2014

Modeling the H2S Concentrations Affected by Shelterbelts Downwind from a Swine Facility

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MODELING THE H_2S CONCENTRATIONS AFFECTED BY SHELTERBELTS DOWNWIND FROM A SWINE FACILITY

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Agricultural and Biosystems Engineering

South Dakota State University

2014

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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ACKNOWLEDGEMENTS

First and foremost I would like to thank Erin Cortus and Richard Nicolai. I would like to thank Erin Cortus for leading me through the development of this thesis and model. I would like to thank Richard Nicolai for asking me to work on this project and leading me through my first few years of graduate school. I could not have completed my research without the prior research that was completed and provided to me by Brett Hofer, so thank you to Brett. I would like to thank Jay Cobb for encouraging me to complete my Master's degree and allowing me to take time off for classwork. I would also like to thank my parents, family, and friends who encouraged me to get a Master's degree and always motivate me in whatever I do.

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ABSTRACT

MODELING THE H_2S CONCENTRATIONS AFFECTED BY SHELTERBELTS DOWNWIND FROM A SWINE FACILITY

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Odor from swine facilities can be a nuisance to the nearby residences and communities. Shelterbelts have been shown to positively impact the downwind air quality, but the impacts are dependent on wind speed and direction, and shelterbelt configuration. The first objective of this research was to develop an empirical model of shelterbelt-induced hydrogen sulfide (H_2S) concentration reductions as a function of horizontal distance beyond a swine facility, based on data from a previous study by Hofer (2009). The Hofer (2009) study measured H_2S concentrations at a swine facility at four discrete distances beyond the barn (55, 246, 510, and 805 m), two measurement heights (1 and 5.5 m), and with four shelterbelt configurations (no shelterbelt, 1-row, 2-row and 3-row).

Data from this study was sorted using a data selection criteria process, resulting in 10 potential regression models. Each regression model was compared to a Computational Fluid Dynamics (CFD) model that was developed by Taylor and Starke (2006), using correlation, Normalized Mean Square Error (NMSE), and line of regression analyses. While the Hofer (2009) research measured H_2S, the Taylor and Starke model (2006) described odor. In this research, H_2S was considered a measure of odor. A single regression model was selected using a two-step selection process with the correlation,

NMSE, and line of regression values. The regression model, $y = 5.7408 * x^{-0.48}$, where y is the percent H_2S reduction caused by the shelterbelt and x is the distance from the barn measured in meters, was selected.

The second objective of this research was to incorporate this empirical model into the South Dakota Odor Footprint Tool (SDOFT) version 4.0. The SDOFT was revised to allow user input of shelterbelts located on one or more sides of the facility. The regression model was also incorporated into the SDOFT to create revised odor annoyance-free setbacks and footprint graphs affected by shelterbelts. A demonstration of odor annoyance-free setbacks and footprint graphs for different typical swine facilities with or without shelterbelts was completed. These demonstration sites illustrate that shelterbelts have greater effect on odor closer to the shelterbelt, with only about a 20% reduction at 1,000 m downwind from the facility.

INTRODUCTION

Livestock facilities emit odor and gases. The emission of these odors and gases has become a larger concern to the general public in recent years. With new and expanding livestock operations, odor complaints from neighboring communities can increase (Rahman and Borhan, 2012). Urban encroachment into areas of animal feeding operations has increased the number of nuisance complaints and regulatory issues related to livestock odor (Parker et al., 2012). In extreme cases, nuisance law suits related to odor from livestock operations have been filed (Lin et al., 2006). Odor management can be a limiting factor in expanding a livestock operation, or establishing a new facility. It is suggested that the future of the swine industry will depend on effective odor mitigation technologies (Rahman and Borhan, 2012).

Planting shelterbelts or vegetative environmental buffers around livestock facilities is gaining interest as a means to addressing neighbor concerns regarding odor. Shelterbelts at swine facilities have shown promise for mitigating odors and particulate matter at swine facilities (Rahman and Borhan, 2012). While shelterbelts are well known to help dilute odors, a quantified odor dispersion capability of shelterbelts and ideal design for odor dispersion still need additional investigation (Lin et al., 2006)

Several livestock facility siting tools, such as the South Dakota Odor Footprint Tool (SDOFT) (Nicolai et al., 2006), Odor from Feedlots Setback Estimation Tool (OFFSET) (Jacobson et al., 2012), and the Nebraska Odor Footprint Tool (Stowell and Powers, 2009), can be used by producers to estimate odor emissions and setbacks from livestock facilities. All three of these tools do not currently have trees or shelterbelts as an odor control technology.

The research that was conducted by Hofer (2009), Parker et al. (2012), and Lin et al. (2006) all showed promising evidence that shelterbelts have an effect on hydrogen sulfide (H_2S) and odor concentrations downwind of swine and livestock facilities. The goal of this research was to address the lack of shelterbelts in current livestock facility siting tools. The specific objectives of this research were to:

1. Develop an empirical model of shelterbelt induced H_2S concentration reductions as a function of horizontal distance beyond a swine facility; and
2. Incorporate this empirical model into the existing SDOFT.

LITERATURE REVIEW

Livestock odor

Midwest Plan Service (2002) describes the general causes, sources, and impacts of odor. Livestock odors are caused by many volatile organic and inorganic compounds. Four primary sources of odors and gases on animal production facilities are livestock buildings and open lots, manure treatment/storage facilities, manure transport systems, and land application areas. Gases, including H_2S, ammonia, carbon monoxide, and methane, can be potential health risks inside of animal buildings. Hydrogen sulfide is generally considered the most dangerous gas in production buildings, and can kill animals and people during agitation of manure storages since it is released more quickly during this time. In ambient air near swine production buildings and manure storages, H_2S measurements were lower than the U.S. Occupational Safety and Health Administration (OSHA) 10 ppm limit for 8-hour H_2S exposure during several field tests (Bicudo et al., 2002).

Odors and gases that travel offsite from animal production facilities are generally considered a nuisance more than a potential health risk. The nuisance level is complex since odors evoke physiological and emotional reactions differently in different people. Larger animal production facilities and an increasing intolerance to odors surrounding facilities have amplified the odor impacts and perception of odors impacts nearby to animal facilities (Midwest Plan Service, 2002).

Measuring odor is complex since both the sense of smell and the odor itself are very complex. In general, there are two different methods to measuring odors. The first method is olfactometry. The advantage of using olfactometry is that it uses trained people, and their sense of smell, to identify the detection threshold and intensities of odors (Midwest Plan Service, 2002). This method has been employed to verify odor dispersion models (Guo et al., 2001), determine relationships between odor measurements and odor annoyance levels (Stowell et al., 2008), and measure odor plumes downwind of shelterbelts (Lin et al., 2006). Olfactometry has the advantage that it measures the complete gas mixture, but it has the disadvantage that it does not measure with the precision of chemical sensors (Akdeniz et al., 2012). Olfactometry is not the optimum method to use when trying to take measurements over a long period of time, since the trained individuals would have to be on-site throughout the entire measurement period.

The second general method of measuring odor is to measure individual gas concentrations. This can be an advantageous method of measurement when taking measurements over long time frames, since various sensors are available to measure and log data measurements. Research has been completed on the specific compounds that are the odor contributors from swine manure (Zhu et al., 1999). In this research, specific bacteria and volatile fatty acids in swine manure were identified as indicators of the manure odor potential. Research has also been completed to predict odor based on specific gas concentrations (Akdeniz et al., 2012). They found significant correlation between odor and H_2S concentration. The disadvantage of measuring an individual or a group of gas concentrations is that relationships between concentrations of specific gases or mixtures of gases and odor cannot definitively be accomplished (Midwest Plan Service, 2002).

Since no simple solution exists to measure odor, the research that was conducted by Hofer (2009) measured H_2S concentrations downwind from a swine facility. Specifically, the Hofer (2009) study measured H_2S concentrations at a swine facility at four distances beyond the barn (55, 246, 510, and 805 m), and with four shelterbelt configurations (no shelterbelt, 1-row, 2-row and 3-row) in an attempt to measure the H_2S reduction caused by shelterbelts.

While H_2S concentrations are not direct odor concentrations, research has shown that H_2S concentrations do have a positive relationship when compared to olfactometry results (Omotoso et al., 2005). Another study verified that the odor levels in animal houses could be obtained by correlating H_2S levels to odor (Zhang et al., 2013). While these studies have shown that there is a relationship between H_2S and odor, other research has indicated that H_2S may not always be a suitable indicator for smell (Zhu et al., 1999).

Odor control strategies

Many different odor control strategies exist on animal production facilities that produce varying levels of odor reduction. There are three general types of odor control strategies at livestock operations including in-house odor control strategies, outdoor odor control technologies, and strategies to control odor during land application of manure. With relation to the in-house and outdoor odor control strategies, some of these strategies attempt to reduce the actual odor produced with methods such as diet manipulation or manure additives. Some of these strategies attempt to reduce odor from leaving either the barn, such as with biofilters, or leaving the manure storage structure, such as with impermeable lagoon covers or straw covers (Rahman and Borhan, 2012).

Shelterbelts or vegetative environmental buffers attempt to control odor after it has left the barns or manure storages at a facility. Shelterbelts can lower odor through interception of odorous compounds and particulate matter within the shelterbelt and through additional mixing and elevating of odors into higher air streams (Rahman and Borhan, 2012). Specifically, shelterbelts have been shown to capture particulate matter on the exterior of their leaves, and gaseous volatile organic compounds within leafy vegetation (Parker et al, 2012). Also, approximately 90% of odor particles are in the size range that can be captured by trees, and are irregularly shaped, which can aid in particles being held on tree surfaces (Tyndall, 2010).

Figure 1 (Nicolai, 2010) shows some of these odor mitigation effects of a shelterbelt. The numbers on Figure 1 correspond to where the shelterbelt:

1. Prevents odors and dust particles from being picked up by wind
2. Encourages deposition of dust particles that transport odors
3. Intercepts and filter odors and dust particles already airborne
4. Disperses and dilute odors

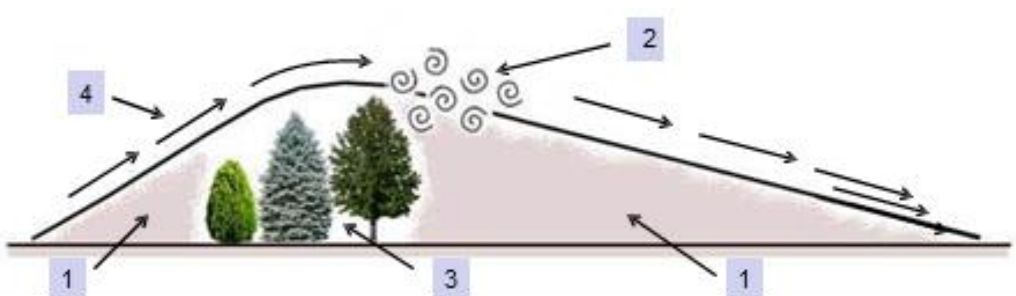

Figure 1. Shelterbelt effects on odor (Nicolai, 2010).

Since the shelterbelt does not capture the odors directly at the odor source, it is challenging to determine the odor reduction caused by shelterbelts. Differences in tree types and orientation within the shelterbelt, shelterbelt location and orientation at the facility, and weather make it challenging to determine the odor reduction caused by shelterbelts (Parker et al., 2012).

Lin et al. (2006) completed olfactometry field studies of odor to a maximum distance of approximately 600 m downwind of shelterbelts and concluded that odor was affected by the optical porosity of the shelterbelt, wind resistance provided by the trees, and weather conditions, specifically air temperature. Low optical porosity, trees that were more resistant to wind, and higher air temperatures all were determined to increase odor dispersion. It was also concluded odor dispersion effectiveness of windbreaks could be more effectively done with modeling, since comparisons were difficult with field testing due to variations in climate, tree, and weather conditions over time.

Modeling research has shown that odor reduction caused by shelterbelts is most effective closest to the shelterbelt, and becomes less effective at distances farther away from the shelterbelt (Taylor and Starke, 2006). Taylor and Starke (2006) developed a Computational Fluid Dynamics (CFD) model that showed a rapid decrease in the odor concentration at ground level for a shelterbelt that was adjacent to a poultry facility. Within and near the trees, the odor concentrations were reduced over 50% compared to a no-tree situation. The odor concentration then gradually converged back to a scenario without trees over a distance downwind from the trees.

Odor dispersion modeling and tools

There are several livestock facility siting tools, such as the SDOFT (Nicolai et al., 2006), Odor from Feedlots Setback Estimation Tool (OFFSET) (Jacobson et al., 2012), and the Nebraska Odor Footprint Tool (Stowell and Powers, 2009). These tools first develop an odor emission value for the facility, which is based on the characteristics of the facility including number of animals, type of housing, and type and size of manure storage. Some odor control technologies are utilized by these tools, such and biofilters and manure storage covers. These tools then use an odor dispersion model that take into account the odor emission value, and weather conditions to determine setbacks for the facility (Jacobson et al., 2005).

Challenges exist in using odor dispersion modeling. Odor concentrations, odor detection threshold, and odor intensity are all challenging to consistently correlate, and are also challenging to produce in an output that is easily understandable to the general public. In addition, limited field data is available to easily verify and evaluate these models (Jacobson et al., 2005).

The SDOFT (Nicolai et al., 2006), Odor from Feedlots Setback Estimation Tool (OFFSET) (Jacobson et al., 2012), and the Nebraska Odor Footprint Tool (Stowell and Powers, 2009) all use odor annoyance-free levels as output. The odor annoyance-free level was defined as an intensity of 2 (faint odor) on a 0 to 5 n-butanol intensity scale. If an odor is equal to or less than 2, it is considered not annoying. An odor annoyance-free frequency is then the percentage of time that the odor is considered not annoying. For example, the distance from a facility that would correspond to the 95% odor annoyance-free level would have annoying odors 5% of the time as predicted by the model (Guo et al., 2005).

The Minnesota Odor from Feedlots – Setback Estimation Tool (OFFSET) model was developed to estimate odor setback distances from animal production sites in Minnesota (Guo et al., 2005). In the development of the OFFSET model, six different weather conditions were used to correspond to odor-annoyance free frequencies (Guo et al., 2005). These six weather conditions and corresponding odor annoyance-free frequency levels are described in Table 1.

Table 1. Weather conditions and corresponding odor annoyance-free frequencies.

Weather Condition	Pasquill Weather Stability Class	Wind Speed, m s^{-1}	Corresponding Odor Annoyance-Free Frequency
W1	F	less than or equal to 1.3	99%
W2	F	less than or equal to 3.1	98%
W3	E	less than or equal to 3.1	97%
W4	E	less than or equal to 5.4	96%
W5	D	less than or equal to 5.4	94%
W6	D	less than or equal to 8.0	91%

MATERIALS AND METHODS

South Dakota Odor Footprint Tool

The SDOFT was developed by air quality research groups at South Dakota State University, University of Nebraska, and University of Minnesota for estimating the odor impacts from livestock facilities (Nicolai, 2006). The SDOFT version 4.0 (Nicolai et al., 2006) was used for this research. The SDOFT utilizes a two-step process. The first step is to determine the average odor emissions from the livestock facility and its manure storages. An individual Odor Emission Rate (OER) from a single source at the site is determined with Equation 1. The sum of all of the OERs at a site is the TOEF.

$$OER = (\text{Odor emission number} \times \text{Plan area} \times \text{Odor control factor}) / 10{,}000 \qquad (1)$$

The second step estimates the atmospheric dispersion of the odor. The dispersion is determined with average local weather conditions in three meteorological regions across South Dakota. The weather data used are the average wind speeds, wind directions and atmospheric stability conditions in South Dakota from various weather stations over a ten year period. The April through October months are the only months considered, since during winter months odor emissions are generally lower.

The output of the SDOFT is represented by odor annoyance-free frequency curves or footprints and numerical annoyance-free frequency values in different directions from the facility. The odor annoyance-free frequency curves represent the percent of time during spring through fall where odors are not considered annoying. The odor annoyance-free levels that are possible options within the SDOFT are 91%, 94%, 96%, 97%, 98%, and 99%.

Measured data

Research by Hofer (2009) was conducted by using emissions from a hog confinement facility to test H_2S dispersion characteristics of a shelterbelt. The Hofer (2009) measured data was used throughout this project. Specifically, the Hofer (2009) measurements were taken with four different shelterbelt conditions at the facility. These four different shelterbelt scenarios were no trees, one row of trees, two rows of trees, and three rows of trees. The shelterbelts in Hofer (2009) are illustrated with Figures 2 – 4. The optical porosity of each of the shelterbelt conditions were measured by the optical method (Loeffler et al., 1992). Values of the porosity for the one row of deciduous ash and honey locust mix was found to be 84% porous, the two row shelterbelt had an average porosity of 51%, and the three row shelterbelt was 38% porous.

Hofer (2009) recorded data for an approximate two-month period for each of the shelterbelt scenarios in the summers of 2007 and 2008. Weather data including the wind direction, wind speed, humidity, and solar radiation and were recorded every eight minutes. The H_2S concentrations were recorded every 17 minutes. Since the weather data and H_2S concentrations were not recorded simultaneously, the weather data measurements were matched to the nearest time reading of H_2S measurements. The data was filtered to conditions when the wind direction was out of the south/southeast, or wind directions between 145 and 180 degrees azimuth. This range of directions corresponded to the direction that the odor plume from the facility would be impacted by the shelterbelt.

Figure 2. The silhouettes of one tree row shelterbelt contrasted to show porosity.

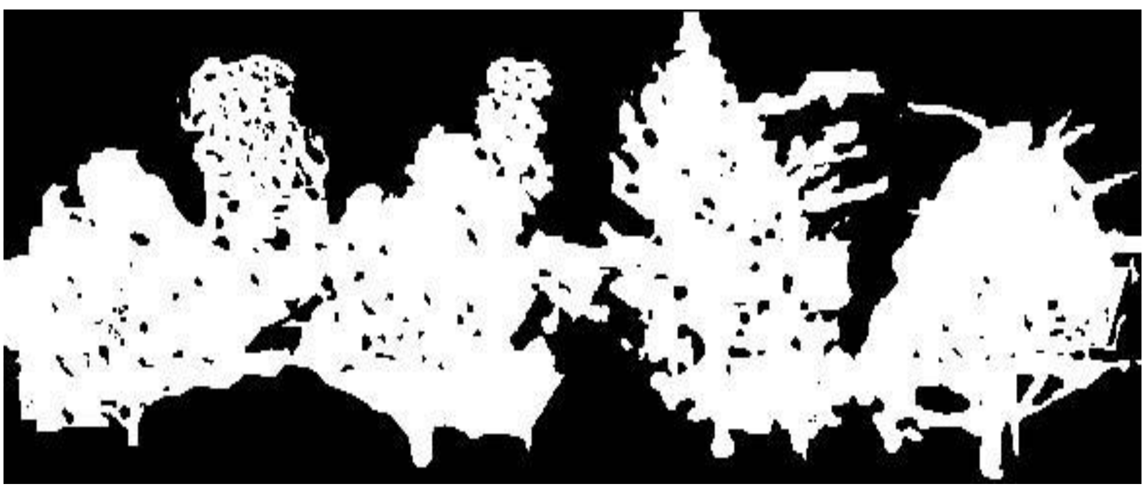

Figure 3. The silhouettes of two tree row shelterbelt contrasted to show porosity.

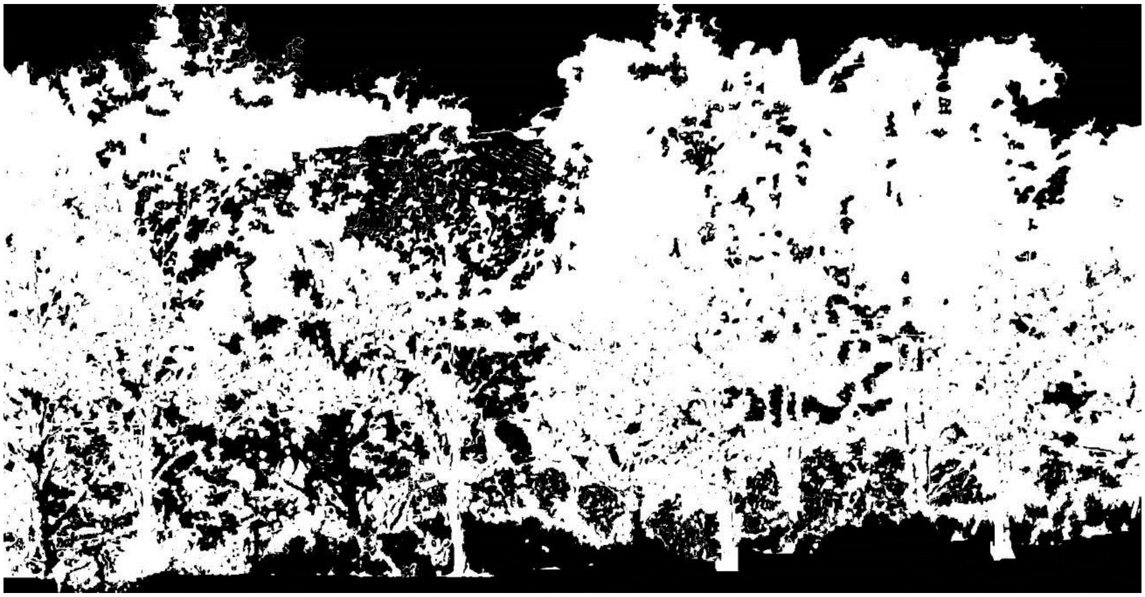

Figure 4. The silhouettes of three tree row shelterbelt contrasted to show porosity.

The Hofer (2009) research data had some limitations. Some limitations of this data included:

- Weather and H_2S concentration measurements were taken at 55 m, 246 m, 510 m, and 805 m fixed horizontal distances at only one swine facility.
- These measurements were taken for four different shelterbelt configurations of no trees, one tree row, two tree row, and three tree rows.
- The measurements were taken for approximately a two month period for each of the four shelterbelt configurations.
- There were some sampling errors at different measurement heights and distances, which led to gaps in the measured dataset.

Dataset formation

For Objective 1, the first step was to aggregate the Hofer (2009) data into representative dataset(s) for further modeling. Given the complexity and limitations of data collected by Hofer (2009), different grouping options were explored.

The Hofer (2009) research included some H_2S measurements that were within the W1 – W6 weather groups (see Table 1) and some measurements that were not. In an effort to utilize only the measured data in the Hofer (2009) research that was within the odor annoyance-free frequency levels, the measurements that were not within any of the W1 – W6 weather groups were not used within this research. The wind speeds and stability classes shown in Table 1 were used to sort measurements into the W1 – W6 weather groups.

Hofer (2009) concluded that many of the average H_2S concentration readings at the 805 m distance from the barns were greater than the readings at the 510 m distance. Hofer (2009) suggested that a farm to the southeast of the facility could have contributed to the slightly higher H_2S concentrations at the 805 m distance than at the 510 m distance. The 805 m H_2S measurements were recorded separately within the Hofer (2009) research, and thus could be removed from the data groupings.

Four conditions and subsequent combinations of the conditions resulted in 24 datasets (Table 2). The four conditions were:

- Measurement height (1 m, 5.5 m)
- The number of tree rows (one row, two rows, three rows)

- W1 – W6 weather groups (all weather groups combined into one dataset, all six weather groups in separate datasets)
- 805 meter H_2S measurement (included in the dataset, not included in the dataset)

Table 2. Datasets resulting from combinations of the Hofer (2009) data.

Type of Data Separation	H_2S Measurement Height, m	Number of Tree Rows	Were the W1-W6 Weather Conditions Combined Into One Dataset?	Was the 805 m H_2S Measurement Included?
1	1	1	No	Yes
2	5.5	1	No	Yes
3	1	2	No	Yes
4	5.5	2	No	Yes
5	1	3	No	Yes
6	5.5	3	No	Yes
7	1	1	Yes	Yes
8	5.5	1	Yes	Yes
9	1	2	Yes	Yes
10	5.5	2	Yes	Yes
11	1	3	Yes	Yes
12	5.5	3	Yes	Yes
13	1	1	No	No
14	5.5	1	No	No
15	1	2	No	No
16	5.5	2	No	No
17	1	3	No	No
18	5.5	3	No	No
19	1	1	Yes	No
20	5.5	1	Yes	No
21	1	2	Yes	No
22	5.5	2	Yes	No
23	1	3	Yes	No
24	5.5	3	Yes	No

Appendix A includes a summary table of the number of H_2S measurements and the average H_2S concentrations from the Hofer (2009) data with groupings described in Table 2. Also included in Appendix A is the base information for the condition with no trees at the facility. A frequency graph of the number of H_2S concentration measurements at different distances from the barn in different concentration ranges is included at the end of Appendix A.

Model dataset selection process

A selection process was used to determine which of the 24 different datasets would be used to create regression models. Ranking values were assigned to the different datasets based on the following rationale:

- Simplicity – Simplicity of the model was a criterion to ensure that the model could be easily incorporated into the SDOFT. Six regression models would need to be developed if the data was in six separate sets, while only one regression model would need to be developed if the data was grouped together. A value of two was assigned to datasets that combined all six weather conditions, and a value of one was assigned to datasets that kept all six weather conditions separate.
- Representative Shelterbelt - Shelterbelts are typically planted with multiple rows of trees in South Dakota. According to NRCS (2013), the base design criterion for shelterbelts for building site and livestock protection is that they should either contain a minimum of six rows or seven rows depending on their major land resource area. Additionally, for windbreaks that are specifically designed to intercept and reduce airborne particulate matter, chemicals, and odors should include multiple rows of tall trees to provide an adequate density in order to protect affected downwind area. In order to use measured data from a shelterbelt that most likely represents a typical South Dakota shelterbelt, a value of three was

given to the three row shelterbelt data, a value of two for the two row shelterbelt data, and a value of one for the one row shelterbelt data.

- Representative Weather Conditions – The model created by this research is intended to represent the effect that the shelterbelt has on odor reduction in the situations where the annoyance-free setback distances are developed within the SDOFT. Data groups that keep each W1 to W6 weather condition separate were considered to be more accurate, since there would be a separate regression model for each weather condition. These datasets would correspond to data separation types one through six and 13 through 18 in Table 2. A value of two was assigned to datasets that kept all six weather conditions separate, and a value of one was assigned to datasets that combined all six weather conditions.
- Data Availability – A regression model's accuracy is dependent on the quantity and quality of data the model is based on. However, sampling problems and natural weather conditions affected the data collected by Hofer (2009). For example, no data was observed during the research that fell into the W4 weather condition. Since there was no data for the W4 weather condition, no regression equation would be able to be developed for this individual weather condition. Because of this, a value of two was assigned to datasets that did have data available within all of its weather groups and sub-groups, and a value of one was assigned to datasets that did not have data available in all of its weather groups and subgroups.

Selection ranking criteria values were assigned to each of the 24 datasets. This can be seen in Table 3. Datasets which scored greater than the median score of seven were used to create a regression model.

Table 3. Datasets and their corresponding ranking criteria values.

Type of Data Separation	Simplicity	Representative Shelterbelt	Representative Weather Conditions	Data Availability	Total
1	1	1	2	1	5
2	1	1	2	1	5
3	1	2	2	1	6
4	1	2	2	1	6
5	1	3	2	1	7
6	1	3	2	1	7
7	2	1	1	3	7
8	2	1	1	3	7
9	2	2	1	3	8
10	2	2	1	3	8
11	2	3	1	3	9
12	2	3	1	3	9
13	1	1	2	1	5
14	1	1	2	1	5
15	1	2	2	1	6
16	1	2	2	1	6
17	1	3	2	1	7
18	1	3	2	1	7
19	2	1	1	3	7
20	2	1	1	3	7
21	2	2	1	3	8
22	2	2	1	3	8
23	2	3	1	3	9
24	2	3	1	3	9

Regression model development process

For the eight datasets selected for further analysis in the previous step, regression models describing H_2S reduction as a function of distance from the barns were created.

First, the H_2S reduction was calculated at each distance from the barn where the H_2S levels were measured. These distances were 55 m, 246 m, 510 m, and 805 m. The reductions were calculated by the following:

$$\% \ H_2S \text{ Reduction} = (1 - (\text{Average } H_2S \text{ concentration with that specific tree condition} / \text{Average } H_2S \text{ concentration with no trees})) * 100 \quad (2)$$

Using MS Excel, both a logarithmic and a power regression equation were then developed with these percent H_2S reduction values and given distance from the barn. Regressions were not completed for all eight datasets, and some of the data was adjusted prior to completing the regression in certain situations. These three situations and the three reasons for this were:

- Measurements at the 1 meter measurement height did not show a reduction in H_2S concentrations from zero trees to the 2 row condition for the 246 meter and the 510 meter distances from the barn. To complete the logarithmic regressions for these two datasets, the H_2S reduction was set to zero at 246 and 510 meters instead of a negative number. Power regressions were not completed for these two datasets.

- Measurements at the 5.5 meter measurement height did not show a reduction in H_2S concentrations from zero trees to the 2 row condition at the 805 meter distance from the barn. To complete the logarithmic regressions for these two datasets, the H_2S reduction was set to zero at 805 meters instead of a negative number. Power regressions were not completed for these two datasets.

- As noted in the appendix, data was not adequately measured at the 805 meter distance for the 1 meter measurement height during the three row shelterbelt data collection period. Since no H_2S reduction calculation could be calculated, no regressions that included the 805 meter distance were calculated.

Taylor and Starke (2006) model

Taylor and Starke (2006) developed a CFD model in order to understand the potential impact of trees on the odor downwind of a poultry facility. Their model simulated the drag or effective resistance that is produced by the porous trees, and how it would affect a ground level odor plume. The Taylor and Starke (2006) model was chosen to compare to the modeling within this paper since it specifically quantified the relationship of odor reduction from trees versus the horizontal distance from those trees.

The CFD model results created by Taylor and Starke (2006) were digitized and scaled using Terramodel Computer-Aided Design (CAD) software (Trimble) for unobstructed (without trees) and obstructed with trees conditions.

The trees in the Hofer (2009) and the Taylor and Starke (2006) model were not exactly the same distance from the barn. The horizontal distances of the Taylor and Starke (2006) results were shifted so the distances would coincide with relation to the downwind edge of the shelterbelt between the Hofer (2009) research and Taylor and Starke (2006) model.

After this horizontal shift, the values for every 50 meter increment for the tree condition and the non-tree condition were exported as a normalized scalar odor concentration. These values are summarized within Table 4. These two values at each 50 meter increment were compared to determine a percent odor reduction of the tree condition versus the non-tree condition at each 50 meter incremental distance from the barns for the Taylor and Starke (2006) CFD model.

Table 4. Odor concentrations for the Taylor and Starke (2006) comparison model.

Distance From Barn, m	Unobstructed Normalized Odor Concentration	Normalized Odor Concentration Obstructed by Trees	Reduction in Odor Concentration
150	0.03093	0.01534	50.41%
200	0.02520	0.01287	48.93%
250	0.02102	0.01115	46.95%
300	0.01781	0.00973	45.35%
350	0.01523	0.00858	43.70%
400	0.01320	0.00763	42.20%
450	0.01160	0.00690	40.56%
500	0.01023	0.00629	38.49%
550	0.00885	0.00575	35.02%
600	0.00746	0.00514	31.05%
650	0.00674	0.00481	28.71%
700	0.00628	0.00449	28.46%
750	0.00569	0.00417	26.68%
800	0.00530	0.00389	26.52%
850	0.00498	0.00377	24.32%
900	0.00463	0.00349	24.58%
950	0.00433	0.00342	21.02%
1000	0.00392	0.00312	20.36%

Regression model comparison with CFD model and selection

The regression models that were developed were evaluated by comparing their agreement with the CFD model that was created by Taylor and Starke (2006). Procedures within Section 5.1.4 of (ASTM, 2008) were used to complete this comparison. Four tools for assessing model performance were calculated, which included the correlation coefficient, r, the line of regression slope, b, and intercept, a, and the Normalized Mean Square Error (NMSE).

These four assessment tools were calculated with paired values between the two models at 50 meter increments. The paired values were compared from 150 m from the barn out to 1,000 meters from the barn. The lower boundary condition of 150 m was chosen, since a typical odor footprint created by the SDOFT would not be within 100 meters of the barns. The upper 1,000 m boundary condition of the regression analysis was chosen since the no data existed past 1,000 meters for the Taylor and Starke (2006) CFD model, and Hofer (2009) measured data was only measured to 805 meters past the barn.

The ASTM D5157 – Standard Guide for Statistical Evaluation of Indoor Air Quality Models suggests adequate model performance criteria boundaries. These boundaries are:

- Correlation coefficient (r) of 0.9 or greater
- Regression slope (b) between 0.75 and 1.25
- Regression intercept (a) 25% or less of the average measured concentration
- NMSE of 0.25 or lower

The first step in this selection process was to eliminate the regression models that did not fall within all four criteria boundaries. The second step in the selection process was to pick a final regression model from the models that remained after the first step. The criterion for the second step in the selection process was to select the regression model that ranked best by the NMSE statistic. If the remaining models had the same NMSE, then the regression model would be chosen by the regression slope and intercept. If the remaining models had the same regression slope and intercept, then the regression model would be chosen by its correlation coefficient.

This ranking system was based on two main factors. The NMSE was considered the most important statistical factor since it measures the magnitude of the difference between the Taylor and Starke (2006) model and the developed model over the entire distance that was analyzed. The correlation coefficient (r) was considered the least important since it measures the relationship between the Taylor and Starke (2006) model and the developed model, but would not show the difference in the magnitude between the models if the difference was consistent along the entire analyzed distance.

Integration of the shelterbelt regression model into the SDOFT

The SDOFT utilizes a two-step process to determine the odor annoyance-free frequency footprints for a facility. The first step is to determine the Total Odor Emissions Factor (TOEF) for the livestock facility and its manure storages. The second step estimates the atmospheric dispersion of the odor. The odor control technologies, such as a biofilter or a pond cover, that are currently in the SDOFT directly reduce the TOEF for the facility in the first step of the process. A shelterbelt affects the atmospheric dispersion of the odor. Because of this, the second step within the SDOFT was modified to incorporate the shelterbelt H_2S reduction regression model.

The existing odor control technologies within the SDOFT, such as biofilters and pond covers, equally reduce the odor annoyance-free setback distances in all directions from a facility. Shelterbelts would only affect the odor annoyance-free setback distances in all directions from a facility if they were planted on all sides of a facility. Shelterbelts are generally not planted on all four sides of a facility. A revised section was added to the user input portion of the SDOFT. This section allows the user to choose shelterbelts located on one or more sides of the facility. This revised user input part of the SDOFT spreadsheet to add trees is noted in green in Figure 5.

County of Site	Brookings				
	Source 1	Source 2	Source 3	Source 4	Source 5
Source Type	Swine Barn	Swine Barn	Swine Barn	Swine Barn	Manure Storage
Housing Type or Manure Storage	Gestation - Pull Plug	Gestation - Pull Plug	Farrowing	Farrowing	Earthen Storage Basin
Emitting Factor	146	146	68	68	63
Emitting Surface					
Width (ft)	80	80	75	75	550
Length (ft)	550	550	400	400	250
Emitting Area (sq ft)	44000	44000	30000	30000	137500
Odor Control Technology	A No Odor Control	A No Odor Control	A No Odor Control	A No Odor Control	A No Odor Control
Odor Control Factor	1	1	1	1	1
Source Emitting Factor	642	642	204	204	866
Shelterbelts	Shelterbelt Locations: ☑ North Side of Site	☑ South Side of Site	☑ East Side of Site	☑ West Side of Site	
			Total Odor Emitting Factor (TOEF)		2559

Figure 5. Shelterbelt entry section (highlighted green) that was added within the SDOFT.

A table within the SDOFT contains calculated odor annoyance-free setback distances that equate to TOEF levels for each SDOFT area, direction, and odor annoyance-free percentage. A revised table was developed by using the shelterbelt H_2S reduction regression model to adjust each setback distance assuming it were affected by a shelterbelt. The shelterbelt H_2S reduction regression model was only applied to setback distances if they were less than or equal to 1,000 m. This maximum boundary was used to match the maximum distance used in the Taylor and Starke (2006) CFD model.

The odor annoyance-free setbacks are shown two different ways within the SDOFT. A table within SDOFT, as shown in Figure 6, shows the setback distances for four different directions from the facility. The directions are North, South, East and West for counties within SDOFT area 1. The directions are Northeast, Southeast, Southwest, and Northwest for counties within SDOFT areas 2 and 3.

SETBACK DISTANCES FROM ODOR SOURCE AT VARIOUS ODOR ANNOYANCE-FREE FREQUENCIES IN FEET						
Direction from source	99% Annoyance-free	98% Annoyance-free	97% Annoyance-free	96% Annoyance-free	94% Annoyance-free	91% Annoyance-free
North	6920	3800	2815	2271	1672	1234
East	4486	2337	1637	1461	1033	530
South	4806	2433	1816	1527	1136	650
West	4666	2257	1750	1339	1086	538

Figure 6. Odor annoyance-free setback output table within the SDOFT.

A graph or footprint of the odor annoyance-free setbacks is also shown within the SDOFT. This graph is developed from the calculated setbacks from 12 different directions from the site. These twelve azimuth directions were 0^o, 10^o, 25^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o, 335^o, and 350^o. The setbacks in the 45^o, 135^o, 225^o, 315^o azimuth directions were selected to be affected by shelterbelts on either one or two different sides of the facility. The setbacks on the other eight azimuth directions would be affected by shelterbelts on only one particular side of the facility. A summary of these directions and which shelterbelts will affect the odor annoyance-free setbacks in the revised SDOFT are shown in Table 5.

Table 5. Effect of shelterbelts on SDOFT setback distances in different directions.

Azimuth Direction	Shelterbelts that Affect SDOFT Setback
0	North
10	North
25	North
45	North, East
90	East
135	South, East
180	South
225	South, West
270	West
315	North, West
335	North
350	North

Demonstration of swine facilities with and without shelterbelts

In order to demonstrate the revised SDOFT that incorporates shelterbelts at facilities, odor footprints for four different swine facilities of varying sizes were calculated. These four swine facilities were:

- Facility A - site with a 40’ x 200’ single swine finishing deep pit barn (approximately a 1,000 head finisher swine facility)
- Facility B - site with three 40’ x 200’ swine finishing deep pit barns (approximately a 3,000 head finisher swine facility)
- Facility C - site with four 80’ x 200’ swine finishing deep pit barns (approximately an 8,000 head finisher swine facility)
- Facility D - site with two 80’ x 550’ swine gestation pull plug barns, two 75’ x 400’ farrowing barns, and a 550’ x 250’ earthen storage basin (approximately a 5,000 head breeding, gestation, and farrowing swine facility)

These facilities were compared with no shelterbelts designated in the SDOFT, and with shelterbelts designated on all four sides of the facility. These comparisons were made for all of the available directions and in all three SDOFT areas. Other than the shelterbelts, no other odor control technologies were selected for this comparison.

RESULTS AND DISCUSSION

Datasets used in model development

Eight different datasets were selected based on the dataset selection criteria. These eight datasets included the measurements taken as shown in Table 6.

Table 6. Datasets selected to create models.

Type of Data Separation	H_2S Measurement Height, m	Number of Tree Rows	Were the W1-W6 Weather Conditions Combined Into One Dataset?	Was the 805 m H_2S Measurement Included?
9	1	2	Yes	Yes
10	5.5	2	Yes	Yes
11	1	3	Yes	Yes
12	5.5	3	Yes	Yes
21	1	2	Yes	No
22	5.5	2	Yes	No
23	1	3	Yes	No
24	5.5	3	Yes	No

These datasets were all of the two and three row shelterbelt measurements where all of the weather conditions W1 – W6 were combined into one set of data. These datasets included both 1 and 5.5 meter H_2S measurement heights. They also both included and did not include the 805 meter measurements from the barn.

Figures 7 and 8 show the percent reduction of H_2S concentrations for the two and three-row shelterbelt configurations versus the corresponding H_2S concentration with no tree rows. The figures show the variation in the distance from the barn, and the elevation of where the measurements were recorded.

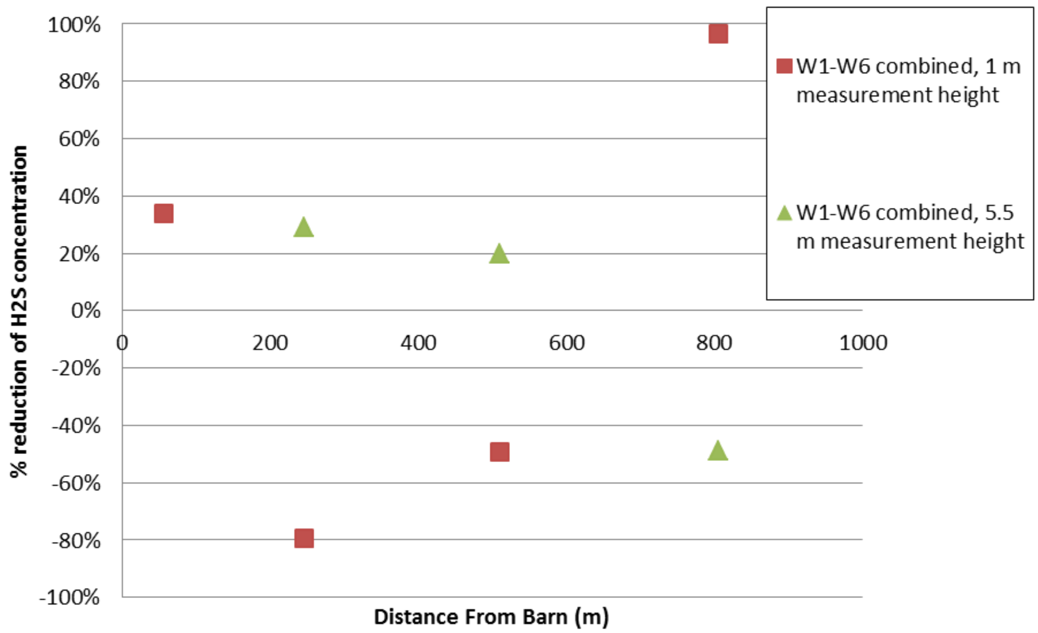

Figure 7. The average H_2S concentration reduction between the two row shelterbelt and the no shelterbelt scenario. The measurements were taken at 1 m and 5.5 m above the ground.

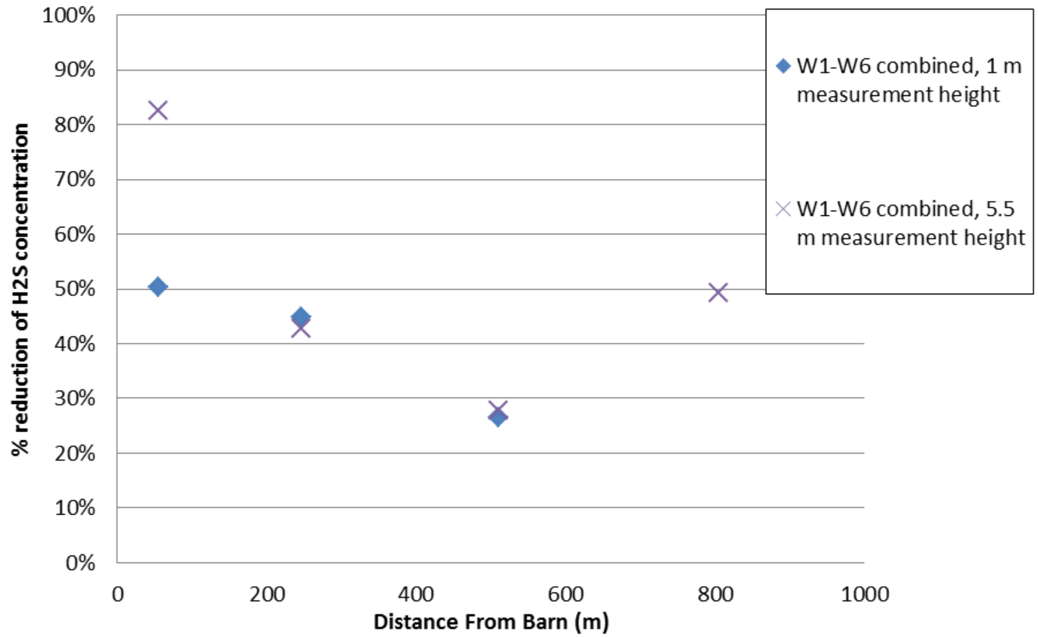

Figure 8. The average H_2S concentration reduction between the three row shelterbelt and the no shelterbelt scenario. The measurements were taken at 1 m and 5.5 m above the ground.

Regression model development

Regression models were developed for the sets of data that met the model selection data criteria. Table 7 includes the regression equations and coefficients of determination for all of the developed models. In the regression equations, y is the percent H_2S reduction caused by the shelterbelt and x is the distance from the barn measured in meters.

Table 7. Regression equations for selected datasets.

Type of Data Separation	Regression Type	Regression Equation (Y = % reduction; x = distance, m)	Coefficient of Determination (R^2)
9	power	[c]	
21	power	[c]	
9 [a]	log	y = 0.1206ln(x) - 0.3503	0.0969
21 [a]	log	y = -0.164ln(x) + 0.9721	0.8969
10	power	[c]	
22	power	[c]	
10 [b]	log	y = -0.235ln(x) + 1.6088	0.8896
22 [b]	log	y = -0.128ln(x) + 0.9939	1
11	power	[d]	
23	power	$y = 1.5089 * X^{-0.257}$	0.7287
11	log	[d]	
23	log	y = -0.097ln(x) + 0.9137	0.7743
12	power	$y = 2.2835 * X^{-0.282}$	0.5475
24	power	$y = 5.7408 * X^{-0.48}$	0.9939
12	log	y = -0.159ln(x) + 1.3992	0.6577
24	log	y = -0.248ln(x) + 1.8128	0.9967

[a] The negative H_2S reduction percentages at 246 m and 510 m distances were adjusted to zero prior to completing the regression.
[b] The negative H_2S reduction percentage at the 805 m distance was adjusted to zero prior to completing the regression.
[c] Power regression lines were not created since H_2S reductions at some distances were negative.
[d] 3 row, 1 meter measurement height data was not adequately recorded at the 805 meter distance.

Both the power and logarithmic regressions for the 3 tree row condition, 5.5 meter measurement height, and not including the 805 meter measurements showed the best fit with coefficients of determinations both over 0.99. All of the regressions developed from the two tree row H_2S reductions were questionable since the data showed an H_2S increase at one or two specific distances from the barn. This is not what is to be expected, but could be attributed to the limited amount of data measured under each specific situation.

Regression model analysis

The performance of the regression models was assessed by comparing them to the odor reduction percentages in the Taylor and Starke (2006) model and the statistical comparisons are summarized in Table 8. The values that do not fall within the adequate model performance criteria, as noted previously, are italicized.

Table 8. Statistical comparison of regression models to Taylor and Starke (2006) model.

Regression Model			Statistical comparison to Taylor and Starke (2006)			
Type of Data Separation	Regression Type	Regression Equation	Correlation Coefficient (r)	Line of Regression Slope (b)	Line of Regression Intercept (a)	NMSE
9	log	y = 0.1206ln(x) - 0.3503	***-0.969***	***-1.442***	***0.924***	0.211
21	log	y = -0.164ln(x) + 0.9721	0.969	1.06	***0.398***	***-9.261***
10	log	y = -0.235ln(x) + 1.6088	0.969	***0.74***	***0.238***	***0.829***
22	log	y = -0.128ln(x) + 0.9939	0.969	***1.359***	0.079	***0.344***
23	power	$y = 1.5089 * X^{-0.257}$	0.951	***2.058***	***-0.287***	0.044
23	log	y = -0.097ln(x) + 0.9137	0.969	***1.793***	***-0.209***	0.034
12	power	$y = 2.2835 * X^{-0.282}$	0.949	***1.435***	***-0.227***	0.033
24	power	$y = 5.7408 * X^{-0.48}$	0.932	1.065	0.027	0.033
12	log	y = -0.159ln(x) + 1.3992	0.969	1.094	-0.101	0.033
24	log	y = -0.248ln(x) + 1.8128	0.969	***0.701***	***0.158***	0.088

The two models that fell within all four adequate model performance criteria boundaries were both for the 3 tree row shelterbelt with a 5.5 meter H_2S measurement height as noted in Table 8. One of these two models was developed with a power regression not using the 805 meter H_2S measurements, and the other model was developed with a logarithmic regression using the 805 meter H_2S measurements. Each of these two models had the same NMSE, so the line of regression slope and intercept were then used to select the final regression model. This model was the 3 tree row shelterbelt, 5.5 m H_2S measurement height, power regression model that didn't use the 805 meter H_2S measurement in the regression. This model, $5.7408 * x^{-0.48}$, was then used to incorporate into the SDOFT and is shown in Figure 9.

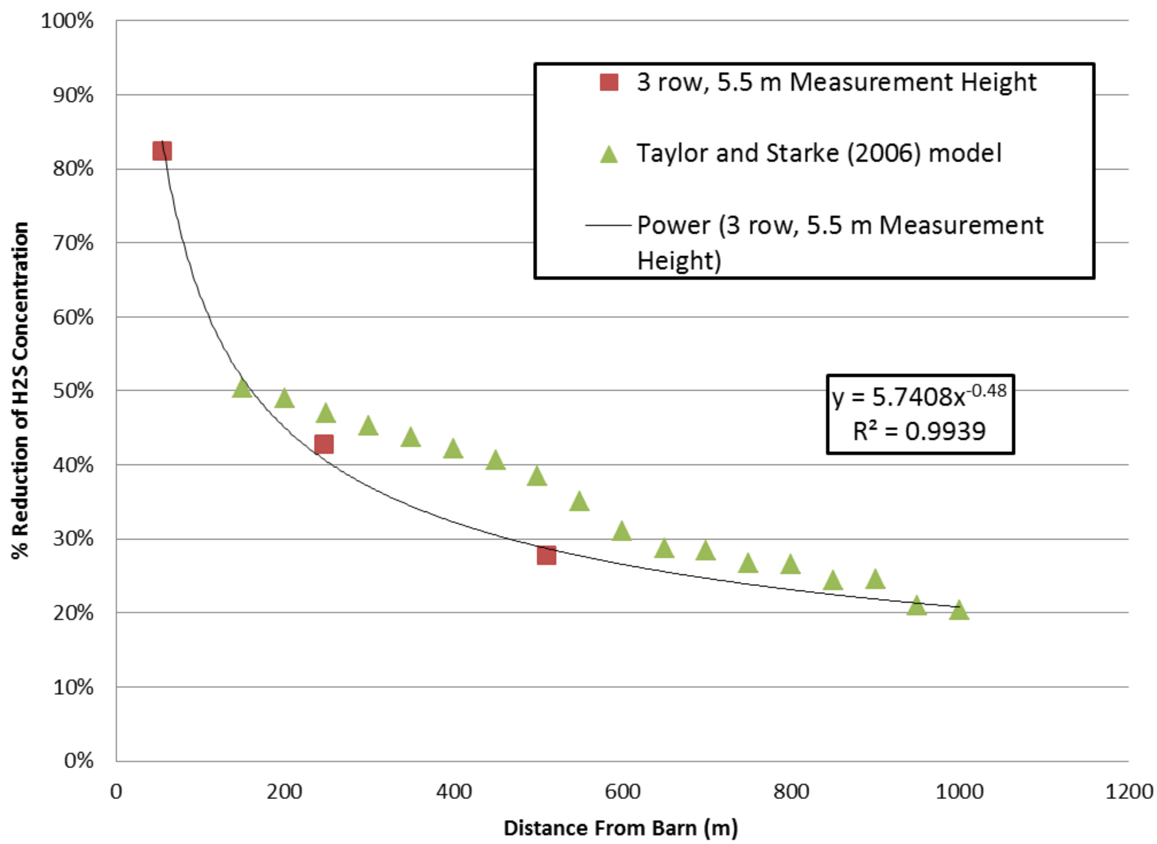

Figure 9. Power regression model based on data from the three row shelterbelt, 5.5 m H_2S measurement height, and not utilizing the 805 m measurements and the Taylor and Starke (2006) model.

The Hofer (2009) data used to develop the empirical model was H_2S concentration, and the Taylor and Starke (2006) CFD model used odor concentration.

While H_2S concentrations are not direct odor concentrations, for the purpose of this research, H_2S reduction and odor reduction caused by shelterbelts are assumed equivalent.

The odor reduction caused by shelterbelts was largest directly downwind of the shelterbelt. The model shows that H_2S concentrations are reduced by about 63% at 100 m downwind from the facility, about 50% at 150 m downwind from the facility, and the reduction is gradually reduced to approximately 20% at 1,000 m downwind from the facility when a shelterbelt is present. Since the model was only compared to the Taylor and Starke (2006) CFD model between 150 m and 1,000 m downwind from the facility, the range of the use of the model should also only be between 150 m and 1,000 m downwind from a facility.

Inclusion of the shelterbelt regression model into the SDOFT

The selected model, $y = 5.7408 * x^{-0.48}$, was incorporated into the SDOFT. An existing table within the SDOFT contains calculated odor annoyance-free setback distances that equate to TOEF levels for each SDOFT area, direction, and odor annoyance-free percentage. A revised table was developed by using the shelterbelt H_2S reduction regression model to adjust each setback distance assuming it were affected by a shelterbelt. This revised table within the SDOFT is shown in Appendix B.

Demonstration of swine facilities with and without shelterbelts

An impact of a shelterbelt on the estimated odor footprint for four swine facilities was calculated using the revised SDOFT. The TOEF calculated by the SDOFT for Site A was 132, Site B was 396, Site C was 1,056, and Site D was 2,559 OU/s x 10^4. For these four facilities, the SDOFT output tables of odor annoyance-free setback distances, as depicted in Figure 6, were summarized in Tables 9 through 11.

Table 9. Setback distances (ft) for demonstration facilities, SDOFT Area 1.

		Odor Annoyance-Free Percentage					
	Shelterbelts =>	99	99	96	96	91	91
		No	Yes	No	Yes	No	Yes
Facility	Direction						
A	North	4689	4689	1561	1098	876	533
A	East	3079	2659	1040	665	427	191
A	South	3291	2857	1080	698	521	259
A	West	3247	2815	1035	661	395	168
B	North	8725	8725	2783	2155	1515	1057
B	East	5473	5473	1672	1190	555	284
B	South	5940	5940	1859	1351	771	449
B	West	5730	5730	1658	1178	616	330
C	North	14377	14377	4479	4479	2251	1689
C	East	9165	9165	2789	2202	651	356
C	South	10113	10113	2909	2309	1092	706
C	West	8989	8989	2868	2273	658	361
D	North	24072	24072	6807	6807	3044	2387
D	East	14326	14326	3869	3869	732	419
D	South	16306	16306	4325	4325	1093	707
D	West	14365	14365	4348	4348	798	471

Table 10. Setback distances (ft) for demonstration facilities, SDOFT Area 2.

Facility	Shelterbelts =>	Odor Annoyance-Free Percentage					
		99	99	96	96	91	91
		No	Yes	No	Yes	No	Yes
	Direction						
A	Northeast	2970	2558	767	447	533	268
A	Southeast	2251	1691	828	495	456	212
A	Southwest	2492	1902	850	513	486	233
A	Northwest	1666	1187	801	474	579	302
B	Northeast	5244	5244	1418	976	936	580
B	Southeast	4170	4170	1465	1015	730	417
B	Southwest	4617	4617	1495	1040	763	443
B	Northwest	3048	2390	1465	1015	1023	650
C	Northeast	8658	8658	2208	1691	1160	762
C	Southeast	6973	6973	2283	1717	847	509
C	Southwest	7764	7764	2413	1831	1088	703
C	Northwest	5489	5489	2486	1934	1648	1171
D	Northeast	14033	14033	3810	3810	2031	1500
D	Southeast	11333	11333	3556	3262	1230	820
D	Southwest	12578	12578	3587	3287	1062	682
D	Northwest	8996	8996	3952	3952	2412	1830

Table 11. Setback distances (ft) for demonstration facilities, SDOFT Area 3.

Facility	Shelterbelts =>	Odor Annoyance-Free Percentage					
		99	99	96	96	91	91
		No	Yes	No	Yes	No	Yes
	Direction						
A	Northeast	1601	1132	606	323	274	86
A	Southeast	1515	1059	781	458	508	250
A	Southwest	1815	1314	756	438	420	185
A	Northwest	1941	1423	953	595	664	367
B	Northeast	2922	2278	1025	652	388	163
B	Southeast	2886	2247	1406	966	850	512
B	Southwest	3240	2561	1305	882	600	317
B	Northwest	3792	3765	1773	1276	1170	770
C	Northeast	4964	4964	1449	1002	381	158
C	Southeast	5063	5063	2290	1723	1276	858
C	Southwest	5522	5522	2218	1661	954	594
C	Northwest	6723	6723	3026	2416	1931	1413
D	Northeast	8079	8079	2085	1545	602	320
D	Southeast	8453	8453	3572	3274	1794	1295
D	Southwest	8960	8960	3142	2858	1191	788
D	Northwest	11420	11420	4909	4909	2980	2330

An odor annoyance-free graph or footprint is created by the SDOFT. As a demonstration of the effect that shelterbelts have on facilities with different TOEFs, three odor footprints are shown in Figures 10 through 12. All of these odor footprints were for the facilities when located in the SDOFT Area 1.

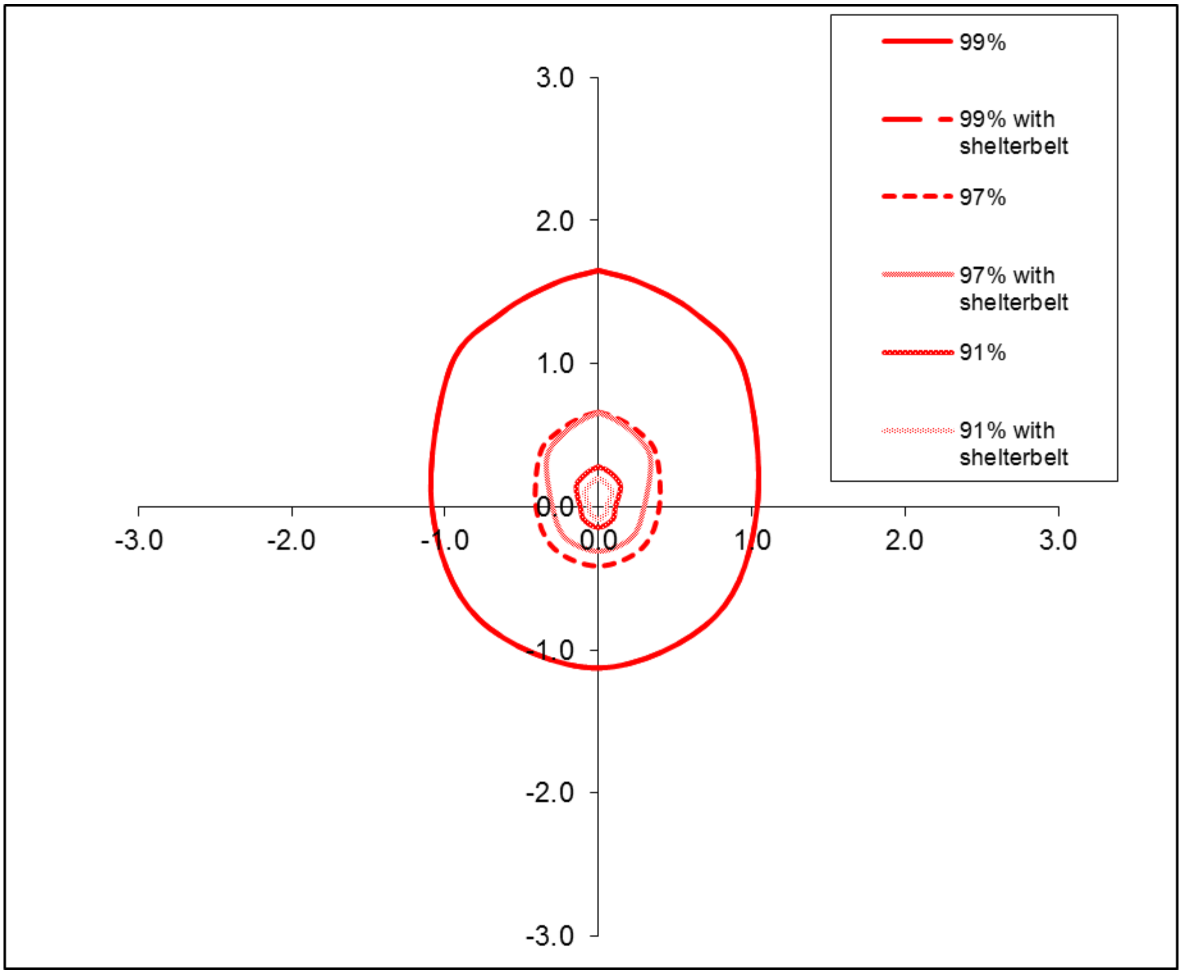

Figure 10. Odor footprint (miles) for Facility B in SDOFT Area 1.

Figure 10 and Figure 11 show the odor footprints for Facility B. The odor footprint for the 99% odor annoyance-free level is unaffected by adding a shelterbelt to all four sides of the facility, while the odor footprint is reduced for the 97% and 91% levels when adding shelterbelts.

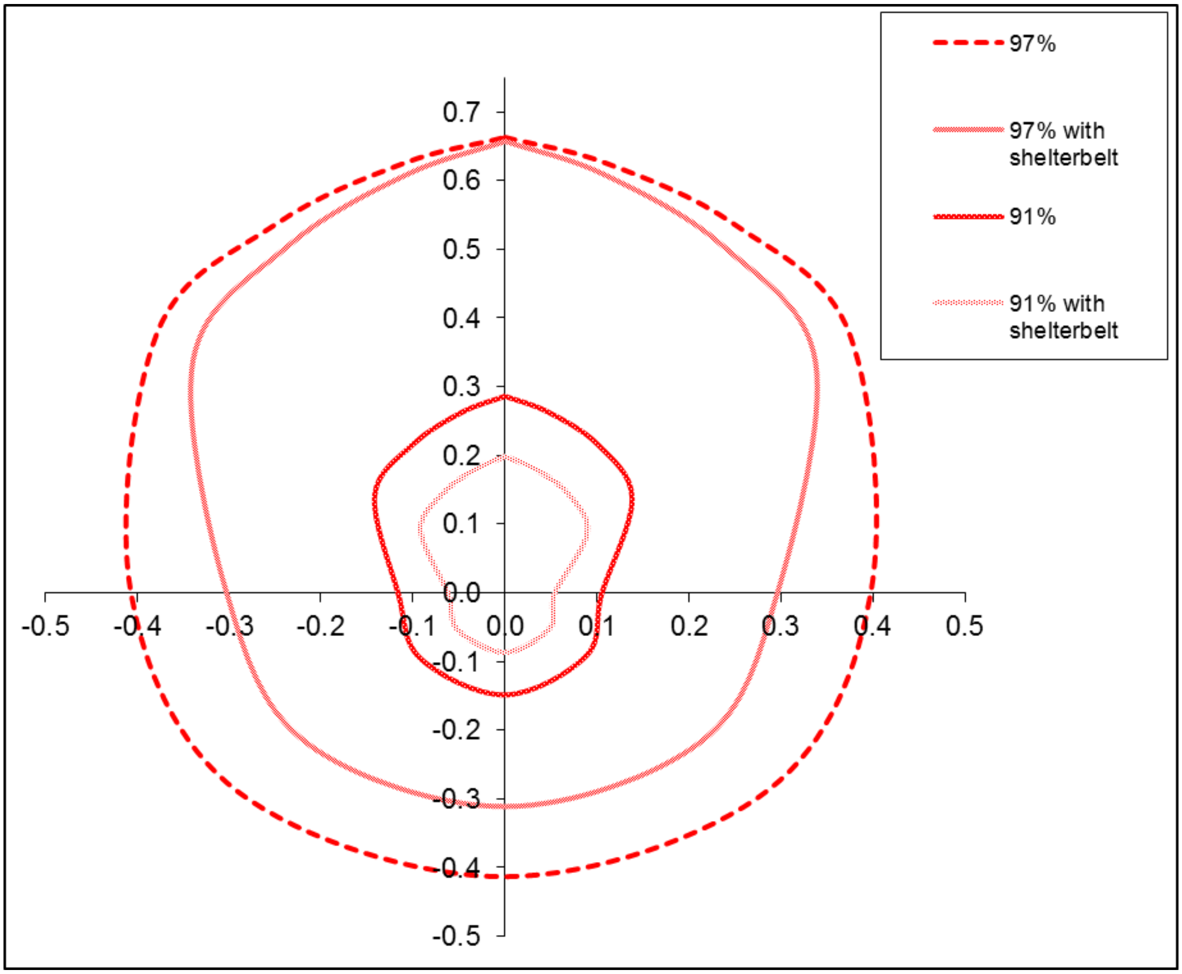

Figure 11. Odor footprint (miles) for Facility B in SDOFT Area 1 (Closer View of 91% and 97% odor annoyance-free frequency levels).

Figure 12 shows the odor footprint for Facility D. The odor footprints for the 98% and 96% odor annoyance-free levels are unaffected by adding a shelterbelt to all four sides of the facility, while the odor footprint is only reduced for the 91% level when adding shelterbelts around the facility.

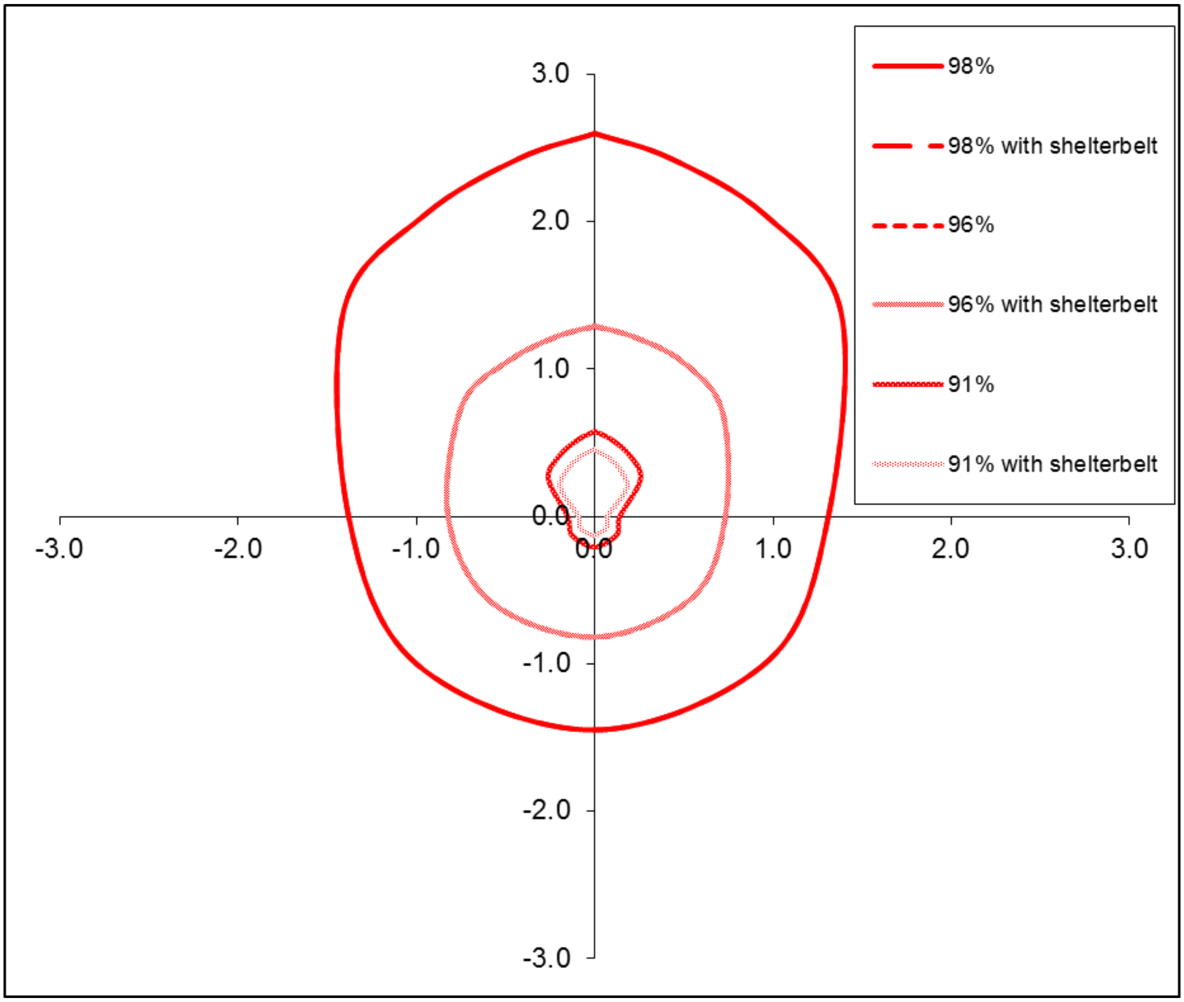

Figure 12. Odor footprint (miles) for Facility D in SDOFT Area 1.

Within the revised SDOFT, the empirical model was only applied to odor annoyance-free setbacks of 1,000 m or less when impacted by shelterbelts. Odor annoyance-free setbacks of 1,000 m or less are generated in the SDOFT for smaller facilities rather than larger facilities and for lower odor annoyance-free percent levels versus higher odor annoyance-free percent levels. This implies that shelterbelts will have the most impact on the SDOFT output for small facilities when low odor annoyance-free percentages are selected. The revised SDOFT output is unaffected when shelterbelts are added to facilities that have non-shelterbelt setback values over 1,000 m.

CONCLUSION

The empirical model, $5.7408 * x^{-0.48}$, describing the H_2S concentration reductions as a function of horizontal distance caused by a shelterbelt was developed. When there is a shelterbelt at the facility, the model shows that H_2S concentrations are reduced by about 63% at 100 m downwind from the facility, and the reduction is gradually reduced to approximately 20% at 1,000 m downwind from the facility. The empirical model was incorporated into a revised version of the SDOFT. The user of the revised SDOFT can select a shelterbelt on any of the four sides of the facility. The revised SDOFT provides adjusted odor annoyance-free setback distances and odor footprints depending on the location of the shelterbelt at the animal facility.

FURTHER RESEARCH

The data that was a used for the model that was developed during this research was from a single swine facility, taken only during a small time frame, with only four locations for measurements downwind from the swine facility. The Taylor and Starke (2006) CFD model was the only model used to compare to the model that was developed during this research. To add to the verification of these models, continued research with additional shelterbelt modeling would be recommended to further understand the interaction of shelterbelts with odor could be considered.

Some specific topics may include studying how tree rows, tree types, seasonal tree changes, tree spacing, and row spacing affects odor reduction. Field studies utilizing additional or alternative odor measurements other than H_2S, longer timeframes for studies, and smaller time intervals between measurements. Additional modeling is needed to further understand how much odor is intercepted by shelterbelts and what controls the distance that odor is affected downwind of a shelterbelt.

APPENDIX A

Summary of the number of measurements and average H_2S concentrations

Table 12 is a summary table of the number of H_2S measurements and the average H_2S concentrations that were used from the Hofer (2009) research data. The summary table includes the data divided into the following categories:

- No tree rows, one tree row, two tree row, and three tree rows situations
- 1 meter and 5.5 meter heights that the data was recorded
- The six different weather classifications, the total of the six different weather classifications, and data not within the six different weather classifications
- The 55 meter, 246 meter, 510 meter, and 805 meter distances from the barn

Table 12. Summary of the number of H_2S measurements and the average H_2S concentrations used from the Hofer (2009).

Number of Tree Rows	H_2S Measurement Height, m	Weather Classification	Distance From Barn, m							
			55	246	510	805	55	246	510	805
			Number of H_2S Measurements				Average H_2S Concentration			
0	1	W1	230	230	158	176	8.18	4.93	5.00	2.88
0	1	W2	100	100	84	86	8.60	3.67	3.12	3.08
0	1	W3	94	94	79	82	11.02	2.12	2.72	2.96
0	1	W4	0	0	0	0				
0	1	W5	1066	1066	749	758	10.92	2.09	1.75	2.28
0	1	W6	462	462	320	320	3.75	0.82	0.64	0.39
0	1	Total of W1 - W6	1952	1952	1390	1422	8.78	2.21	2.00	2.02
0	1	Not Within W1 - W6	1106	1106	809	826	2.53	0.64	2.28	1.84
0	5.5	W1	230	230	176	176	34.89	7.67	3.49	4.29
0	5.5	W2	100	100	86	86	24.59	6.76	3.54	6.06
0	5.5	W3	94	94	82	82	16.78	3.54	3.25	2.63
0	5.5	W4	0	0	0	0				
0	5.5	W5	1066	1066	758	758	15.26	2.83	2.20	2.80
0	5.5	W6	461	462	320	320	8.47	1.48	0.78	0.46
0	5.5	Total of W1 - W6	1951	1952	1422	1422	16.52	3.31	2.18	2.65
0	5.5	Not Within W1 - W6	1105	1106	826	817	6.51	1.19	1.31	2.88

Number of Tree Rows	H_2S Measurement Height, m	Weather Classification	Distance From Barn, m							
			55	246	510	805	55	246	510	805
			Number of H_2S Measurements				Average H_2S Concentration			
1	1	W1	144	144	70	75	4.54	1.29	0.08	0.90
1	1	W2	164	164	78	81	3.42	1.16	0.00	0.45
1	1	W3	102	102	37	77	6.39	0.34	0.03	0.64
1	1	W4	0	0	0	0				
1	1	W5	2036	2036	543	1377	1.90	1.47	0.42	0.52
1	1	W6	1504	1504	574	403	0.34	0.57	0.34	0.18
1	1	Total of W1 - W6	3950	3950	1302	2013	1.58	1.08	0.33	0.46
1	1	Not Within W1 - W6	1130	1130	369	570	2.55	2.44	1.40	1.81
1	5.5	W1	144	144	0	105	7.44	0.53		1.79
1	5.5	W2	164	164	0	121	6.02	0.36		0.54
1	5.5	W3	101	102	0	89	8.26	0.33		0.39
1	5.5	W4	0	0	0	0				
1	5.5	W5	1726	2036	0	1701	4.90	0.35		0.65
1	5.5	W6	958	1504	0	952	1.74	0.14		0.21
1	5.5	Total of W1 - W6	3093	3950	0	2968	4.40	0.28		0.54
1	5.5	Not Within W1 - W6	930	1130	0	837	3.18	0.56		2.01
2	1	W1	286	286	281	286	9.33	7.39	4.82	0.03
2	1	W2	106	106	106	106	6.16	6.74	3.91	0.21
2	1	W3	106	106	103	106	5.21	1.21	2.31	0.18
2	1	W4	0	0	0	0				
2	1	W5	838	838	837	838	5.28	3.43	2.87	0.07
2	1	W6	226	226	226	226	3.36	1.53	1.00	0.00
2	1	Total of W1 - W6	1562	1562	1553	1562	5.80	3.96	2.99	0.07
2	1	Not Within W1 - W6	948	948	948	948	3.71	2.68	1.95	0.00
2	5.5	W1	0	143	286	286		1.34	3.94	4.00
2	5.5	W2	0	53	106	106		4.13	2.76	9.33
2	5.5	W3	0	53	106	106		1.63	1.64	7.66
2	5.5	W4	0	0	0	0				
2	5.5	W5	0	419	838	838		2.68	1.14	3.45
2	5.5	W6	0	113	226	226		1.87	0.83	1.38
2	5.5	Total of W1 - W6	0	781	1562	1562		2.35	1.75	3.94
2	5.5	Not Within W1 - W6	0	474	948	948		5.43	0.67	2.10

Number of Tree Rows	H_2S Measurement Height, m	Weather Classification	Distance From Barn, m							
			55	246	510	805	55	246	510	805
			Number of H_2S Measurements				Average H_2S Concentration			
3	1	W1	157	219	121	0	1.84	1.05	2.37	
3	1	W2	135	136	68	2	4.15	1.65	4.52	
3	1	W3	91	80	48	0	17.74	1.51	2.52	
3	1	W4	0	0	0	0				
3	1	W5	788	822	549	0	4.20	1.24	2.15	
3	1	W6	655	735	603	0	3.64	1.15	0.52	
3	1	Total of W1 - W6	1826	1992	1389	2	4.36	1.22	1.47	
3	1	Not Within W1 - W6	572	528	357	0	2.43	0.74	0.80	
3	5.5	W1	217	230	208	17	7.10	4.13	2.87	5.35
3	5.5	W2	148	157	114	12	4.78	3.44	3.38	2.63
3	5.5	W3	85	100	56	20	4.99	3.18	2.57	3.94
3	5.5	W4	0	0	0	0				
3	5.5	W5	781	886	688	204	2.51	1.26	1.29	1.51
3	5.5	W6	647	739	714	246	1.46	1.46	1.11	0.66
3	5.5	Total of W1 - W6	1878	2112	1780	499	2.90	1.90	1.58	1.34
3	5.5	Not Within W1 - W6	540	637	416	149	0.92	0.81	1.37	0.96

Figure 13 is a frequency table of the number of H_2S measurements corresponding to different H_2S concentration ranges. This figure includes all measurements for the three tree row configuration taken at the 5.5 measurement height.

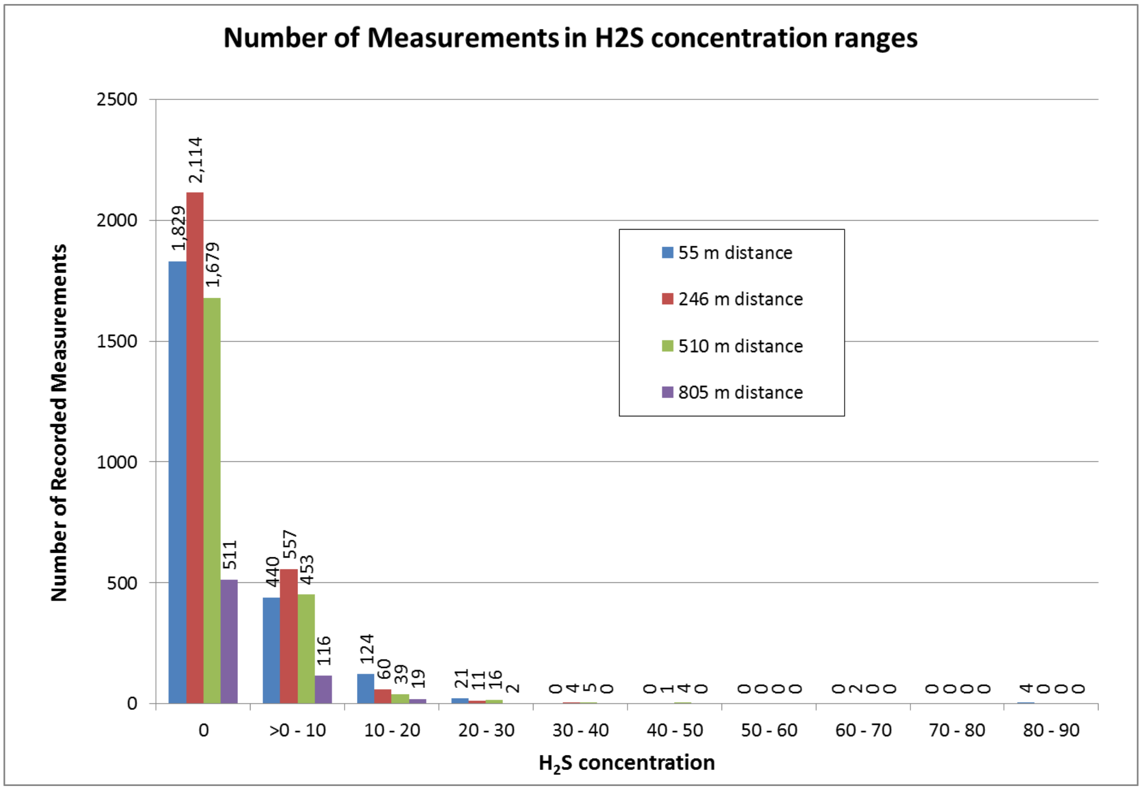

Figure 13. Number of H_2S measurements corresponding to different H_2S concentration ranges for three tree rows at the 5.5 m measurement height.

APPENDIX B

SDOFT setback tables revised to account for shelterbelts

The following tables 13 through 24 are included in the revised SDOFT for setback distances that are affected by a shelterbelt in all directions.

Table 13. Setback distances (mi) reduced for shelterbelts, Area 1, North direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.238	0.092	0.054	0.040	0.034	0.023
100	0.775	0.311	0.224	0.178	0.125	0.086
200	1.129	0.624	0.345	0.272	0.192	0.132
300	1.413	0.773	0.452	0.353	0.244	0.169
400	1.662	0.925	0.667	0.410	0.286	0.202
500	1.864	1.062	0.760	0.465	0.323	0.218
1000	2.646	1.610	1.104	0.830	0.469	0.314
2000	4.015	2.253	1.585	1.154	0.762	0.424
3000	4.988	2.870	1.922	1.396	0.940	0.474
4000	5.983	3.470	2.208	1.580	1.049	0.691

Table 14. Setback distances (mi) reduced for shelterbelts, Area 1, East direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.115	0.070	0.053	0.044	0.034	0.026
100	0.394	0.168	0.132	0.107	0.072	0.029
200	0.738	0.278	0.190	0.166	0.112	0.051
300	0.913	0.366	0.237	0.206	0.132	0.050
400	1.042	0.422	0.297	0.226	0.141	0.054
500	1.206	0.625	0.337	0.273	0.171	0.063
1000	1.696	0.831	0.631	0.400	0.256	0.067
2000	2.413	1.147	0.868	0.706	0.335	0.068
3000	2.950	1.437	1.033	0.753	0.337	0.089
4000	3.431	1.606	1.133	0.792	0.337	0.092

Table 15. Setback distances (mi) reduced for shelterbelts, Area 1, South direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.194	0.091	0.064	0.050	0.035	0.022
100	0.424	0.200	0.139	0.113	0.083	0.044
200	0.790	0.301	0.213	0.172	0.120	0.060
300	0.978	0.378	0.269	0.219	0.152	0.071
400	1.131	0.455	0.310	0.257	0.179	0.086
500	1.301	0.654	0.360	0.293	0.190	0.091
1000	1.865	0.881	0.658	0.420	0.275	0.134
2000	2.759	1.265	0.895	0.736	0.347	0.134
3000	3.348	1.593	1.086	0.885	0.428	0.134
4000	3.813	1.754	1.274	1.001	0.463	0.134

Table 16. Setback distances (mi) reduced for shelterbelts, Area 1, West direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.177	0.085	0.061	0.050	0.035	0.022
100	0.419	0.175	0.120	0.108	0.068	0.028
200	0.776	0.284	0.215	0.162	0.113	0.039
300	0.944	0.342	0.251	0.178	0.144	0.059
400	1.091	0.403	0.305	0.225	0.155	0.063
500	1.226	0.478	0.349	0.252	0.175	0.068
1000	1.661	0.915	0.663	0.412	0.275	0.068
2000	2.397	1.246	0.894	0.744	0.354	0.076
3000	2.976	1.488	1.046	0.886	0.417	0.099
4000	3.262	1.719	1.254	0.913	0.427	0.104

Table 17. Setback distances (mi) reduced for shelterbelts, Area 2, Northeast direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0						
50	0.238	0.092	0.054	0.040	0.034	0.023
100	0.379	0.142	0.089	0.069	0.054	0.041
200	0.709	0.215	0.138	0.117	0.095	0.072
300	0.874	0.274	0.175	0.151	0.127	0.097
400	0.998	0.323	0.215	0.186	0.150	0.110
500	1.146	0.361	0.252	0.221	0.177	0.132
1000	1.598	0.646	0.365	0.302	0.229	0.140
2000	2.337	0.892	0.710	0.622	0.378	0.226
3000	2.911	1.105	0.917	0.800	0.638	0.330
4000	3.269	1.287	1.065	0.923	0.727	0.360

Table 18. Setback distances (mi) reduced for shelterbelts, Area 2, Southeast direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.177	0.085	0.061	0.050	0.035	0.022
100	0.273	0.137	0.097	0.078	0.056	0.033
200	0.420	0.211	0.155	0.127	0.092	0.056
300	0.668	0.266	0.199	0.161	0.116	0.066
400	0.795	0.320	0.236	0.194	0.138	0.079
500	0.868	0.375	0.271	0.222	0.160	0.092
1000	1.287	0.691	0.395	0.317	0.200	0.095
2000	1.885	0.958	0.725	0.466	0.299	0.128
3000	2.353	1.208	0.892	0.737	0.385	0.177
4000	2.756	1.414	1.024	0.833	0.425	0.189

Table 19. Setback distances (mi) reduced for shelterbelts, Area 2, Southwest direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.194	0.091	0.064	0.050	0.035	0.022
100	0.304	0.143	0.102	0.082	0.059	0.038
200	0.480	0.226	0.161	0.129	0.094	0.058
300	0.746	0.288	0.207	0.167	0.121	0.074
400	0.880	0.346	0.248	0.198	0.144	0.084
500	0.980	0.394	0.279	0.223	0.163	0.089
1000	1.433	0.727	0.420	0.338	0.238	0.132
2000	2.093	1.045	0.753	0.487	0.329	0.144
3000	2.610	1.272	0.908	0.729	0.372	0.117
4000	3.022	1.468	1.052	0.836	0.431	0.143

Table 20. Setback distances (mi) reduced for shelterbelts, Area 2, Northwest direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.115	0.070	0.053	0.044	0.034	0.026
100	0.189	0.116	0.090	0.075	0.061	0.047
200	0.301	0.184	0.144	0.122	0.100	0.078
300	0.389	0.239	0.185	0.160	0.133	0.104
400	0.455	0.287	0.223	0.194	0.160	0.124
500	0.669	0.332	0.257	0.226	0.183	0.141
1000	1.012	0.634	0.396	0.349	0.285	0.216
2000	1.495	0.916	0.750	0.662	0.425	0.316
3000	1.868	1.146	0.932	0.817	0.662	0.370
4000	2.218	1.319	1.092	0.960	0.772	0.438

Table 21. Setback distances (mi) reduced for shelterbelts, Area 3, Northeast direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0						
50	0.110	0.060	0.061	0.032	0.016	0.007
100	0.181	0.098	0.070	0.052	0.027	0.013
200	0.286	0.155	0.110	0.081	0.041	0.023
300	0.360	0.198	0.141	0.101	0.054	0.017
400	0.434	0.236	0.166	0.124	0.058	0.031
500	0.623	0.265	0.192	0.134	0.080	0.033
1000	0.916	0.400	0.271	0.185	0.107	0.029
2000	1.352	0.719	0.380	0.275	0.155	0.047
3000	1.671	0.868	0.472	0.306	0.142	0.071
4000	1.965	0.981	0.662	0.336	0.141	0.066

Table 22. Setback distances (mi) reduced for shelterbelts, Area 3, Southeast direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.105	0.065	0.050	0.042	0.032	0.023
100	0.168	0.106	0.085	0.072	0.056	0.039
200	0.270	0.170	0.137	0.117	0.092	0.064
300	0.356	0.226	0.179	0.152	0.119	0.082
400	0.428	0.269	0.215	0.184	0.143	0.097
500	0.626	0.312	0.247	0.211	0.163	0.110
1000	0.934	0.476	0.378	0.317	0.239	0.159
2000	1.383	0.874	0.704	0.478	0.358	0.215
3000	1.773	1.080	0.863	0.732	0.431	0.270
4000	2.084	1.251	1.009	0.857	0.644	0.294

Table 23. Setback distances (mi) reduced for shelterbelts, Area 3, Southwest direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.133	0.070	0.051	0.042	0.030	0.018
100	0.210	0.114	0.085	0.070	0.050	0.030
200	0.331	0.180	0.135	0.110	0.077	0.046
300	0.417	0.231	0.177	0.151	0.107	0.062
400	0.488	0.276	0.208	0.168	0.110	0.060
500	0.704	0.318	0.238	0.190	0.129	0.069
1000	1.019	0.487	0.373	0.308	0.209	0.112
2000	1.495	0.884	0.684	0.431	0.269	0.125
3000	1.856	1.096	0.797	0.629	0.348	0.168
4000	2.163	1.273	0.960	0.754	0.370	0.180

Table 24. Setback distances (mi) reduced for shelterbelts, Area 3, Northwest direction.

	Annoyance Free Percentage					
OU/s x 10^4	99	98	97	96	94	91
0	0	0	0	0	0	0
50	0.136	0.086	0.066	0.056	0.043	0.033
100	0.224	0.142	0.110	0.094	0.074	0.058
200	0.366	0.226	0.179	0.152	0.123	0.095
300	0.475	0.295	0.233	0.199	0.161	0.125
400	0.723	0.362	0.283	0.244	0.193	0.147
500	0.818	0.414	0.327	0.275	0.223	0.173
1000	1.238	0.800	0.644	0.436	0.342	0.261
2000	1.878	1.195	0.950	0.818	0.650	0.385
3000	2.388	1.497	1.190	1.017	0.795	0.486
4000	2.847	1.763	1.396	1.184	0.935	0.703

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