environments

Article

Experimental Study of Grain Dryer Noise Emissions

William Lubitz [1,*], Kyle Teeter [1], Ethan Parker [1], Rachel Dalton [1] and James Dyck [2]

[1] School of Engineering, University of Guelph, Guelph, ON N1G 2W1, Canada
[2] Ontario Ministry of Agriculture, Food and Rural Affairs, Vineland Station, ON L0R 2E0, Canada
* Correspondence: wlubitz@uoguelph.ca; Tel.: +1-519-824-4120 (ext. 54387)

Abstract: There is increasing interest in the environmental noise emissions from grain dryers and the potential impact of practical noise pollution mitigations such as barriers adjacent to dryers. Grain dryers are an essential part of grain production in many parts of the world, including Ontario, Canada. Most dryers are large, stationary units that include a burner to provide process heat and a fan or blower to move heated air through the grain being dried. This study measured sound levels at a range of distances from multiple grain drying facilities in Ontario, Canada, over two drying seasons. It was found that the sound level at a given distance varied substantially, depending on the dryer type and presence of blocking features such as grain bins or buildings. Noise emissions did not necessarily correlate to the size or drying capacity of the facility, with some smaller top dry dryers having higher noise emissions than other much larger tower dryers. Targeted investigations of the impact of practical remediations in the form of physical sound barriers showed sound level reductions were possible that were similar in magnitude to those achieved by highway sound walls along roadways, with most sound reduction being at higher frequencies.

Keywords: grain dryer; stationary source; environmental noise; sound level; noise pollution; mitigation

check for updates

Citation: Lubitz, W.; Teeter, K.; Parker, E.; Dalton, R.; Dyck, J. Experimental Study of Grain Dryer Noise Emissions. *Environments* **2023**, *10*, 100. https://doi.org/10.3390/environments10060100

Academic Editors: Gaetano Licitra, Vogiatzis Konstantinos and Yiannis G. Matsinos

Received: 6 March 2023
Revised: 24 May 2023
Accepted: 9 June 2023
Published: 12 June 2023

1. Introduction and Background

Grain dryers and related equipment can be one of the most intense noise sources in agricultural operations [1,2]. High sound levels from agricultural operations are a concern for on-site agricultural workers. McCullagh [3] reports that exposure to high levels of occupational noise and hearing loss are common in agriculture. Multiple studies over the last half century have consistently found higher levels of noise-induced hearing loss among farmers than in similar non-farming populations. Over these time periods (and up to the current time), there has been little innovation or improvement in noise exposure in agricultural settings [4].

The fans and burners in grain dyers have been observed to produce sound levels from 85 dB(A) up to 112 dB(A) at a location 1 m in front of the dryer fan [5]. In Ontario, Canada, workers must not be exposed to time-weighted average sound levels greater than 85 dB(A) over an eight-hour period (O. Reg. 381/15) [6].

Environmental noise pollution from stationary sources can also have significant impacts on neighboring land uses and residents, including a range of potential health and psychological impacts [5,7]. However, environmental noise pollution from stationary agricultural sources such as grain dryers is much less studied than the impacts of workers at facilities or of environmental noise pollution from transportation [8] or in urban areas [9]. One survey-based study suggests rural residents may accept lower levels of ambient environmental noise than urban residents and would be willing to accept increased noise if related air pollution is reduced [10].

In Ontario, Canada, the Ministry of Environment, Conservation and Parks (MECP) provides guidelines for noise emissions from stationary sources in NPC-300, although exceptions are provided for agricultural applications [11]. O. Reg, 381/15 and NPC-500 also provide guidance on requirements for sound level measurements for the purposes of regulatory compliance.

Sources of grain dryer noise emissions include fans, burners, and grain handling equipment [12]. The Prairie Agricultural Machinery Institute evaluated and reported on a series of grain dryers in the 1980s [13], and among the tested dryers, noise levels at the operator's position were lower for units with centrifugal fans compared to those with axial fans. Noise from fans can often be directional, with higher intensities often associated with exposure to the fan intake. Modifying the fan intake with a muffler, often in the form of customized intake ducting that includes bends and baffles, can reduce these peak noise emissions [2]. Surrounding a fan with sound absorbing panels can also reduce emissions, whether the fan is fully enclosed [2] or only partially shielded [5]. Prior researchers have noted that grain loading or unloading operations can temporarily double sound emissions at operating dryers [14].

The last significant study of grain dryer noise in Ontario, Canada, was conducted by Clarke et al. [10] in 1998. Measurements were taken at 14 Ontario farms with dryers in the fall of 1997, and data from 12 of these sites were analyzed. Clarke et al. [14] examined only farm-scale corn dryers (150 to 8800 tons per season), not larger commercial facilities. Only one site utilized a centrifugal fan; all others were axial flow. Large differences in sound levels and distribution were noted between the four types of dryers examined (continuous flow, bin, overhead batch, and portable), resulting in different recommendations for orientation and operation depending on dryer type. These findings show that measurements and models for sound levels from one type of dryer should not be used to predict sound levels of different dryer types or configurations. Measurements from the range of dryer types operating in a region are needed, and it is expected that there will be different best management practices for minimizing noise emissions.

The last survey of grain storage and drying facilities in Ontario was completed in 1996 (as reported by Clarke et al. [14]), and the survey report is not readily accessible. Since 1998, the size and types of dryers used in Ontario, Canada, have changed. The small dryers using axial fans examined by Clarke et al. [14] are not as common and not representative of newer models of dryers [15]. Additionally, the amount of drying activity overall has also increased [15], but there has been no further significant study of grain drying activity in Ontario for the past two decades. There are now a wide range of dryer types, from in-bin natural dryers to large centralized continuous flow dryers [16], including new and upgraded models.

Telephone and online surveys of farmers, elevator operators, and industry contacts in 2021 found that the number of types and sizes of grain dryers used in Ontario have been increasing [15]. The amount of on-farm permanent grain storage capacity in Ontario has risen from 9,520,000 metric tons in March 2015 to 11,160,000 metric tons in March 2019 [17]. This represents a storage capacity growth rate of 4%/year. It is likely that drying capacity has also increased. Notably, newer dryers often utilize quieter fans. Axial fans, typically louder than centrifugal types, are less common on newer dryers. However, it should be noted that grain dryers are durable infrastructure, often used for multiple decades, with fans and burners being replaced individually if needed instead of replacing the entire dryer [15].

Studies reporting sound levels surrounding operating grain dryers are few. The Clarke et al. report [14] measured sound levels around a series of different on-farm dryers in eastern Ontario. Fraser et al. [5] describe a survey of sound levels surrounding a small grain drying installation in Ontario. Reinvee et al. [18] conducted sound level surveys around four different grain dryers in Estonia. Sound level measurements should be recorded for one minute at each location, and then weighted averaged [14,18]. Reinvee et al. [18] recommended screening samples in the field for impacts due to transient noise by checking that the range between maximum and minimum intensity of the recorded values was less than 10 dB(A).

Mitigating noise emissions from existing dryers can be challenging. Grain dryers often must operate 24 h per day during drying season, making limiting operating times a non-ideal solution. Additionally, it has been noted that in many agricultural operations, the actual use of personal hearing protection by workers is inconsistent [4]. Therefore, if noise abatement is needed, measures that reduce sound emissions from the source without impacting dryer operations are recommended.

The minimum needed distance between the grain dryer and neighbouring receptors (residents or land uses) is an essential planning tool. Typical background sound levels in rural areas are 50 dB(A) [14]. While air pollution emissions are typically evaluated at property lines for compliance evaluation purposes, noise emissions are usually evaluated at receptor locations (e.g., window locations of houses) [19].

During the design stage of a grain drying facility, Fraser [5] lists a series of recommended design features to reduce noise emissions from the site, including using centrifugal instead of axial flow blowers, orienting fans or blowers away from neighbouring receptors, and shielding with other structures. Centrifugal fans typically have lower noise emissions, particularly in the frequency ranges most impactful to humans, and are recommended instead axial flow fans [18]. Fan mufflers can further reduce noise emissions [2,12]. Sound absorbing panels near the fan can also reduce off-site sound levels: an on-farm test in Ontario showed sound absorbing panels near the fan inlet reduced surrounding sound levels by 8 dB(A) to 9 dB(A) [5].

The distance between grain dryers and neighbours should be maximized to bring sound levels close to the typical rural ambient noise level of 50 dB [14]. Locating trees and plants between a dryer and a noise receptor can also reduce the sound levels at the receptor, in many cases providing a stronger feeling of noise reduction to affected persons than actually occurs [20].

It is common to assume that grain dryers are a point source, and that sound will propagate outward from the dryer uniformly in all directions. If L_1 and L_2 are sound levels (in dB(A)) at two points at distances d_1 and d_2 from the point source, then

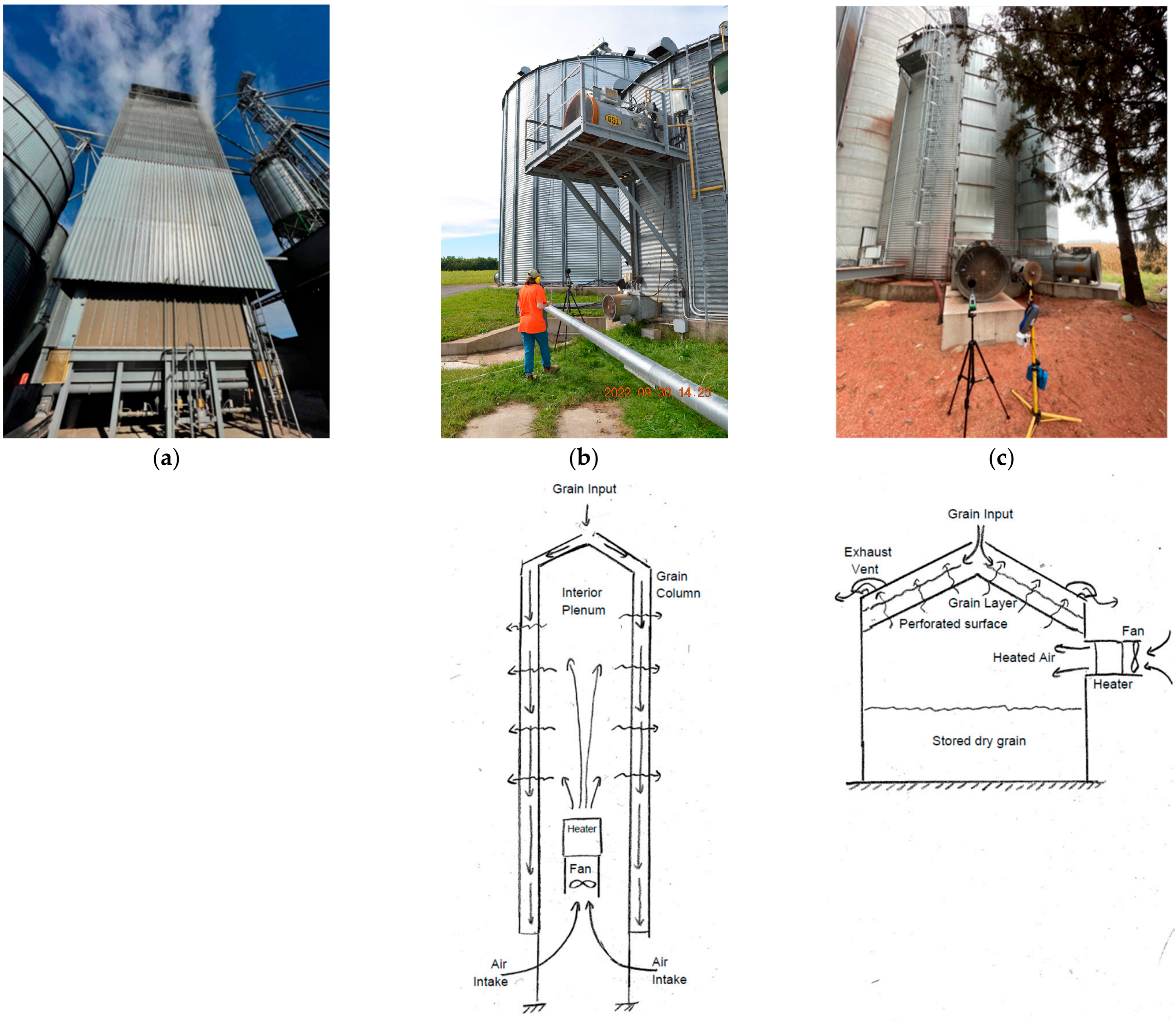
$$L_2 = L_1 - N \log_{10}(d_2/d_1) \tag{1}$$

where setting constant N to 20 corresponds to the theoretical inverse distance-squared dependence of sound level with distance from a point source. This relationship was used (with $N = 20$), but not tested, by both Reinvee et al. [18] and Clarke et al. [14]. When considering a line sound source, such as a highway adjacent to a sound wall, sound spreading is in only two dimensions (instead of three), and N is set to 10 [21].

Although ambient sound levels near grain dryers have not been well-studied, the related problem of mitigating noise emissions from highways using purpose-built walls has [22]. Insertion loss is the primary mechanism by which sound walls reduce noise at receptor locations. Inserting a wall between the source and receptor increases the path length between them, resulting in a longer path over which attenuation may occur. The presence of a sound wall between the source and receptor point will reduce the sound pressure level at the receptor point by 5 dB(A) to 8 dB(A), depending on the height of the wall [23]. A “shadow zone” of increased attenuation occurs in the region immediately behind sound walls [24] or other obstacles such as trees or dense vegetation [25]. Typically, this shadow zone extends laterally several times the height of the obstacle. At increasing distances, attenuation due to the presence of the obstacle is gradually reduced until, at great distances, attenuation becomes minimal.

1.1. Grain Dryers

Grain dryers can be categorized as either continuous, in which a flow of grain passes through the dryer on an ongoing basis, or batch, in which a quantity of grain is placed in the dryer, dried, and then removed. The majority of the sites tested in this study were upright tower, continuous-flow, cross-flow dryers [26], commonly called “tower dryers” (Figure 1a). These are typically larger capacity dryers with fans and burners located centrally in the bottom portion of the dryer. The dryer consists of a vertical central plenum surrounded by a double perforated-wall jacket through which grain moves continuously downward at a steady speed. Air is drawn in at the bottom of the dryer, heated, passed upwards through the center of the dryer, and then passes out through the double walls and the grain to be dried (Figure 1d). Most of these dryers are single pass: moist air leaving the grain is exhausted to the surroundings. Because of the vertical orientation of the fan and burner in these dryers, and their location in the interior plenum, sound levels tend to be more consistent with angular location around the dryer.


(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 1. Photos of (**a**) tower dryer, (**b**) bin-mounted top dryer, and (**c**) ground-mounted top dryer and sketches of (**d**) tower dryer and (**e**) bin-mounted top dryer.

Other types of dryers were also studied, including roof-mounted, bin-batch drying systems [27] commonly called "top dryers" (Figure 1b,c). Top dryers are installed in the top of a conventional steel storage bin. A layer of grain to be dried is fed to the top of the bin and distributed across a perforated surface near the bin roof. An external fan draws air in and passes it through an adjacent combustion heater and into the bin just below the perforated floor. Heated air passes through the perforated floor and the grain and then exits through vents in the bin roof (Figure 1e) [27]. Top dryers, as well as mixed-flow and horizontal continuous-flow dryers, have fans and burners that are usually clustered on one side of the dryer unit, typically resulting in higher sound pressure levels in directions on the side facing the fan intake than on other sides. (Note that at all sites examined, the presence of grain bins, handling equipment, and other obstacles meant it was not practical to verify the directionality of sound pressure levels independent of effects of these other obstacles.)

1.2. Objectives

Policy makers and dryer installation designers require information on the sound levels to expect from modern grain dryers when trying to assess or mitigate the noise impacts of drying facilities on neighbours or the environment. Sound levels that could be expected at adjacent roadways or homes, which are often several hundred meters distant, is of particular interest.

There is little data on actual measured sound levels in the vicinity of grain dryers, with the exception of a few cases (e.g., [5,14,18]). None of the prior data are for the larger tower dryers that are increasingly common in Ontario, Canada, and other regions: Fraser and Clarke et al. only examined smaller types of dryers [5,14], while Reinvee et al. [18] studied four "continuous flow" dryers but did not further describe dryer type and only measured sound levels at a single 25 m distance from the dryers in all cases. There is even less information available on the effects of surrounding structures such as grain storage bins on sound levels at distances from grain drying facilities, which is not addressed in any of the prior studies noted [5,14,18].

A few practical mitigations, such as easily constructed barriers, have been examined (e.g., [2,5,12]), but typically only as case studies for particular fans or dryer types. These prior studies provide useful examples but are not sufficient. While a universal mitigation strategy was outside the scope of this study, additional case studies of practical interventions would provide additional useful data to inform further study of mitigation methods.

The goals of this study are to document the ambient measured sound levels at distances from operating grain dryers in Ontario, including tower dryers, and characterize the effect of possible mitigations that could be readily applied to reduce sound levels at a distance from operating grain dryers.

2. Materials and Methods

Measurements were collected at 13 unique grain drying facilities in southern Ontario, Canada, during the fall 2021 and fall 2022 drying seasons. Corn (maize) was the grain being dried in all cases. Sound level measurements were recorded using a Brüel & Kjær 2245 Class 1 sound level meter (Brüel & Kjær, Virum, Denmark) equipped with a Brüel & Kjær UA-1650 foam microphone wind shield. Calibration accuracy was confirmed before and after each set of field measurements using a Brüel & Kjær 4231 Sound Calibrator portable calibrator. The sound level meter was supported on a portable tripod with the microphone at a height of 1.5 m above ground level. Sound level measurements were recorded at each receptor point for 60 s. In some cases, if a transient sound occurred from another source (such as a truck passing near the meter), the measurement would be repeated, and the first measurement including the additional sound source was flagged and not used for analysis. Results are reported as A-weighted equivalent continuous sound pressure level (L_{Aeq}) measurements, in units of A-weighted decibels (dB(A)).

A second portable tripod supported a combined wind vane and anemometer (Davis Instruments) at 1.5 m above ground level, and a temperature sensor (XR5-SE, Pace Scientific, Boone, NC, USA) within a multi-plate radiation shield. Output from these instruments were recorded continuously and averaged during all field measurement campaigns at one-minute resolution.

Before each field site visit, a series of potential measurement points were calculated using a custom-written spreadsheet to produce a series of points circularly distributed around the grain dryer at distances of 50 m and 100 m from the dryer. Radial transects consisting of a series of points on a straight line outward from the dryer were also mapped, some with clear line-of-sight to the dryer, and some with obstacles such as grain bins present along the transect. Figure 2 shows an example of the resulting pre-planned measurement points. A specific location is not shown to maintain the anonymity of the studied sites. All points were mapped using Google Earth aerial imagery of the site, and a list of potential receptor positions was produced for use in the field. The GPS integrated into the noise meter was used to position the instruments at points farther (approximately 20 m or greater) from structures. At locations closer to dryers, grain bins, and other structures, positional errors in GPS measurements of up to several meters in both lateral position and altitude were sometimes observed. For this reason, instruments were positioned at points near structures based on the pre-mapped locations and sighting of the relative position of structures and other features, without using the GPS.

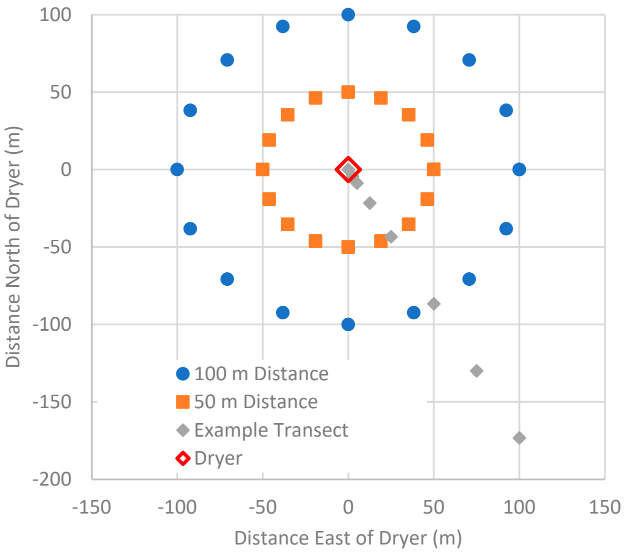


Figure 2. Example of pre-planned measurement points around a dryer location, including regularly spaced points at 50 m and 100 m distances from the dryer and an example transect of points at a range of distances in a single direction from the dryer.

At most locations it was not feasible to take measurements at many of the pre-mapped points at 50 m or 100 m distances from the dryer. Usually, this was due to the presence of buildings, active roadways, other obstacles such as trees, unharvested fields, or property lines. In these cases, measurements were taken at all 50 m or 100 m distance points that were reasonably possible to use as receptors. It is notable that most dryers were partially or almost completely surrounded by other structures, particularly large, circular footprint steel grain storage bins. One of the goals of this study was to examine the effect of these adjacent structures on ambient sound levels at greater distances.

Additional information was noted during each site visit, including dryer make and model, drying rate on the day of the test, site configuration (including differences from aerial imagery and maps used for visit planning), and other information. Presence and location of structures and other features on site were verified against aerial imagery used during visit planning, and if necessary, planned receptor points were supplemented or modified.

3. Results and Discussion

Measurements were taken at 13 unique sites in southern Ontario, Canada, during the 2021 and 2022 fall corn drying seasons (October to early December). Measurements were also collected at two unique sites with grain bin dryers and at one highway sound wall in fall 2022.

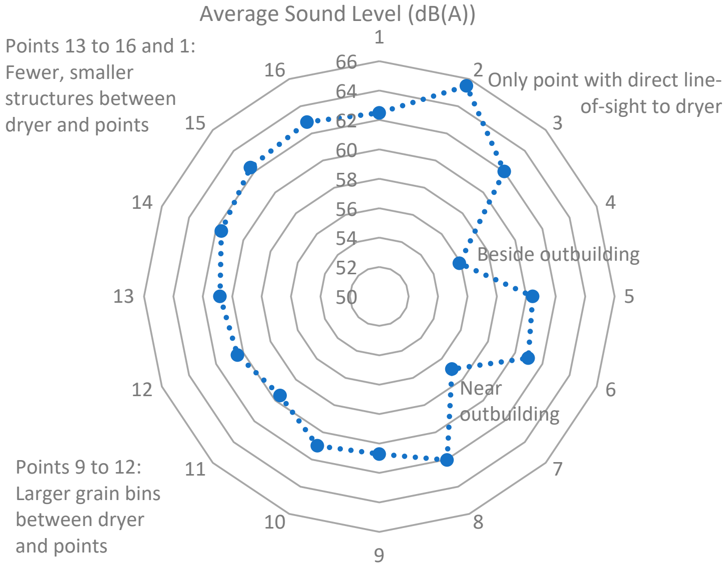
3.1. Sound Levels at 50 m and 100 m Distances from Dryers

Sufficient data were collected at 50 m or 100 m (or both) from the dryer, in a range of directions, at 11 of the sites. Table 1 shows the maximum and minimum recorded one-minute A-weighted sound level pressure among the points at 50 m from the dryer and also among the points at 100 m from the dryer at these 11 sites. The number of unique points at the specified distance, each at different angular locations, is also given. (In a few cases, it was not possible to collect enough measurements at five or more unique points all in different directions from the dryer and at the specified distance. Data are not provided in the table for those instances.)

Table 1. Ranges of sound levels observed at unique points at distances of 50 m and 100 m from the grain dryer. Missing data represent insufficient unique points at the given distance.

		Sound Level (dB(A))					
Site	**Dryer Type**	**Max. 100 m**	**Min. 100 m**	**# pts. 100 m**	**Max. 50 m**	**Min. 50 m**	**# pts. 50 m**
A	2 × Top Dry (Bin)	72.8	54.4	16	79.0	60.9	10
B	Top Dry (Ground)	67.3	52.7	17	76.4	59.3	15
C	Tower	68.2	56.4	9	85.3	64.0	7
D	Tower	67.8	57.2	11			
E	Tower	66.6	58.0	9	85.5	58.4	13
F	Tower	65.6	47.9	5	71.3	65.5	12
G	Tower	65.5	55.9	16			
H	Tower	64.0	47.5	11	69.3	54.8	12
I	Continuous Flow	69.2	59.5	5			
J	Mixed Flow	61.8	42.3	17			
K	Stack				81.2	64.0	16

Site G (in Table 1) was relatively open and flat in all directions from the tower dryer and was one of the few locations where it was possible to take measurements at a consistent distance (in this case, 100 m) from the dryer in all directions at equally spaced points. The tower dryer was mostly surrounded by a set of large (taller than the dryer) steel grain bins. Figure 3 shows the measured noise levels at evenly spaced points on a 100 m radius circle centered on the dryer. Points are numbered as labeled in Figure 3. Grain bins are located between the point and the dryer at most locations, with special cases indicated. The typical sound level in most directions from the dryer was on the order of 60 dB(A) to 63 dB(A). Point 2 corresponds to a point that is unobstructed by bins or other structures and has a direct line-of-sight to the dryer from the measurement location. Point 4, with notably a reduced sound level, is immediately adjacent to the side of a smaller out-building, while point 7 is near an outbuilding and in a location of local topographic variation in an otherwise relatively flat landscape.



Points 13 to 16 and 1: Fewer, smaller structures between dryer and points

Only point with direct line-of-sight to dryer

Beside outbuilding

Near outbuilding

Points 9 to 12: Larger grain bins between dryer and points

Figure 3. Average sound levels measured at different equally spaced points on a circle with radius of 100 m centered on the grain dryer at Site G. Numerical values on plot circumference are point labels.

3.2. Distance Effects on Sound Levels

The rate of reduction in sound levels with increasing distance from the dryer is particularly relevant when considering potential noise mitigation. The inverse square relationship (Equation (1)) has been used to model sound level as a function of distance in prior studies [14,18], but the potential accuracy of predicted sound levels using Equation (1) has not been examined. One goal of this study was to attempt to gauge how well Equation (1) could be expected to predict sound levels at actual sites.

At several of the sites in Table 1, sound level measurements were taken along transects extending radially outward from the dryer location. Each transect included at least five measurements at different distances. Maximum (and in some cases minimum) distances were based on site constraints.

Equation (1) was fit to each measured transect, using the most distant point as a reference point and adjusting N to minimize mean absolute error (MAE) between measured and predicted sound levels at points along the transect. Points less than 5 m were excluded from fitting. At such close distances to the dryers, sound levels were highly variable due to the details of the configuration of each dryer and surrounding equipment. Values of N included in Figure 4 are those that resulted in the minimum MAE.

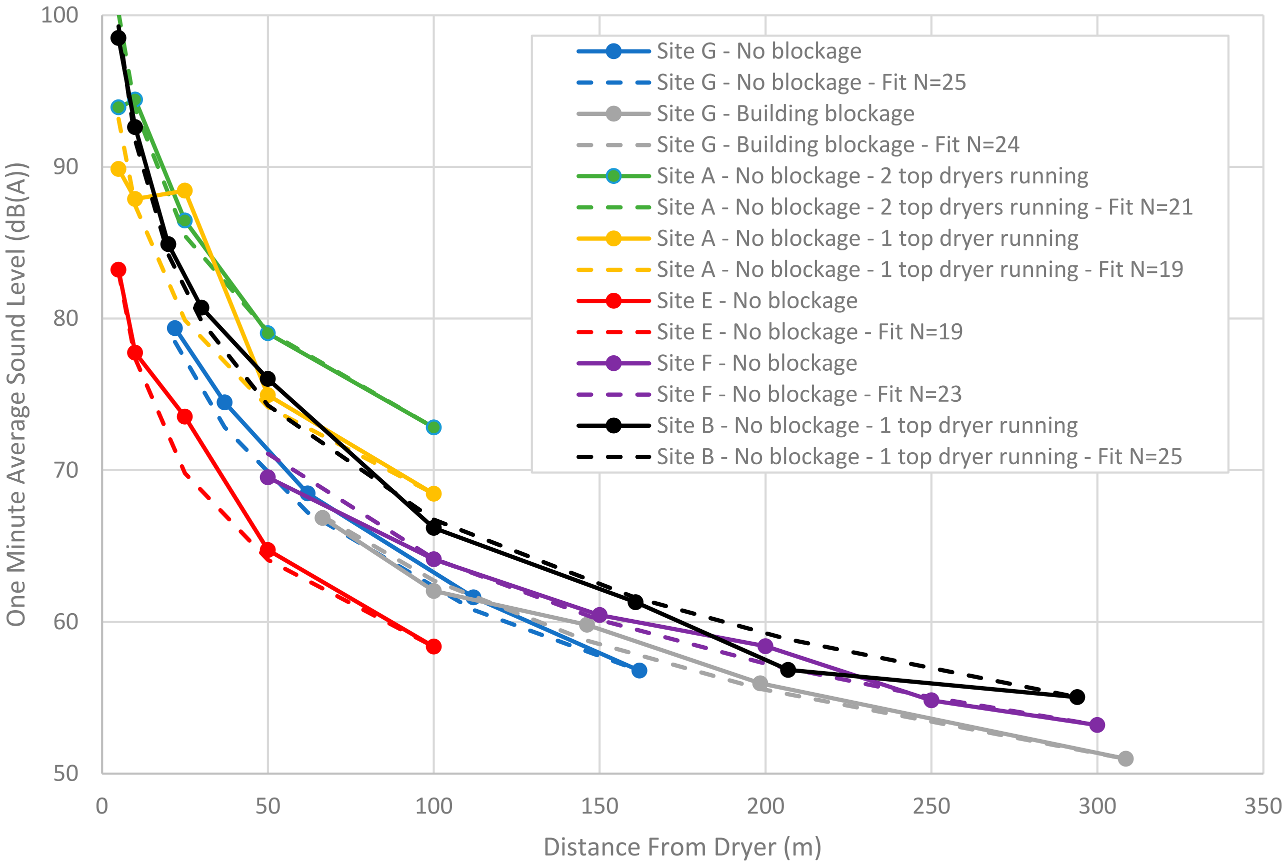


Figure 4. Measured average sound levels (L) versus distance from dryer along straight-line radial transects. Locations in legend reference Table 1. Lines of best fit for each set of data are based on Equation (1) using value of N in legend.

Sites A and B in Figure 4 were top dryers; all others were tower dryers. Since the top dryer's noise emission intensity depended on the relative direction from the dryer inlet, transects shown are directly outward from the dryer inlet aligned with the dryer inlet axis. Site A included two bin-mounted top dryers on adjacent grain bins (Figure 5b,c); the dryer in Figure 5c with the yellow cover was the primary operating dryer from which the Site A transects extended. Figure 4 shows data with only the single dryer aligned with the transect operating and also with both dryers operating. Site B was a ground-mounted top dryer (Figure 1c).

(**a**) (**b**) (**c**)

Figure 5. Views of top dryer (**a**) without barriers installed, showing perforated metal sheet platform flooring; (**b**) with plywood wall barriers installed during test; and (**c**) showing transect with sound meter at 20 m distance from bin wall.

Figure 4 clearly shows that some dryers produced greater sound emissions than others. Notably, the top dryers at Sites A and B produced higher sound levels at a given distance than the much larger tower dryers. These data support the suggestion that the choice and configuration of fans and other equipment may be a more important factor in dryer sound emissions than the scale of the drying operation.

At site G, two transects were measured: the first included no obstructions and had clear line-of-sight to the dryer from all points, while the second passed through one of the several large steel grain bins that partly surrounded the site. Site G was also notable for being the most flat and open site studied, with few obstructions other than the grain bins and related equipment in the immediate vicinity of the dryer. Comparing the measurements along these two transects (Figure 4), it is notable that at any given distance, the sound level variation between the two measurements is generally only a few dB(A) and likely within the practical uncertainty of the experiment.

Inspection of the fit equations to the longer transects (those with measurements at distances greater than 100 m) reveals that the best fits occurred with N between 23 and 25. This means that sound levels were decreasing with increasing distance at a rate faster than the ideal inverse square law (N = 20) would suggest. In contrast, the fits to the transects less than or equal to 100 m have value of N between 19 and 21. This increased value of N in the longer transect fits may be due to effects of ground surface absorption and upward scattering of acoustic energy with distance [21].

The data in Figure 4 are not definitive but suggest that the use of Equation (1) with a measurement near a dryer to predict sound levels at greater distances may overestimate sound levels. Small changes in N can have significant impacts on predicted results. Table 2 shows predictions of the distance at which a sound level of 50 dB(A) (similar to rural background [14]) would occur for each site in Figure 4, using both N = 20 and the best fit value of N in Figure 4. Differences in the predicted distances to 50 dB(A) can be considerable.

Table 2. Predicted distance from dryer at which sound level of 50 dB(A) would be reached, based on sound level measured at 100 m distance, using Equation (1) with given values of N.

				Distance to 50 dB(A) Sound Level (m)		
Site	**Dryer Type**	**Sound Level at 100 m (dB(A))**	**Optimum N (from Figure 4)**	**Opt. N**	**N = 20**	**% Difference**
A	1 Top Dry (Bin) Running	68.5	19	936	837	12%
A	2 Top Dry (Bin) Running	72.8	21	1221	1384	−12%
E	Tower	58.4	19	276	262	5%
B	1 Top Dry (Ground) Running	66.2	25	445	646	−31%
F	Tower	64.1	23	411	509	−19%
G	Tower (no blockage) *	61.6	25	327	427	−23%
G	Tower (w/building blockage)	62.0	24	317	400	−21%

* Sound level at 112 m.

3.3. Top Dryer Noise Mitigation

One practical method of mitigating noise emissions is adding barriers adjacent to dryer intakes. During this study, the impact of adding plywood sound barriers adjacent to the fan intake of a top dryer was measured.

Measurements were taken at a GSI Maual Batch TopDry (model 2TFC-40151NM; Grain Systems Inc., Duluth, GA, USA) mounted on a steel-framed platform with a perforated steel floor (Figure 5a). Measurement height was 1.5 m above ground for this test. The platform floor was 3.5 m above ground, and the center of the dryer intake was 4.1 m above ground. The dryer intake was 1.2 m in diameter and 1.88 m outward from the side of the grain bin. Air temperature was 16 °C, and local wind speeds were low, averaging 0.8 m/s over the study period. There were no other significant noise sources during the tests. A transect was measured outward from the edge of the grain bin below the dryer, aligned with the long axis of the dryer (Figure 5c). Measurements were taken at distances from the bin wall of 0.4 m to 20 m for each of three test cases: (a) baseline configuration with no sound barriers, (b) 1.2 m tall vertical plywood sound barriers added to edges of platform (Figure 4b), and (c) plywood sound barriers on the perforated floor around the dryer intake plus the vertical barriers, as used in case (b).

Figure 6a shows measured sound levels for the three test cases. The increase in sound level pressure over the first few meters from the grain bin wall occurs because the dryer inlet (with center at 1.88 m from the bin wall and 2.6 m above measurement height) is the primary noise source. Notably, the sound levels directly below the dryer are higher for case (b) (wall barriers only) than for either case (a) (no barriers) or case (c) (wall and floor barriers). This is believed to be due to some additional sound being reflected downward by the barrier directly in front of the inlet. This theory is supported by the lower sound levels for case (b) than case (a) at greater distances from the bin wall.

Both mitigations provided noticeable, consistent sound level reductions at greater distances from the dryer and bin wall (Figure 6a). Considering all points between 7 m and 20 m from the bin wall, the mean attenuation (sound level reduction) due to wall barriers only (case (b)) was 5.4 dB(A) (standard deviation 0.45 dB(A)). Attenuation with both wall and floor barriers (case (c)) was 7.2 dB(A) (standard deviation 0.34 dB(A)). This magnitude of reduction is generally consistent with other studies.

Figure 6b shows the frequency distribution in one-third octave bands at 7.0 m from the bin wall for each of the three cases. Consistent with sound propagation theory, most of the reduction in sound levels occurred at the higher frequencies above about 500 Hz.

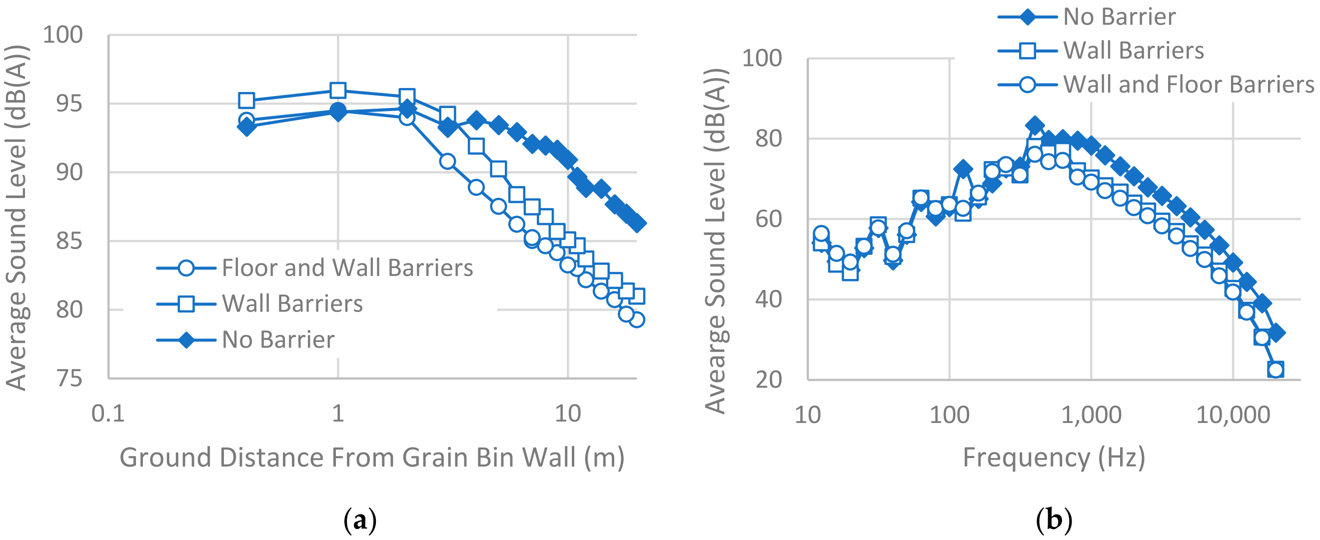


Figure 6. Measured sound level pressure (dB(A)) at 1.5 m above ground (**a**) as a function of horizontal distance from grain bin wall and (**b**) by frequency at a horizontal distance of 20 m from the bin wall.

3.4. Mitigation of Sound Levels Using Vertical Barriers

A possible mitigation strategy for grain dryers and similar equipment (such as grain bin aeration fans) is the addition of a vertical wall constructed of available materials to block line-of-site and increase insertion losses. A series of tests were conducted at a bin fan to measure the effect of a freestanding wall barrier in front of the fan inlet. Tests were conducted on 13 December 2022. The average temperature was −1 °C with very low wind speeds (average 0.2 m/s over the test period).

The bin aeration fan was a Coldwell model ILC18−312 axial centrifugal fan driven by a 3 kW electric motor. The fan had a circular inlet 0.54 m in diameter and was aligned perpendicular to the bin wall. The fan was supported on a concrete pad 0.31 m tall. The inlet center was 0.68 m above ground level. Measurements for this test were taken at distances between 0.85 m and 13.85 m from the fan inlet, with the microphone 0.82 m above ground, the lowest feasible height of the available equipment.

Baseline measurements were conducted without a barrier present, after which a barrier wall was constructed centered at 4.35 m from the fan inlet, consisting of 25 straw bales, stacked 5 bales wide and 5 bales high (Figure 7a). The resulting barrier was a vertical wall of straw 1.85 m high, 4.8 m wide, and 0.47 m deep. Tests with the bale wall were conducted with the bale wall as-built and then with additional surfaces of steel (commonly used for barn siding) or plywood sheets placed on the fan-facing side of the wall. A final test case involved removing the straw bale barrier and placing vertical sheets of particle board (each 2.4 m tall by 1.2 m wide) immediately in front of the fan inlet, and on both sides, enclosing the fan inlet with a three-sided box open on the top and on the binward side (Figure 7b). Each test was conducted twice to observe the repeatability of the measurements.

(**a**) (**b**)

Figure 7. Views of (**a**) grain bin with fan on left with straw bale barrier in place 4.35 m from fan inlet, and (**b**) three-sided box enclosing fan inlet.

Figure 8 shows the measured one-minute average sound levels for each case as a function of distance from the fan inlet. Both tests of each case are shown in Figure 8. For the case of the three-sided box, all measured points were behind the barrier, so the measured sound level at the closest point to the fan is much lower than for all the other cases. Interestingly, at the larger distances measured, all of the treatments resulted in an attenuation of approximately 10 to 12 dB(A) compared to the baseline case.

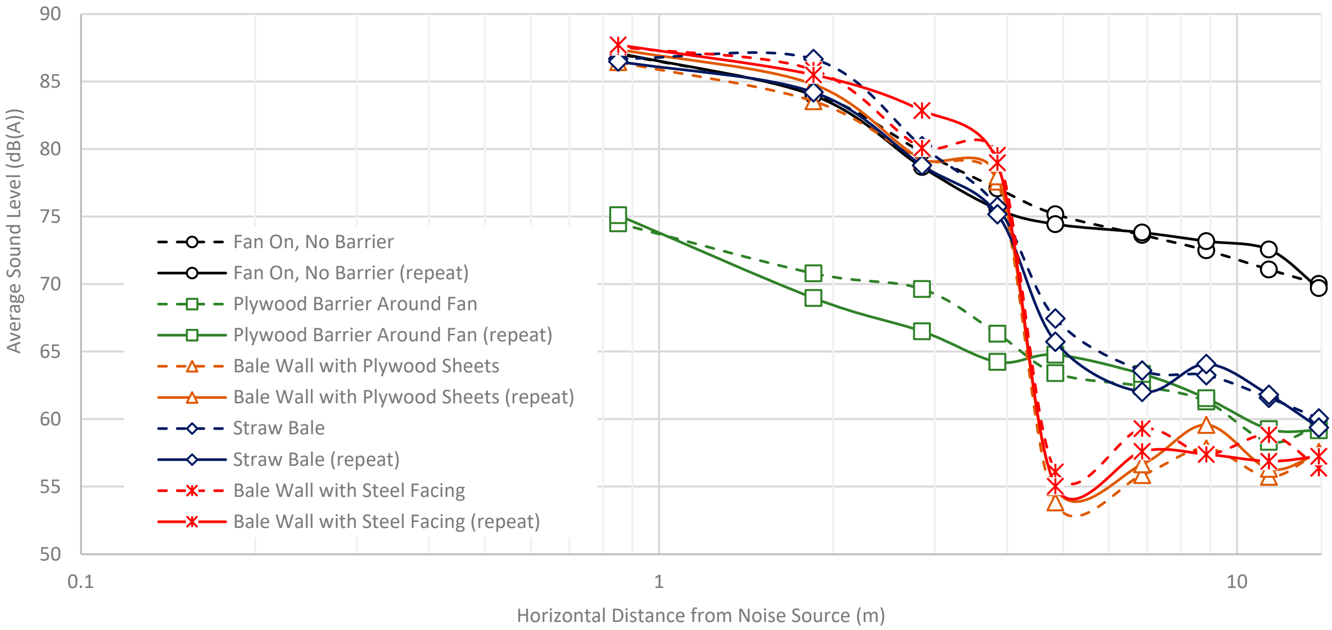


Figure 8. Measured sound level pressure (dB(A)) at 0.85 m above ground as a function of horizontal distance from fan inlet for different mitigation strategies.

4. Discussion

4.1. Site Surveys

A total of eleven sites surveyed had multiple points at 50 m and/or 100 m distance in a range of directions (Table 1). The greatest 100 m distance sound level observed across all sites was 72.8 dB(A) at Site A, with two bin-mounted top dryers in operation. All of the tower dryers (Sites C to H) had lower maximum 100 m sound levels, ranging between 64.0 dB(A) and 68.1 dB(A). Notably, the two dryers at Site A are much lower capacity than any of the tower dryers. The higher sound levels at Site A are believed to be due to the exposed location of the fan and heater units on the bin-mounted top dryers (e.g., Figure 1b). Sound propagation from the top dryer fans would be expected to be more directional than at the tower dryers.

Of the sites in Table 1, it was possible to take measurements at 100 m distances in all directions from the dryer(s) at Sites A, B, and G. The range in measured sound levels at 100 m (difference between maximum and minimum) at these sites was greatest for the two bin-mounted top dryers of Site A (18.5 dB(A)), somewhat lower for the single top dryer with a ground-mounted fan and heater at Site B (14.6 dB(A)), and lowest for the tower dryer at Site G (9.6 dB(A)). At all three sites, the dryer(s) were partially, but not completely, surrounded by steel grain storage bins. Interestingly, the lowest observed sound level at 100 m distance at each of the three sites varied less than the maximums (Site A: 54.4 dB(A), Site B: 52.7 dB(A), Site G: 55.9 dB(A)) and the highest 100 m minimum sound level was at the tower dryer. These observations suggest the interior mounting and vertical orientation of fans and heaters in the tower dryers result in the lowered directionality of noise emissions.

4.2. Sound Level Variation with Distance

An important question not examined in detail in prior literature is the measurement of the rate of sound level decrease as distance from the dryer increases. At greater distances (in the order of 100 m or more), Table 2 shows sound levels were observed to decrease somewhat faster than the inverse squared law would suggest (i.e., optimum N in Equation (1) was greater than 20), while the mitigation experiments generally saw a persistent attenuation of sound levels at all greater distances (out to approximately 15 m to 20 m) measured by adding a sound barrier (Figures 5a and 6). It is believed these results are compatible. When a barrier is placed near a dryer, as in the experiments here, sound levels are reduced behind the barrier, typically in the order of 5 dB(A) to 10 dB(A), likely due to a combination of reflection and insertion loss. As the sound propagates further, some is absorbed or reflected upward by the ground surface (which is typically soil or crops). The effect of insertion loss decreases as distance increases, but upward reflection or absorption of sound by the ground plain would be expected to increase. This latter effect would be expected to predominate at large distances, which is reflected in the results in Table 2 showing sound level attenuating with distance at a rate greater than the inverse of the distance squared (i.e., $N > 20$ in Equation (1)).

The choice of N in Equation (1) has a significant effect on the distance at which a predicted sound level would be observed. Table 2 summarizes the predicted distance at which Equation (1) predicts a 50 dB(A) sound level for a range of dryers, both assuming $N = 20$ (the normal use of the equation) and using the value of N in each case that produced the best fit to the data. The best-fit values of N ranged from 19 to 25, with higher values associated with the longer transects.

At Site G, there was little difference in predicted distance to 50 dB(A) between the two cases with and without storage bin blockage along the transect. This supports the observation that insertion loss is a primary mechanism for sound attenuation with blockage by structures, and so the attenuation due to blockage by structures will be greatest at shorter distances from the dryer, with decreasing effects on attenuation at greater distances.

4.3. Mitigation with Barriers near Fan Inlets

Overall, both mitigation experiments (plywood barriers adjacent to the fan of the top dryer and straw bale walls in front of the bin fan) attenuated sound levels relative to no-barrier tests. In the case of the top dryer, attenuation was 5.4 dB(A) with the wall barriers, increasing to 7.2 dB(A) with wall and floor barriers. This is comparable to the typical attenuation of 5 dB(A) to 8 dB(A) achieved with highway sound walls [23]. Fraser [5] observed an 8 dB(A) to 9 dB(A) reduction at similar distances with a sound absorbing panel installed in front of the inlet of a similar top dryer. The plywood panels in this study likely absorbed less acoustic energy than the panel used by Fraser [5], a possible explanation of the somewhat lower attenuation seen in the current study. Attenuation at the three-sided vertical plywood panel barrier (Figure 7b) was about 12 dB(A) (Figure 8), possibly due to the relatively higher extent of the barrier increasing both insertion length and potential for sound reflection.

The straw bale wall barrier also attenuated sound levels. Figure 8 shows that in all cases with the wall barrier present, a noticeable reduction in sound level is visible immediately behind the wall (at the 4.85 m distance) compared to the next closest points. A similar reduction does not occur in the baseline case. It was noted that adding the steel or plywood facing on the bin-facing side of the barrier resulted in additional attenuation immediately behind the barrier compared to the use of the barrier alone. However, at greater distances, this additional attenuation decreased. It is believed this may be a very local effect due to the location of the measurement point being very close to the rear face of the bale wall and the steel or plywood on the front face providing a more uniform blockage.

The repeated tests shown in Figure 8 also give an indication of test uncertainty and suggest that individual measurements have a practical uncertainty of one to two dB(A). The presence of the vertical straw bale wall results in an immediate attenuation for all barrier treatments that does not appear in the control case with no barrier present.

One concern when implementing a barrier is that placement of the barrier too close to the fan inlet (within a distance equal to a few inlet diameters) may increase air flow resistance at the inlet and result in decreased air flow or increased energy use. We did not have the instrumentation necessary to measure this effect; however, it would be valuable to include it in future mitigation experiments.

4.4. Changes in Dryer Technology

This study has experimentally measured the sound levels at distances from operating grain dryers, with modern tower dryers being the most represented. In 1997, Clarke et al. [14] measured sound levels at a dozen dryers, all but one of which used axial flow fans. These are known to be louder than centrifugal fans or blowers of comparable capacity. The tower dryers included in this study usually have fans or blowers located more centrally, in a manner that likely does not lead to the same direction-dependent high sound levels observed by Clarke et al. [14]. It is also notable that the industry is generally moving away from the loudest types of axial fans in newer grain dryers of all sizes. The field measurements in this current study suggest that grain drying technology (and expected sound levels) have changed considerably since Clarke et al. [14], and further study of current dryers and usage is warranted. The field experiments documented here can provide insights, but there remain too many uncontrolled variables between sites and even within the same site to be able to generalize the results.

5. Conclusions

This study measured ambient sound levels at various distances in a range of different operating grain drying facilities in Ontario, Canada. The effectiveness of barrier-based noise mitigation was also experimentally examined in two experimental case studies. Several overall conclusions can be drawn based on the results of these investigations.

Sound levels at a given distance from a grain dryer do not necessarily correlate to the size of the dryer. Larger tower dryers often produced lower sound levels at a given distance than other types of smaller dryers, likely due to the fans and burners being located centrally within the tower structure and oriented vertically, in contrast to the side-mounted horizontal fan intakes in other dryer types.

Most of the dryers studied were located adjacent to, and in some cases, almost surrounded by, large, circular-footprint steel grain storage bins. These obstacles reduced sound levels relative to unobstructed dryers, although the attenuation decreased at larger distances from the dryer. The primary mechanism of attenuation by the surrounding obstacles is likely insertion loss (i.e., increasing path distance between dryer and receptor) rather than sound absorption. Limiting line-of-sight visibility between a dryer and a receptor point is good practice.

The inverse-squared relationship for a point source (Equation (1)) was applied in prior studies to predict sound levels at a distance but was not tested. Our experimental results suggest that complicating factors such as varying absorption properties of ground surfaces and obstacles, weather, and details of dryer design introduce significant uncertainty when using this equation to extrapolate distances at which acceptable sound levels would occur. Extrapolation of sound levels to distances of several hundred meters from a dryer should be done with caution, assuming a relatively large uncertainty. At these distances, it may be appropriate to assume that sound levels decrease faster than the inverse square of the distance, likely to absorption and reflection from the ground plane.

Two different experiments suggested that barriers of common materials (plywood sheets, straw bales) adjacent to dryer or fan inlets may be effective ways to reduce noise emissions, and reductions in the order of 5 dB(A) to 10 dB(A) can be readily achieved in regions close to the dryer. At greater distances, measurements at operating dryers suggested that sound attenuation might be expected to decrease. Additional study would be recommended, since predicting the degree of sound attenuation is dependent on the dryer and surrounding structures, as well as characteristics of the surrounding ground and vegetation.

Author Contributions: Conceptualization, W.L. and J.D.; methodology, W.L. and J.D.; experiments, field measurements, data quality control and analysis, R.D., E.P. and K.T.; writing—original draft preparation, W.L., R.D., E.P. and K.T.; writing—review and editing, W.L. and J.D.; supervision, W.L.; project administration, W.L. and J.D.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), Ontario Agri-Food Innovation Alliance—Special Initiatives program, grant UG-SI-2020-100747: Investigating Noise Impacts of Grain Dryers on Neighbouring Land Uses).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to requirement to ensure confidentiality of data collection sites.

Acknowledgments: We wish to thank all the grain dryer owners and operators who provided information and access to their facilities.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Humann, M.; Sanderson, W.; Donham, K.; Kelly, K. Task-based Noise Exposures for Farmers Involved in Grain Production. *J. Agric. Saf. Health* **2013**, *19*, 101–113. [PubMed]
2. Holger, D. A Muffler for Agricultural Fans. *Trans. Am. Soc. Agric. Eng. (ASAE)* **1978**, 1178–1184. [CrossRef]
3. McCullagh, M. Preservation of Hearing Among Agricultural Workers: A Review of Literature and Recommendations for Future Research. *J. Agric. Saf. Health* **2002**, *8*, 297–318. [CrossRef] [PubMed]
4. Evans, J.; Whyte, R.T.; Price, J.S.; Bacon, J.M.; Semple, D.A.; Scarlett, A.J.; Stayner, R.M. *Practical Solutions to Noise Problems in Agriculture*; Silsoe Research Institute (UK) Research Report; HSE Books: Norwich, UK, 2004; p. 212.
5. Fraser, H. Understanding and Reducing Noise Nuisance from Stationary Farm Equipment. In *OMAFRA Factsheet*; Order No. 12-029, AGDEX 700; Ontario Ministry of Agriculture Food and Rural Affairs: Guelph, ON, Canada, 2012.
6. Noise Regulation (O. Reg. 381/15). Ontario Ministry of Labour, Training and Skills Development. Available online: https://www.labour.gov.on.ca/english/hs/pubs/noise/ (accessed on 9 April 2020).
7. Stansfeld, S.A.; Matheson, M.P. Noise pollution: Non-auditory effects on health. *Br. Med. Bull.* **2003**, *68*, 243–257. [CrossRef] [PubMed]
8. Khan, J.; Ketzel, M.; Kakosimos, K.; Sørensen, M.; Jensen, S.S. Road traffic air and noise pollution exposure assessment–A review of tools and techniques. *Sci. Total Environ.* **2018**, *634*, 661–676. [CrossRef] [PubMed]
9. Morillas, J.M.; Gozalo, G.R.; González, D.M.; Moraga, P.A.; Vílchez-Gómez, R. Noise pollution and urban planning. *Curr. Pollut. Rep.* **2018**, *4*, 208–219. [CrossRef]

10. León, C.J.; Hernández-Alemán, A.; Fernández-Hernández, C.; Araña, J.E. Are rural residents willing to trade-off higher noise for lower air pollution? Evidence from revealed preferences. *Ecol. Econ.* **2023**, *207*, 107784. [CrossRef]
11. NPC-300. Environmental Noise Guideline—Stationary and Transportation Sources—Approval and Planning (NPC-300). Ministry of Environment, Conservation and Parks. Available online: https://www.ontario.ca/page/environmental-noise-guideline-stationary-and-transportation-sources-approval-and-planning (accessed on 12 April 2020).
12. Ige, M.; Finner, M. Reduction of the aerodynamic noise generated by crop drying fans. *Trans. Am. Soc. Agric. Eng. (ASAE).* **1974**, *17*, 1177–1181.
13. PAMI. Resource Library: Drying, Grading and Storage Equipment. Prairie Agricultural Machinery Institute. 2020. Available online: http://pami.ca/resources/equipment-report-index/#group1 (accessed on 18 April 2020).
14. Clarke, S.; Toombs, M.; Rambié, S.; Richardson, R. Quantifying Grain Dryer Noise to Prevent Hearing Loss and Nuisance Complaints. In Proceedings of the Canadian Society of Agricultural Engineering (CSAE) Conference, Vancouver, BC, Canada, 5–9 July 1998.
15. Lubitz, W.D.; Teeter, K.; Parker, E. Noise Emissions from Ontario Grain Dryers. In Proceedings of the Canadian Society for Bioengineering Annual Conference, Charlottetown, PE, Canada, 24–27 July 2022. Paper No. CSBE22-128.
16. Bucklin, R.; Thompson, S.; Montross, M.; Abdel-Hadi, A. Grain storage systems design. In *Handbook of Farm, Dairy and Food Machinery Engineering*; Academic Press: Cambridge, MA, USA, 2019; pp. 175–223.
17. StatsCan. Statistics Canada. Canadian Grain Commission. Available online: https://www.grainscanada.gc.ca/en/grain-research/statistics/ (accessed on 7 February 2023).
18. Reinvee, M.; Luik, M.; Kliimak, P. Noise Emissions from Grain Dryers and Potential Noise Pollution. *Agron. Res.* **2013**, *11*, 457–462.
19. Dony, J.; (GHD, Waterloo, ON, Canada). Personal Communication, 13 April 2020.
20. Yang, F.; Bao, Z.Y.; Zhu, Z.J. An assessment of psychological noise reduction by landscape plants. *Int. J. Environ. Res. Public Health* **2011**, *8*, 1032–1048. [CrossRef] [PubMed]
21. Rossing, T.D.; Rossing, T.D. (Eds.) *Springer Handbook of Acoustics*; Springer: New York, NY, USA, 2014.
22. Lee, C.S.; Fleming, G.G. *Measurement of Highway-Related Noise*; No. FHWA-PD-96-046; Federal Highway Administration: Washington, DA, USA, 1996.
23. Klingner, R.E.; McNerney, M.T.; Busch-Vishniac, I.J. *Design Guide for Highway Noise Barriers*; Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin: Austin, TX, USA, 2003.
24. MacDonald, J.; Wayson, R.; Ei-Aassar, A.; Berrios, M. Sound levels and shadow zones behind barriers in Florida. *Transp. Res. Rec.* **2004**, *1880*, 158–164. [CrossRef]
25. Fang, C.F.; Ling, D.L. Guidance for noise reduction provided by tree belts. *Landsc. Urban Plan.* **2005**, *71*, 29–34. [CrossRef]
26. Maier, D.E.; Bakker-Arkema, F.W. Grain Drying Systems. In Proceedings of the 2002 Facility Design Conference of the Grain Elevator & Processing Society, St. Charles, IL, USA, 28 July 2002; pp. 28–31. Available online: https://fyi.extension.wisc.edu/energy/files/2016/09/Grain-drying-Systems-GEAPS-2002-secured.pdf (accessed on 2 April 2023).
27. Sadaka, S.; Jayas, D.S. Cereal grain drying systems. In *Storage of Cereal Grains and Their Products*; Rosentrater, K., Ed.; Woodhead Publishing: Sawston, UK, 2022; Chapter 10; pp. 293–329. [CrossRef]