

			Airflow rates, L/s per m³ (cfm/bu)					
			27.0 (2)		13.5 (1)		6.8 (0.5)	
			No heat	Heat	No heat	Heat	No heat	Heat
MC (%)	Oct. 15	Measured	13.0	13.1	13.3	13.2	13.2	13.2
	Oct. 29	Calculated	7.6	6.1	10.9	9.2	11.7	11.3
		Measured	7.7	6.4	10.1	9.3	11.4	11.5
	Min.	Calculated	7.6 (Oct 29)	4.6 (Oct 25)	10.9 (Oct 29)	9.2 (Oct 29)	11.7 (Oct 29)	11.3 (Oct 29)
Days to Dry			4.3	3.5	-	7.5	-	-

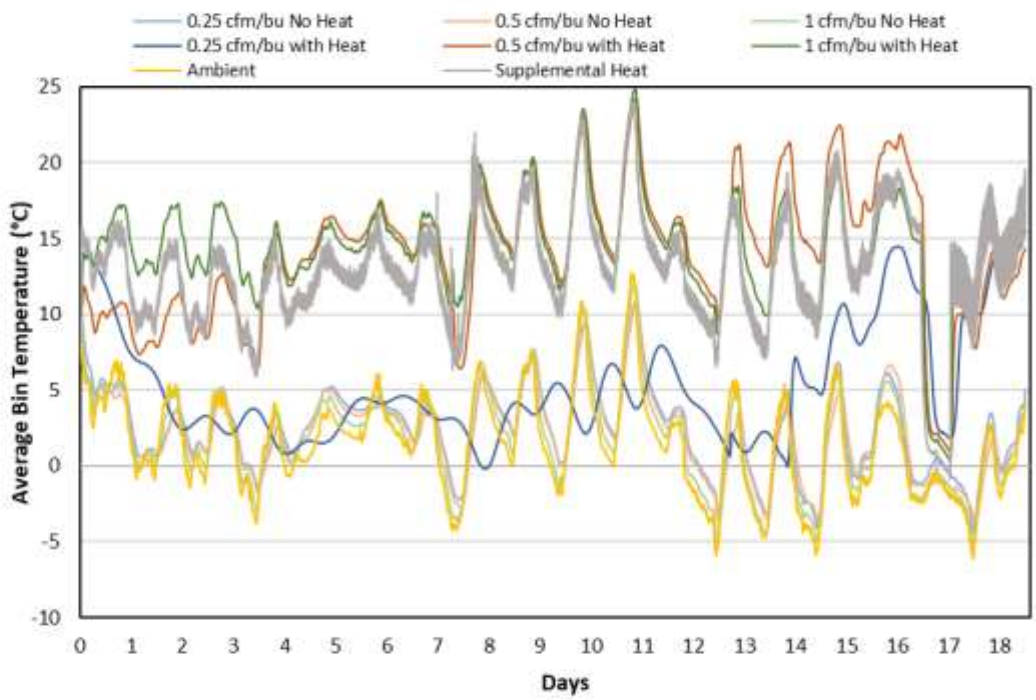

Figure A-1. Ambient temperature compared to grain temperature at the bottom of the bin for the Year 1 wheat drying trial (September 26, to October 15, 2018). On day 14, the low airflow rate was increased to 1.5 cfm/bu.

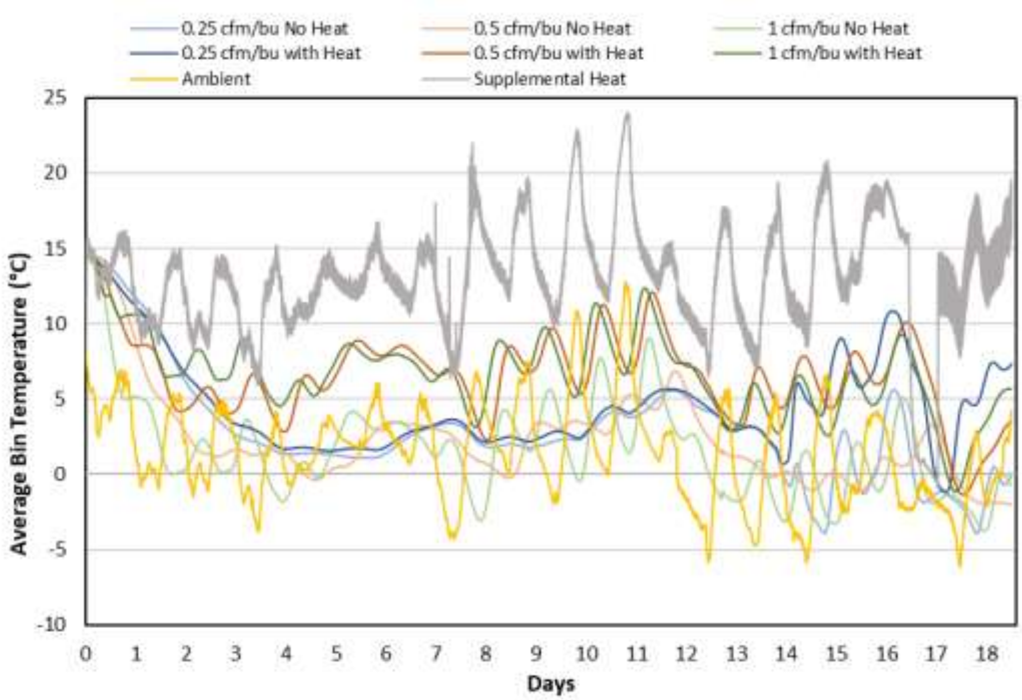

Figure A-2. Ambient temperature compared to grain temperature at the top of the bin for the Year 1 wheat drying trial (September 26, to October 15, 2018). On day 14, the low airflow rate was increased to 1.5 cfm/bu.

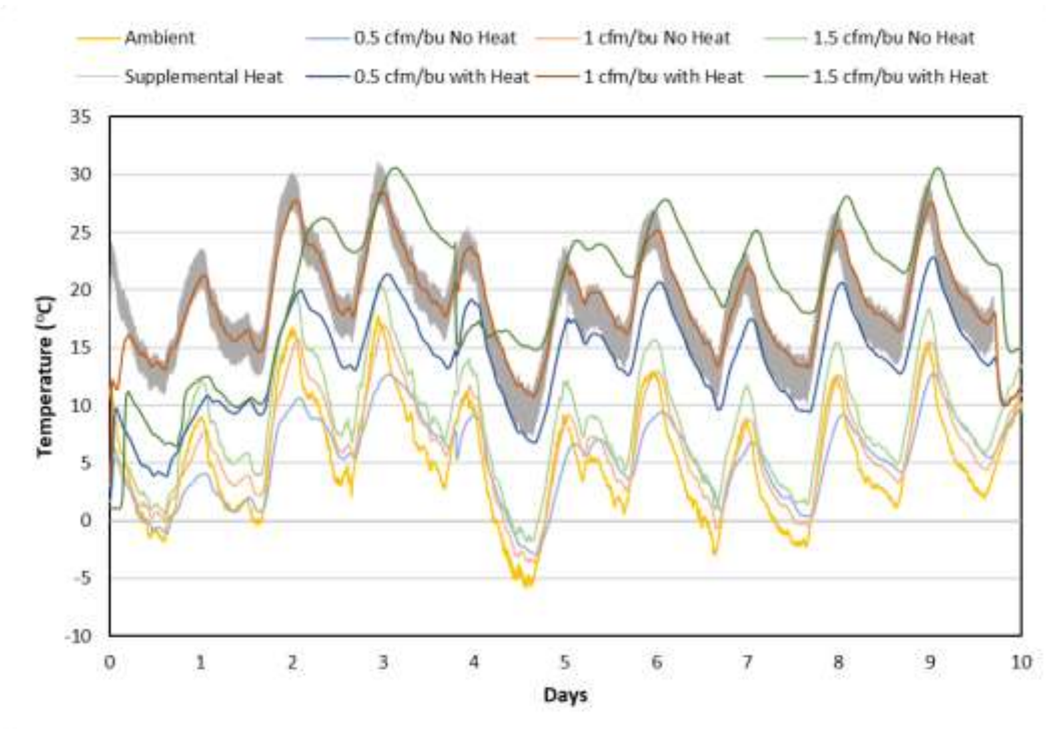

Figure A-3. Ambient temperature compared to grain temperature at the bottom of the bin for the Year 1 canola drying trial (October 15, to 25, 2018).

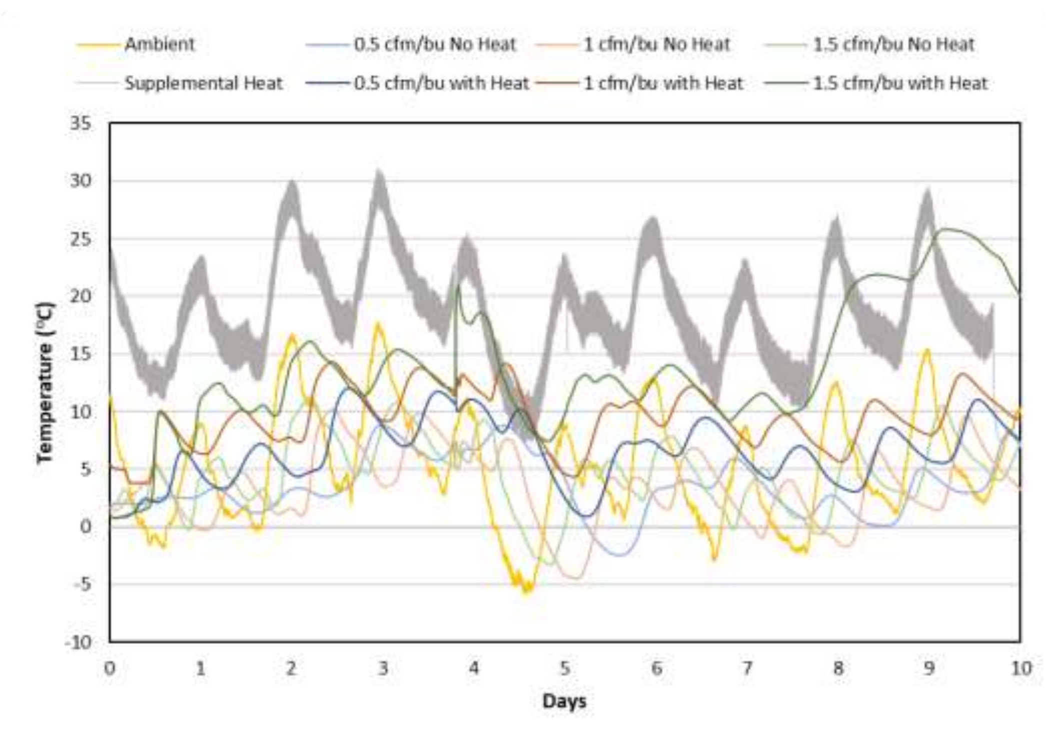

Figure A-4. Ambient temperature compared to grain temperature at the top of the bin for the Year 1 canola drying trial (October 15, to 25, 2018).

Appendix B

Equilibrium Moisture Content Verification

Year 1 (2018) Wheat Trial

Table B-1. September 28, 2018 - RHSW EMC and actual MC (measured and calculated).

09/28/18		Bin Sensors - Modified Chung-Pfost[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	6.15	77.62	20.54	17.04			Dry Weight
	2	6.72	69.93	18.28	15.45	16.60	-1.15	755.60
	3	6.46	71.97	18.83	15.85	17.70	-1.85	Wet Weight
	4	6.84	72.62	18.99	15.96	18.50	-2.54	908.36
	5	13.94	24.83	9.07	8.32	14.20	-5.88	**MC (%)**
	6	10.38	29.38	10.12	9.19			16.82
Bin 2	1	5.12	78.97	21.06	17.39			Dry Weight
	2	4.80	71.45	18.80	15.83	17.80	-1.97	769.95
	3	3.58	70.23	18.56	15.65	18.20	-2.55	Wet Weight
	4	0.03	70.01	18.74	15.78	17.80	-2.02	928.27
	5	0.79	64.18	17.29	14.74	16.70	-1.96	**MC (%)**
	6	2.11	38.23	12.21	10.88			17.06
Bin 3	1	5.27	84.91	23.41	18.97			Dry Weight
	2	6.60	71.89	18.80	15.83	17.70	-1.87	762.53
	3	6.31	70.01	18.32	15.49	17.40	-1.91	Wet Weight
	4	4.41	52.97	14.73	12.84	17.40	-4.56	916.71
	5	8.26	44.14	12.85	11.39	15.70	-4.31	**MC (%)**
	6	11.14	28.30	9.88	8.99			16.82
Bin 4	1	5.12	84.23	23.11	18.77			Dry Weight
	2	9.00	74.92	19.51	16.33	17.70	-1.37	782.76
	3	7.53	73.23	19.11	16.05	17.90	-1.85	Wet Weight
	4	3.96	53.34	14.83	12.91	18.00	-5.09	948.57
	5	5.41	72.41	19.02	15.98	17.50	-1.52	**MC (%)**
	6	13.03	26.91	9.51	8.68			17.48
Bin 5	1	6.04	83.84	22.88	18.62			Dry Weight
	2	9.14	73.36	19.05	16.00	18.20	-2.20	749.19
	3	5.44	71.86	18.87	15.87	18.20	-2.33	Wet Weight
	4	3.14	69.03	18.28	15.46	17.80	-2.34	906.84
	5	1.00	61.05	16.58	14.23	17.00	-2.77	**MC (%)**
	6	1.65	52.69	14.86	12.94			17.39
Bin 6	1	3.07	68.28	18.10	15.33			Dry Weight
	2	1.05	64.61	17.37	14.80	17.70	-2.90	765.23
	3	-0.19	66.48	17.89	15.17	17.10	-1.93	Wet Weight
	4	-0.31	71.16	19.07	16.01	17.80	-1.79	918.69
	5	1.07	58.09	15.96	13.76	16.60	-2.84	**MC (%)**
	6	1.86	50.51	14.43	12.61			16.70
Bin MC Averages	Bin 1				13.63	16.75		16.82
	Bin 2				15.05	17.63		17.06
	Bin 3				13.92	17.05		16.82
	Bin 4				14.79	17.78		17.48
	Bin 5				15.52	17.80		17.39
	Bin 6				14.61	17.30		16.70

[1]Sample time unknown, therefore, temperature and RH data averaged over morning (8:00 a.m. - 12:00 p.m.)

Table B-2. September 29, 2018 - RHSW EMC and actual MC (measured and calculated).

09/29/18		Bin Sensors - Modified Chung-Pfost[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	5.75	73.92	19.43	16.27			Dry Weight
	2	6.30	71.18	18.63	15.70	17.40	-1.70	755.60
	3	9.25	68.60	17.78	15.10	17.80	-2.70	Wet Weight
	4	7.03	74.12	19.40	16.25	18.10	-1.85	905.24
	5	17.20	25.25	8.96	8.22	12.80	-4.58	**MC (%)**
	6	12.44	36.63	11.27	10.13			16.53
Bin 2	1	2.72	65.76	17.52	14.91			Dry Weight
	2	1.32	70.49	18.78	15.81	17.60	-1.79	769.95
	3	1.00	69.77	18.61	15.69	17.80	-2.11	Wet Weight
	4	0.18	70.94	18.98	15.95	17.40	-1.45	926.86
	5	4.90	62.94	16.73	14.33	16.20	-1.87	**MC (%)**
	6	4.42	46.63	13.55	11.93			16.93
Bin 3	1	4.05	74.16	19.61	16.39			Dry Weight
	2	4.32	72.56	19.13	16.06	17.40	-1.34	762.53
	3	3.38	69.39	18.36	15.51	17.20	-1.69	Wet Weight
	4	4.51	53.94	14.91	12.97	17.20	-4.23	914.73
	5	12.51	39.69	11.80	10.56	14.60	-4.04	**MC (%)**
	6	13.39	34.62	10.86	9.79			16.64
Bin 4	1	5.25	73.61	19.37	16.23			Dry Weight
	2	3.88	72.89	19.26	16.15	17.60	-1.45	782.76
	3	2.59	71.84	19.05	16.00	17.60	-1.60	Wet Weight
	4	7.76	51.71	14.27	12.49	17.60	-5.11	947.11
	5	2.44	72.07	19.13	16.06	16.70	-0.64	**MC (%)**
	6	15.33	30.66	10.04	9.13			17.35
Bin 5	1	5.65	72.51	19.03	15.99			Dry Weight
	2	3.24	70.05	18.54	15.64	17.60	-1.96	749.19
	3	0.79	70.73	18.88	15.88	17.60	-1.72	Wet Weight
	4	0.65	68.93	18.43	15.56	17.40	-1.84	906.27
	5	4.88	61.24	16.36	14.06	16.70	-2.64	**MC (%)**
	6	4.16	62.38	16.66	14.28			17.33
Bin 6	1	2.25	61.38	16.57	14.21			Dry Weight
	2	0.17	65.35	17.60	14.96	17.40	-2.44	765.23
	3	0.16	68.38	18.32	15.49	17.40	-1.91	Wet Weight
	4	2.51	74.14	19.70	16.46	17.40	-0.94	917.55
	5	4.88	60.00	16.10	13.87	16.00	-2.13	**MC (%)**
	6	4.45	60.09	16.15	13.90			16.60
Bin MC Averages	Bin 1				13.61	16.53		16.53
	Bin 2				14.77	17.25		16.93
	Bin 3				13.55	16.60		16.64
	Bin 4				14.34	17.38		17.35
	Bin 5				15.24	17.33		17.33
	Bin 6				14.82	17.05		16.60

[1]Sample time unknown, therefore, temperature and RH data averaged over the afternoon (1:00 p.m. - 5:00 p.m.)

Table B-3. October 2, 2018 - RHSW EMC and actual MC (measured and calculated).

10/02/18		Bin Sensors - Modified Chung-Pfost[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	7.10	78.37	20.72	17.17			Dry Weight
	2	7.96	73.70	19.22	16.12	18.00	-1.88	755.60
	3	11.80	42.77	12.39	11.02	18.50	-7.48	Wet Weight
	4	8.14	72.72	18.93	15.92	17.10	-1.18	900.60
	5	14.59	31.61	10.26	9.30	12.40	-3.10	**MC (%)**
	6	10.06	47.96	13.43	11.84			16.10
Bin 2	1	1.76	67.53	18.00	15.26			Dry Weight
	2	1.81	71.04	18.89	15.89	17.80	-1.91	769.95
	3	3.52	72.17	19.08	16.02	17.80	-1.78	Wet Weight
	4	2.91	71.46	18.93	15.92	17.80	-1.88	925.85
	5	3.44	69.04	18.26	15.44	16.10	-0.66	**MC (%)**
	6	2.36	59.10	16.08	13.85			16.84
Bin 3	1	4.20	80.52	21.67	17.81			Dry Weight
	2	8.70	77.02	20.18	16.79	17.50	-0.71	762.53
	3	5.11	70.99	18.66	15.72	17.50	-1.78	Wet Weight
	4	8.51	56.71	15.19	13.19	18.00	-4.81	912.41
	5	15.24	33.60	10.57	9.56	13.60	-4.04	**MC (%)**
	6	16.18	31.34	10.12	9.19			16.43
Bin 4	1	2.66	70.73	18.75	15.79			Dry Weight
	2	1.71	72.21	19.21	16.12	18.90	-2.78	782.76
	3	1.79	72.38	19.25	16.15	17.80	-1.65	Wet Weight
	4	6.86	54.95	14.95	13.01	17.80	-4.79	946.75
	5	4.45	74.66	19.73	16.48	16.60	-0.12	**MC (%)**
	6	12.95	38.35	11.54	10.34			17.32
Bin 5	1	2.76	69.11	18.33	15.49			Dry Weight
	2	1.11	68.71	18.34	15.50	17.80	-2.30	749.19
	3	0.44	71.13	19.01	15.97	18.00	-2.03	Wet Weight
	4	3.15	71.46	18.91	15.91	17.80	-1.89	905.89
	5	3.74	65.96	17.50	14.89	16.60	-1.71	**MC (%)**
	6	2.25	76.48	20.43	16.96			17.30
Bin 6	1	3.62	69.92	18.48	15.60			Dry Weight
	2	3.61	67.12	17.78	15.10	17.30	-2.20	765.23
	3	2.85	69.56	18.44	15.57	17.50	-1.93	Wet Weight
	4	3.13	66.68	17.71	15.04	17.50	-2.46	916.63
	5	2.82	72.68	19.27	16.16	16.80	-0.64	**MC (%)**
	6	2.42	74.54	19.83	16.55			16.52
Bin MC Averages	Bin 1				13.56	16.50		16.10
	Bin 2				15.40	17.38		16.84
	Bin 3				13.71	16.65		16.43
	Bin 4				14.65	17.78		17.32
	Bin 5				15.79	17.55		17.30
	Bin 6				15.67	17.28		16.52

[1]Sample time unknown, therefore, temperature and RH data averaged over morning (8:00 a.m. - 12:00 p.m.)

Table B-4. October 9, 2018 - RHSW EMC and actual MC (measured and calculated).

10/09/18		Bin Sensors - Modified Chung-Pfost[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	7.82	51.77	14.28	12.49			Dry Weight
	2	3.57	72.15	19.07	16.02	17.90	-1.88	755.60
	3	8.83	32.88	10.83	9.78	15.60	-5.82	Wet Weight
	4	6.05	49.33	13.94	12.23	13.30	-1.07	885.29
	5	17.39	13.68	6.57	6.17	11.20	-5.03	**MC (%)**
	6	16.25	12.53	6.36	5.98			14.65
Bin 2	1	2.73	59.77	16.20	13.94			Dry Weight
	2	1.44	70.16	18.68	15.74	17.50	-1.76	769.95
	3	0.22	69.09	18.50	15.61	17.20	-1.59	Wet Weight
	4	-1.57	66.39	17.96	15.23	16.50	-1.27	921.02
	5	1.57	61.47	16.63	14.26	15.40	-1.14	**MC (%)**
	6	4.78	22.26	9.16	8.39			16.40
Bin 3	1	7.45	59.91	15.92	13.73			Dry Weight
	2	4.05	76.78	20.40	16.94	17.20	-0.26	762.53
	3	5.09	63.08	16.75	14.35	17.50	-3.15	Wet Weight
	4	4.47	45.32	13.31	11.74	16.30	-4.56	906.25
	5	18.23	17.86	7.45	6.93	11.50	-4.57	**MC (%)**
	6	17.80	11.46	6.00	5.66			15.86
Bin 4	1	4.17	65.41	17.34	14.78			Dry Weight
	2	3.31	73.79	19.55	16.35	17.50	-1.15	782.76
	3	3.41	73.47	19.45	16.28	17.20	-0.92	Wet Weight
	4	6.17	40.47	12.34	10.98	17.50	-6.52	943.42
	5	1.59	72.47	19.29	16.17	14.90	1.27	**MC (%)**
	6	16.15	15.84	7.14	6.66			17.03
Bin 5	1	5.09	57.39	15.55	13.46			Dry Weight
	2	3.26	70.27	18.59	15.68	17.70	-2.02	749.19
	3	2.15	71.04	18.87	15.87	17.00	-1.13	Wet Weight
	4	0.44	69.92	18.69	15.75	16.10	-0.35	903.00
	5	1.65	55.98	15.50	13.42	16.30	-2.88	**MC (%)**
	6	4.67	30.26	10.64	9.62			17.03
Bin 6	1	2.33	54.05	15.07	13.10			Dry Weight
	2	-1.39	65.48	17.74	15.06	17.00	-1.94	765.23
	3	-2.28	62.44	17.11	14.61	16.50	-1.89	Wet Weight
	4	-2.41	63.93	17.45	14.86	15.80	-0.94	906.44
	5	3.63	41.90	12.76	11.31	16.10	-4.79	**MC (%)**
	6	4.90	28.34	10.28	9.32			15.58
Bin MC Averages	Bin 1				10.44	14.50		14.65
	Bin 2				13.86	16.65		16.40
	Bin 3				11.56	15.63		15.86
	Bin 4				13.54	16.78		17.03
	Bin 5				13.96	16.78		17.03
	Bin 6				13.04	16.35		15.58

[1]Sample time unknown, therefore, temperature and RH data averaged over the afternoon (1:00 p.m. - 5:00 a.m.)

Year 1 (2018) Canola Trial

Table B-5. October 16, 2018 - Canola EMC and actual MC (measured and calculated).

10/16/18		Bin Sensors - Modified Henderson[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	6.83	87.87	17.42	14.84			Dry Weight
	2	8.19	81.59	14.87	12.94	13.10	-0.16	648.87
	3	6.32	82.49	15.53	13.44	13.40	0.04	Wet Weight
	4	6.97	82.41	15.37	13.32	13.40	-0.08	744.44
	5	16.00	27.00	4.63	4.42	12.00	-7.58	**MC (%)**
	6	15.28	30.47	5.12	4.87			12.84
Bin 2	1	2.70	82.69	16.42	14.11			Dry Weight
	2	2.57	81.86	16.18	13.92	13.20	0.72	658.58
	3	3.54	82.78	16.25	13.98	13.40	0.58	Wet Weight
	4	0.29	83.45	17.32	14.76	13.20	1.56	756.55
	5	1.23	88.22	19.06	16.01	13.40	2.61	**MC (%)**
	6	2.69	54.81	9.92	9.02			12.95
Bin 3	1	2.06	87.19	18.34	15.50			Dry Weight
	2	5.61	84.88	16.51	14.17	13.30	0.87	667.23
	3	1.83	79.23	15.52	13.43	13.60	-0.17	Wet Weight
	4	3.85	61.69	11.00	9.91	13.20	-3.29	764.58
	5	6.26	76.41	13.79	12.12	13.40	-1.28	**MC (%)**
	6	11.77	38.77	6.46	6.07			12.73
Bin 4	1	7.08	89.36	18.04	15.28			Dry Weight
	2	7.65	83.96	15.74	13.60	13.40	0.20	668.25
	3	6.74	83.14	15.66	13.54	14.00	-0.46	Wet Weight
	4	18.48	25.02	4.26	4.08	13.60	-9.52	767.61
	5	7.54	84.35	15.90	13.72	12.10	1.62	**MC (%)**
	6	21.69	18.78	3.34	3.24			12.94
Bin 5	1	3.17	83.85	16.72	14.32			Dry Weight
	2	1.55	82.33	16.59	14.23	13.00	1.23	654.62
	3	-0.38	82.21	17.05	14.57	13.20	1.37	Wet Weight
	4	0.30	83.83	17.46	14.86	13.10	1.76	749.42
	5	4.65	65.64	11.64	10.43	12.80	-2.37	**MC (%)**
	6	2.46	71.39	13.29	11.73			12.65
Bin 6	1	3.55	86.92	17.82	15.13			Dry Weight
	2	2.04	80.49	15.86	13.69	13.20	0.49	666.41
	3	0.18	80.89	16.45	14.13	13.30	0.83	Wet Weight
	4	-0.21	83.30	17.40	14.82	13.10	1.72	765.97
	5	2.95	72.22	13.40	11.81	12.50	-0.69	**MC (%)**
	6	2.55	No Data[2]	-	-			13.00
Bin MC Averages	Bin 1				10.64	12.98		12.84
	Bin 2				13.63	13.30		12.95
	Bin 3				11.87	13.38		12.73
	Bin 4				10.58	13.28		12.94
	Bin 5				13.36	13.03		12.65
	Bin 6				13.91	13.03		13.00

[1]Sample time unknown, therefore, temperature and RH data averaged over morning (8:00 a.m. - 12:00 p.m.)

[2]No data due to bad sensor

Table B-6. October 19, 2018 - Canola EMC and actual MC (measured and calculated).

10/19/18		Bin Sensors - Modified Henderson[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	10.46	94.19	20.10	16.74			Dry Weight
	2	11.89	82.59	14.48	12.65	13.00	-0.35	648.87
	3	9.80	82.17	14.74	12.84	13.70	-0.86	Wet Weight
	4	10.67	83.10	14.86	12.94	13.50	-0.56	733.64
	5	18.78	24.28	4.15	3.98	5.50	-1.52	MC (%)
	6	17.86	29.03	4.79	4.57			11.55
Bin 2	1	7.10	82.91	15.50	13.42			Dry Weight
	2	6.57	82.11	15.35	13.31	13.10	0.21	658.58
	3	8.99	83.08	15.18	13.18	13.20	-0.02	Wet Weight
	4	5.54	84.18	16.28	14.00	13.00	1.00	752.86
	5	6.80	54.03	9.23	8.45	8.80	-0.35	MC (%)
	6	5.38	52.28	9.12	8.36			12.52
Bin 3	1	8.29	91.78	19.03	15.99			Dry Weight
	2	11.19	84.59	15.25	13.23	13.10	0.13	667.23
	3	8.47	79.63	14.24	12.47	13.40	-0.93	Wet Weight
	4	8.37	62.49	10.48	9.48	13.30	-3.82	759.46
	5	13.61	35.76	5.91	5.58	6.60	-1.02	MC (%)
	6	14.36	37.43	6.08	5.73			12.14
Bin 4	1	11.18	90.42	17.62	14.98			Dry Weight
	2	12.03	84.74	15.14	13.15	13.50	-0.35	668.25
	3	16.88	40.44	6.30	5.92	12.80	-6.88	Wet Weight
	4	23.73	18.34	3.22	3.12	5.50	-2.38	738.03
	5	23.93	16.39	2.97	2.89	5.50	-2.61	MC (%)
	6	24.79	16.94	3.01	2.93			9.45
Bin 5	1	5.80	82.45	15.63	13.52			Dry Weight
	2	5.52	84.29	16.32	14.03	12.40	1.63	654.62
	3	4.61	83.69	16.32	14.03	12.40	1.63	Wet Weight
	4	8.74	45.97	7.75	7.19	11.50	-4.31	733.07
	5	8.66	55.87	9.30	8.51	6.70	1.81	MC (%)
	6	4.92	69.50	12.41	11.04			10.70
Bin 6	1	7.47	88.67	17.62	14.98			Dry Weight
	2	7.17	81.10	14.92	12.98	12.90	0.08	666.41
	3	5.30	81.81	15.53	13.44	12.80	0.64	Wet Weight
	4	4.03	83.62	16.43	14.11	12.60	1.51	759.32
	5	6.58	58.42	10.00	9.09	7.00	2.09	MC (%)
	6	5.09	No Data[2]	-	-			12.24
Bin MC Averages	Bin 1				10.62	11.43		11.55
	Bin 2				11.79	12.03		12.52
	Bin 3				10.41	11.60		12.14
	Bin 4				7.16	9.33		9.45
	Bin 5				11.39	10.75		10.70
	Bin 6				12.92	11.33		12.24

[1]Sample time unknown, therefore, temperature and RH data averaged over morning (8:00 a.m. - 12:00 p.m.)

[2]No data due to bad sensor

Table B-7. October 22, 2018 - Canola EMC and actual MC (measured and calculated).

10/22/18		Bin Sensors - Modified Henderson[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	8.44	78.19	13.86	12.17			Dry Weight
	2	7.82	76.44	13.51	11.90	10.10	1.80	648.87
	3	11.33	50.83	8.21	7.59	13.40	-5.81	Wet Weight
	4	7.07	82.68	15.43	13.37	13.80	-0.43	722.99
	5	20.77	14.66	2.84	2.76	5.50	-2.74	MC (%)
	6	19.45	16.16	3.08	2.99			10.25
Bin 2	1	6.68	71.61	12.57	11.16			Dry Weight
	2	5.59	81.86	15.48	13.41	12.90	0.51	658.58
	3	2.49	81.90	16.21	13.95	12.90	1.05	Wet Weight
	4	-0.89	83.05	17.50	14.89	13.00	1.89	747.73
	5	5.66	54.41	9.44	8.62	7.50	1.12	MC (%)
	6	7.41	29.83	5.55	5.26			11.92
Bin 3	1	8.31	86.67	16.59	14.23			Dry Weight
	2	6.31	84.21	16.11	13.88	13.10	0.78	667.23
	3	8.17	80.47	14.54	12.69	13.10	-0.41	Wet Weight
	4	4.12	62.29	11.07	9.97	13.50	-3.53	755.68
	5	15.96	25.04	4.38	4.20	6.10	-1.90	MC (%)
	6	15.50	22.67	4.09	3.93			11.70
Bin 4	1	10.90	70.95	11.76	10.52			Dry Weight
	2	10.24	79.77	13.96	12.25	10.10	2.15	668.25
	3	20.71	19.07	3.42	3.30	9.10	-5.80	Wet Weight
	4	25.57	10.70	2.18	2.14	5.50	-3.36	716.50
	5	22.83	15.59	2.90	2.82	5.50	-2.68	MC (%)
	6	26.82	9.46	1.99	1.95			6.73
Bin 5	1	4.10	62.01	11.02	9.92			Dry Weight
	2	1.91	81.82	16.32	14.03	10.70	3.33	654.62
	3	2.79	83.60	16.72	14.32	12.10	2.22	Wet Weight
	4	7.13	50.43	8.61	7.93	8.00	-0.07	721.79
	5	10.37	36.02	6.19	5.83	6.60	-0.77	MC (%)
	6	7.58	38.22	6.73	6.31			9.31
Bin 6	1	5.91	67.74	11.86	10.61			Dry Weight
	2	1.00	79.12	15.68	13.56	12.40	1.16	666.41
	3	-0.78	80.76	16.66	14.28	12.60	1.68	Wet Weight
	4	1.65	84.20	17.23	14.70	12.60	2.10	750.78
	5	7.31	46.19	7.93	7.35	7.20	0.15	MC (%)
	6	7.77	36.96	6.53	6.13			11.24
Bin MC Averages	Bin 1				8.46	10.70		10.25
	Bin 2				11.22	11.58		11.92
	Bin 3				9.82	11.45		11.70
	Bin 4				5.50	7.55		6.73
	Bin 5				9.72	9.35		9.31
	Bin 6				11.10	11.20		11.24

[1]Sample time unknown, therefore, temperature and RH data averaged over afternoon (1:00 p.m. - 5:00 p.m.)

Table B-8. October 29, 2018 - Canola EMC and actual MC (measured and calculated).

10/29/18		Bin Sensors - Modified Henderson[1]				Grain Samples	MC Difference	Bin Weight (Load Cell)
Bin #	Sensor	Temp (°C)	RH (%)	MCd (%)	MCw (%)	MCw (%)		
Bin 1	1	5.02	76.34	14.02	12.29			Dry Weight
	2	4.02	81.35	15.67	13.55	11.30	2.25	648.87
	3	6.58	48.35	8.35	7.70	11.90	-4.20	Wet Weight
	4	8.41	41.40	7.12	6.64	6.80	-0.16	714.77
	5	6.15	52.19	9.01	8.26	7.30	0.96	**MC (%)**
	6	4.34	67.34	12.05	10.75			9.22
Bin 2	1	4.44	81.14	15.51	13.43			Dry Weight
	2	2.39	81.35	16.05	13.83	12.60	1.23	658.58
	3	4.73	82.38	15.84	13.68	12.50	1.18	Wet Weight
	4	3.72	84.30	16.75	14.34	12.40	1.94	746.06
	5	5.58	63.03	10.98	9.90	8.20	1.70	**MC (%)**
	6	4.35	52.80	9.34	8.54			11.73
Bin 3	1	3.94	84.37	16.72	14.32			Dry Weight
	2	4.33	84.35	16.62	14.25	12.80	1.45	667.23
	3	2.37	79.10	15.35	13.31	12.90	0.41	Wet Weight
	4	6.75	31.29	5.81	5.49	12.60	-7.11	752.38
	5	6.30	55.24	9.49	8.67	7.50	1.17	**MC (%)**
	6	4.46	67.75	12.11	10.80			11.32
Bin 4	1	8.76	42.46	7.24	6.75			Dry Weight
	2	9.28	42.41	7.18	6.70	6.30	0.40	668.25
	3	8.69	46.58	7.85	7.28	6.30	0.98	Wet Weight
	4	8.03	49.73	8.40	7.75	6.30	1.45	711.45
	5	8.57	47.76	8.04	7.44	6.70	0.74	**MC (%)**
	6	4.48	63.76	11.30	10.15			6.07
Bin 5	1	6.06	70.98	12.53	11.14			Dry Weight
	2	8.08	54.39	9.13	8.37	8.30	0.07	654.62
	3	7.52	56.57	9.56	8.72	7.80	0.92	Wet Weight
	4	8.29	50.56	8.50	7.83	7.80	0.03	708.52
	5	8.17	53.38	8.96	8.22	6.90	1.32	**MC (%)**
	6	4.18	68.64	12.35	10.99			7.61
Bin 6	1	5.09	80.70	15.23	13.22			Dry Weight
	2	4.53	80.52	15.30	13.27	12.10	1.17	666.41
	3	4.54	61.93	10.93	9.86	12.00	-2.14	Wet Weight
	4	6.23	61.19	10.54	9.54	8.60	0.94	747.66
	5	6.56	54.17	9.28	8.49	7.80	0.69	**MC (%)**
	6	4.37	66.90	11.95	10.67			10.87
Bin MC Averages	Bin 1				9.87	9.33		9.22
	Bin 2				12.29	11.43		11.73
	Bin 3				11.14	11.45		11.32
	Bin 4				7.68	6.40		6.07
	Bin 5				9.21	7.70		7.61
	Bin 6				10.84	10.13		10.87

[1]Sample time unknown, therefore, temperature and RH data averaged over morning (8:00 a.m. - 9:12 a.m)

Appendix C – Available Supplemental Heating Technologies

Available Supplemental Heating Technologies

Company Name	Website	Technology/ Equipment	Notes:
GSI	http://www.grainsystems.com/products/conditioning/bullseye-controller.html	Controls/Monitoring	Monitors EMC and CEMC to run fans during storage - maintains temperatures - remote communication - on-board static pressure monitoring - C02 sensor.
Adaptive Agriculture	https://adaptiveagriculture.ca/aboutbindapt.html	Controls/Monitoring	Fits all centrifugal and inline aeration fans - controls heat and regulates temperature - wireless
Avonlea Farm Sales Ltd. (Manitoba)	https://avonleagroup.net/BIN-SENSE/adid/14296371/BIN-SENSE%C2%AE-Grain-Bin-Fan-Controls	Controls/Monitoring	Connects aeration fans through BIN-SENSE® LIVE system allowing fans to be remotely controlled from mobile or desktop device.
AGI Suretrack - BINManager	https://intellifarms.com/solutions/bin-manager	Controls/Monitoring	Grain bin automation (fan/heater operation)
FUSE	https://www.fusesmartfarming.com/storage/?gclid=Cj0KCQjwl8XtBRDAARIsAKfwtxDHsNqkPiDdr6kzA0-vpSoo0rz0BnHn0tY3VAT5Ko685RlUWMoeXLAaAiWAEALw_w	Controls/Monitoring	Wide range of monitoring equipment for all phases of crop production
GSI	http://www.grainsystems.com/products/conditioning/watchdog-technology.html	Controls/Monitoring	Proprietary software allows remote monitoring from any device allowing adjustments, monitoring and notifications - simple user interface.
Aerotech Herman Nelso	https://www.hermannelson.com/heater-catalog/	Fans/Blowers/Heaters	Diesel and LP/NG - 200,000 to 600,000 BTU (dpending on model)
AgHeaters.com	https://agheaters.com/product-category/shop/val6-econodri-combo/	Fans/Blowers/Heaters	Radiant heater - Val6-Econodri Combo (heater and air-decelerating cabinet); cabinet has a patented internal thermal energy collector assembly that absorbs the radiant energy and heat through which the decelerated air-flow passes through; Diesel, NG, LP
Air-O-Matic	http://teresa.sasktelwebhosting.com/index.html	Fans/Blowers/Heaters	Runs on propane gas or natural gas. Vacuum switch proves the aeration fan is running; the thermostat calls for heat; the electronic ignition lights the burner; air temperature rises to thermostat setting. Burner cuts out, thermostat cools and unit recycles, thus providing a constant warm temperature. No direct flame gases not mixed with the incoming air. Cold air intake between
Brock	https://www.brockgrain.com/products.php?product_id=228	Fans/Blowers/Heaters	Various axial and centrifugal downstream models; BTU range of 250,000 to 5,000,000; liquid propane, propane vapor, or natural gas fuels
Chief Agri	https://agri.chiefind.com/products/caldwell-grain-conditioning/heaters.html	Fans/Blowers/Heaters	Various models and range of BTU; Natural gas and liquid or vapour propane; bin transitions available
Conley Max	http://www.conleymax.com/solutions/grain-drying.php	Fans/Blowers/Heaters	Automated drying unit limits max drying temp - designed for turnkey operation - "Set it and forget it" - Positive air shutoff - dry multiple bins at a time - no exhaust fumes in the air - claimes to save
Dryair (St. Brieux, SK)	https://dryair.ca/agriculture/	Fans/Blowers/Heaters	Indirect heat - Natural gas fired - Central heating module system with manifold & hose distribution to multiple bins
Flagro (Ontario)	https://flagro.ca/category/heaters/	Fans/Blowers/Heaters	Indirect heaters (ductable) ranging from 200,000 to 800,000 BTU Direct heaters (ductable) ranging from 85,000 to 330,000 BTU Electric heaters (ductable) from 68,000 to 512,000 (depending on model)
Frost Fighter (Winnipeg)	https://www.frost-fighter.com/heating-products/idf-series	Fans/Blowers/Heaters	Oil/Diesel & LP/NG models - get 2,500 to 3,250 CFM (depending on model) - Heating capacity of 350,000 to 420,000 BTU/h (depending on model) - ductable up to 50' (HS model C/W 6-blade fan and 1.5 HP motor allows for ducting up to 100')
Frost Fighter (Winnipeg)	https://www.frost-fighter.com/heating-products/idhqr-series	Fans/Blowers/Heaters	Compact/lightweight - Oil-Diesel & LP/NG models - get 1,610 to 4,800 CFM (depending on model) - Heating capacity of 170,000 to 500,000 BTU/h - ductable up to 100'
Grain Guard (Nobleford, AB)	http://grainguard.com/products/heaters/low-temperature-propane-natural-gas-heaters/	Fans/Blowers/Heaters	C/W fan - 60, 000 to 200,000 BTU (depending on model) - high heat limit safety switch; propane or natural gas; in-line or high-speed centrifugal models

Company Name	Website	Technology/ Equipment	Notes:
GSI	file:///C:/Users/mkimmen/Downloads/original%20(1).pdf	Fans/Blowers/Heaters	Axial heater - 50,000 to 3,000,000 BTU (depending on model) - LP/NG
NAD Discussion Thread	https://talk.newagtalk.com/forums/thread-view.asp?tid=601972&DisplayType=flat&setCookie=1	Fans/Blowers/Heaters	Comment on page: A guy I know built heat exchangers out of plywood and copper pipes. I could be off on size but it looks like they are 4x8 sides and 3 feet wide full of 1 copper tubing. He places them between the bin and the fan. Than hooks his wood boiler to them that heats his shop. He uses it as a drying bin and transfers it out to other storage. But it must work because he bought another boiler he has mounted on a trailer to use at different farms.
Shivers	https://www.shivvers.com/products/c25/fan-heater-combinations-/	Fans/Blowers/Heaters	Various axial and centrifugal downstream models; BTU range of 3.2 to 7 million; NG or LP
Shortline Ag	http://shortlineag.com/fans%20&%20heaters.html	Fans/Blowers/Heaters	Various manufacturers of axial and centrifugal heaters
Solex Thermal Science	https://www.solexthermal.com/products-solutions/drying/	Fans/Blowers/Heaters	Indirect heating bulk solids through conduction (using steam/waste heat), significantly increasing the moisture-carrying capacity of the cross-flow air for precise temperature and moisture control.
Sukup	https://www.sukup.com/Products/List/101	Fans/Blowers/Heaters	Various axial and centrifugal models
Patent Pending	https://patents.google.com/patent/US6202319B1/en	Fans/Blowers/Heaters	For use on existing grain dryers or integral to new grain dryers that recovers heat from the moist hot exhaust air leaving the grain columns and uses this recovered heat to preheat ambient air being drawn into the grain dryer via a blower.
Guardian Grain Drying Solutions (Lloydminster, SK)	https://www.guardianplumbing.ca/mached-mobile-unit	Fans/Blowers/Heaters	Mobile, customizable units - 200,000 to 600,000 BTU (depending on model) - 6-pass high-efficiency coils - burns 0.21 GJ of NG/h of full flame or 8L of LP/h on full flame
ClimateTechWiki	https://www.climatetechwiki.org/technology/jiqweb-edf	Renewable Fuel	Possible reconfiguration for a bin setup
USDA-SARE Study	https://projects.sare.org/project-reports/fnc17-1080/	Renewable Fuel - Geo	Using geothermal heat for drying in-bin corn
N/A	https://www.albertafarmexpress.ca/2019/06/03/dry-grain-while-the-sun-shines-harnessing-solar-power-for-drying-	Renewable Fuel - Solar	Case study: Alberta farmer created homemade system using irrigation pipes heated by sun, a manifold, and fans to distribute heated air to bins. Cost ~$3000 on materials (exculding fan).
Paper - Purdue University - Solar Heat for Grain Drying	https://www.extension.purdue.edu/extmedia/AE/AE-108.html	Renewable Fuel - Solar	Case study- Corn - Low-temperature drying is quite well adapted to solar energy. Being a slow process that uses natural or slightly heated air to dry the grain while in storage, solar energy can provide the supplemental heat to raise the temperature and reduce the relative humidity of the
Presentation - Szent Istvan University - Hungary	http://indico.ictp.it/event/a09136/session/76/contribution/52/material/0/0.pdf	Renewable Fuel - Solar	In-bin solar grain drying.

Appendix D

Supplemental Heating FAQ

PAMI
Innovative Solutions for Agriculture and Beyond

Supplemental Heating FAQ

Using Supplemental Heat to Manage Grain in the Bin

Rain, snow and cool temperatures at harvest time mean producers must manage grain in the bin as carefully as they manage it in the field. Adding supplemental heat to natural air drying (NAD) can be an efficient and effective way to dry stored grain if done correctly. Here are the answers to some frequently asked questions about supplemental heat.

NOTE: The recommendations below apply to all varieties of crops.

Q: What does supplemental heat mean? How is it different from other drying systems?

A: Supplemental heating means adding heat to a fan used for natural air drying. Adding heat increases the capacity of air to hold moisture and, therefore, its capacity to dry grain. A comparison of systems, including pros and cons, is shown here:

	Description	Pros	Cons
Heated air drying	• Usually a small batch process • Uses hot air (45-80° C) to dry grain • Uses very high air flow rates (approx. 20 cfm/bu)	• Success does not depend on ambient conditions • Dries grain quickly (hours) • Suitable for any ambient condition	• Can result in seed damage • Requires cooling cycle • High capital and energy costs
Natural air drying (NAD)	• Turns the grain bin into a "dryer" • Blows ambient air (5-25° C) through grain • Uses moderate air flow rates (approx. 1 cfm/bu)	• Energy savings • Smaller investment • Reduced risk of heat damage • Most suitable when ambient > 15ºC	• Slow (can take weeks) • Requires management • Success dependent on ambient conditions
NAD with heat	• Adding a heater to a NAD fan to increase the temperature of the air going into the bin	• Turns a "poor" drying day into a "good" drying day • Minimal capital investment • Most suitable when ambient > 0ºC • Reduces drying time to days	• Requires management (and grain turning) • Few options for temperature control • Energy cost

NOTE: cfm/bu = cubic feet per minute per bushel

Photo by: Amy Hogemann

Q: How much does adding heat affect the capacity of air to dry grain?

A: For every 10° C increase in the temperature of the air going into the bin, the relative humidity (RH) of the air is cut in half.

With added heat, a cold, drizzly fall day can be turned into a beautiful drying day. For example, the equilibrium moisture content (EMC) chart for wheat is shown below.

On a day when ambient air conditions are 5°C and 70% RH, the air will have no capacity to dry since the EMC for wheat is 16.1% (and target moisture content is 14.4%). But, by increasing the air temperature to 15° C using some heat, the resulting RH will be cut in half, to about 35%, and the air will have capacity to dry since its EMC for wheat will be 10.3%.

EMC chart for wheat

Temp ºC	Relative humidity (%)										
	35	40	45	50	55	60	65	70	75	80	85
-2	11.5	12.2	13.0	13.7	14.5	15.3	16.0	16.9	17.7	18.7	19.8
2	11.1	11.9	12.6	13.4	14.1	14.9	15.6	16.4	17.3	18.2	19.3
5	10.9	11.7	12.4	13.1	13.8	14.6	15.3	16.1	17.0	17.9	19.0
8	10.7	11.5	12.2	12.9	13.6	14.3	15.1	15.8	16.7	17.6	18.7
10	10.6	11.3	12.0	12.7	13.4	14.2	14.9	15.7	16.5	17.4	18.5
13	10.4	11.1	11.8	12.5	13.2	13.9	14.6	15.4	16.2	17.1	18.2
15	10.3	11.0	11.7	12.4	13.1	13.8	14.5	15.2	16.1	17.0	18.0
18	10.1	10.8	11.5	12.2	12.9	13.6	14.3	15.0	15.8	16.7	17.7
22	9.9	10.6	11.3	11.9	12.6	13.3	14.0	14.7	15.5	16.4	17.4
26	9.7	10.4	11.1	11.7	12.4	13.0	13.7	14.4	15.2	16.1	17.1
28	9.6	10.3	11.0	11.6	12.3	12.9	13.6	14.3	15.1	15.9	16.9

Photo by: Danielle Bergen

Q: Should I turn the heater off when it is raining?

A: Unless the rain affects the safe operation of the heater and fan, you do not have to turn off the heater. Air with an RH of 100% can be turned into air with an RH of approximately 50% by increasing the temperature of the air by 10° C.

Q: Should I avoid propane or direct-fired heating systems because they add water to the air?

A: Not necessarily. Combustion of fuels like propane or natural gas does generate water, but the amount of water added to air is negligible compared to the amount of water being removed from the bin. For example, the amount of water added to the air using a propane heater (assuming 10° C increase for 5,000 cfm) is approximately 7 lb/hr. The amount of water being removed from the bin is approximately 120-200 lb/hr.

An indirect heating system like a heat exchanger or hydronic heating system will be slightly more efficient because it will not be adding any water to the air, but if a propane or natural gas heater is available or more convenient, they are very effective.

Q: What temperature increase should I target?

A: The target temperature increase will depend on ambient conditions. Plan for a target air plenum temperature of 15-25° C (possibly 30° C with sufficient air flow). Any increase in air temperature will increase the capacity of air to dry, but the optimal temperature is 15-25° C.

Be cautious with using higher temperatures when it is very cold outside. First, it will require a large heater, and resulting higher fuel costs, to achieve temperatures in the 15 to 25° C range. Second, there is an increased chance of condensation and freezing grain at the edge of the bin when it is very cold outside. Limit the temperature and reduce the drying rate of NAD and supplemental heat when it is cold outside.

Q: If warm air is good, hot air is better, right? Should I crank up the temperature as high as I can?

A: No. The air temperature is what pulls the moisture out of the grain kernel itself, but it is the air flow (measured in cubic feet per minute – cfm) from the fan that pulls the moisture out of the grain mass and out the top of the bin. The relatively low air flow from aeration or NAD fans cannot keep up with high water removal rates. The temperature needs to be matched with the fan capacity.

A minimum of 0.75 cfm/bu air flow rate is recommended for any NAD with supplemental heat. With that air flow rate, you should be able to use plenum temperatures of 15-20° C. Higher temperatures will require higher air flow rates.

Q: How do I determine how large of a heater I need? Or, I have an existing heater that is 100,000 btu/hr – how much grain will it dry?

A: The size of heater you need depends on two things:

1. the air flow rate (cfm) from your fan, and
2. your desired temperature increase.

Heater capacity (btu/hr) = temperature increase (degrees C) x air flow rate (cfm) x 2.05

Example: to raise the air temperature by 10° C for a bin/fan that is pushing 5000 cfm, the required heater capacity is 10 x 5000 x 2.05 = 102,500 btu/hr

Example: if you have a 100,000 btu/hr heater and you attach it to a bin/fan that is pushing 7500 cfm, the expected temperature increase will be 100,000/7500/2.05 = 6.5° C.

Keep in mind these equations assume a highly efficient heat transfer setup meaning all of the heat generated by the heater ends up in the air. The overall efficiency of some systems may be as low as 50%, so estimate the required size of your heater accordingly.

Q: Which fuel type is most cost effective?

A: The total fuel cost theoretically depends on its cost ($/L) AND its energy density. The cost will fluctuate from month to month and region to region, but the energy density is constant.

Fuel	Fuel cost *(variable)*	DIVIDED BY	Energy density *(fixed)*	EQUALS	Fuel cost *(variable)*	X 1056	Fuel cost *(variable)*
Diesel	$1.00/L		38.6 MJ/L		$0.026/MJ		$27.45 per million btu
Natural gas	$0.1387/$m^3$		37.0 MJ/m^3		$0.0037/MJ		$3.90 per million btu
Propane	$0.49/L		25.3 MJ/L		$0.019/MJ		$20.45 per million btu

If a carbon tax is applied, that will increase the cost per million btu. The amount of that increase depends on the fuel since each fuel emits a different amount of carbon per L burned.

Also note that propane and natural gas are considered "clean burning" fuels, so they can be used to directly heat the air entering the fan or bin. Diesel should only be used as an indirect source of heat.

Q: How do I best manage a NAD system with supplemental heat?

A: Some general management practices include:

1. Only use a CSA certified heater that is designed for use with grain storage fans for safety and grain quality reasons. Follow manufacturer's instructions for installation and operation.
2. Ensure adequate air flow rate (minimum 0.75 cfm/bu) or there is a risk of overheating the grain.
    - Low air flow rates may not have enough energy to fully remove moisture from the bin.
    - Refer to pami.ca/storage for information on measuring air flow rate.
3. Limit air temperature increase to 15°C or less.
    - Higher temperature increases result in high fuel costs, reduced heat transfer efficiency, increased chance of over drying, and increased chance of freezing/sticking at edge of bin.
    - For every temperature increase of 10°C, the RH of the air is cut in half.
4. Do not exceed an inlet (after heater) temperature of 30°C.
    - Even though higher temp = more drying capacity, you do not want to overheat the grain.
    - Air flow rates of 0.75 to 1 cfm/bu can "keep up" with moderate drying rates, but not with high drying rates associated with high temperatures (>30°C).
5. As much as possible, maintain a CONSISTENT air temperature going into the bin.
    - Thermostatic controllers are becoming more common and will help achieve a consistent temperature going into the bin. This will help minimize day-to-night variations in temperature.
6. Ensure adequate ventilation in the headspace since condensation on a cold bin roof can cause moisture problems in the stored grain.
    - A minimum of one square foot of vent space for every 1000 cfm of air flow is required.
    - Consider the use of "active" ventilation in the headspace which helps to expel moist air more effectively.
7. Consider turning the grain partway through drying to distribute over-dry grain at the bottom.
8. Grain MUST BE turned and cooled to less than 15°C after drying
    - Cooling will also remove some moisture, so drying may be complete when moisture is within 1% of target.
9. Monitor grain conditions with in-bin cables and/or samples during drying.

For further information with regards to this report, please contact:
Charley Sprenger – cspreger@pami.ca or Roy Maki – rmaki@pami.ca

Saskatchewan Operations
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264

Manitoba Operations
Box 1060
390 River Road
Portage la Prairie, MB R1N 3C5
1-800-561-8378

Corporate Services
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264