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South Dakota Odor Footprint Tool (SDOFT), Part I: Principles and Tool Formulation

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Introduction

Livestock and poultry producers continually face economical and time restraint challenges. They seek a lifestyle that does not demand 10 to 16 hours of labor each day. As a result, producers have expanded and concentrated their operations in recent years to make the operation more efficient and bring in additional labor to share the workload. However, this expansion has also resulted in a community concern about emissions of air pollutants, especially odorants. Because of this concern, there has been an increase in complaints towards animal production facilities (Figure 1).

To address these concerns between livestock production facilities and community residences, local regulators establish minimum setback (separation) distances through local zoning and/or state regulatory procedures. Unfortunately, very few of these setback requirements have a scientific basis because the science did not exist and decisions by local officials were based on empirical rules or emotions.

To provide the needed science, air quality researchers at South Dakota State University, University of Nebraska, and University of Minnesota developed the South Dakota Odor Footprint Tool (SDOFT) for estimating odor impacts from livestock and poultry facilities to the surrounding community. These estimates are useful for local government land-use planners and citizens concerned about the odor impact of existing, expanding, or new animal production sites.

The SDOFT involves a two-step procedure. Step 1 estimates the average emissions from a variety of animal facilities and manure storages. This estimate is based on odor measurements from livestock and poultry farms in the upper Midwest. Step 2 estimates the atmospheric dispersion of the emissions from the site. This dispersion is simulated based on AERMOD, an Environmental Protection Agency (EPA) approved air dispersion model using South Dakota climatic conditions.

The SDOFT results provide rural communities and local government officials with the information needed to incorporate science and objectivity into the permitting process. They decide what levels of odors are acceptable and then determine the consequence of the "acceptance" level. Also, the tool provides the livestock producers with science-based information that can be used to properly site livestock facilities.

Why Dispersion Modeling? Why SDOFT?

The livestock industry in the U.S. is largely exempt from the Clean Air Act, the most relevant environmental law dealing with air quality management. However, this exemption has been challenged by environmentalists and other non-farm groups. A recent example of such efforts was a court ruling made by the Court of Appeals for the D.C. in 2017, which demands livestock farms to report the releases of air pollutants such as hydrogen sulfide and ammonia. Although the rule was later repealed, possible new regulations or enforcement of existing regulations could come in the future. Thus, it is helpful to take a look at how air emissions from industrial sources are regulated under the Clean Air Act.

For most industrial sources, air permitting is required before commencing the construction of a new facility or expansion of an existing facility. In general, there are two air permits involved: a New Source Review (NSR) permit and a Title V operating permit. For both permits, air dispersion modeling is usually mandatory. The purpose of the modeling is to simulate the movement and dilution of air pollutants in the outdoor air so that the air pollutant concentrations at the locations of interest or concern (e.g., a residential community) can be calculated. By comparing the predicted concentrations with air quality standards, regulatory agencies, such as the South Dakota Department of the Environment and Natural Resources, can then determine whether the facility construction or expansion should be permitted, or whether a control technology or practice should be implemented for the facility to reduce its air pollutant emissions.

Two air dispersion models are currently listed by the U.S. EPA as regulatory models: AERMOD and CALPUFF. That is to say, only the modeling results generated by the two models can be used for regulatory purposes, including the determination of compliance with air quality regulations. Both models demand numerous input parameters, including meteorological conditions, terrains, emission source characteristics, receptors, modeling options, output options, etc. As a result, air dispersion modeling is usually done by professionals for a fee.

Again, the livestock industry is currently exempt from the Clean Air Act but this exemption could be removed in the future. To address the air quality challenges related to livestock production, simplified air dispersion modeling tools have been developed and they are free to the general public. Examples include SDOFT for South Dakota, OFFSET for Minnesota (https://extension.umn.edu/manure-management/manure-air-and-water-quality), and NOFT for Nebraska (https://water.unl.edu/manure/odor-footprint-tool). These tools are structured similarly to the U.S. EPA's regulatory air dispersion models but have been substantially simplified and streamlined so that producers, land-use planners, and community residents can understand and use those tools for air quality management.

Different from general-purpose air dispersion models such as AERMOD and CALPUFF, SDOFT is specifically for odor dispersion modeling. Instead of calculating the average odor concentrations downwind from a livestock farm and comparing the concentrations with air quality standards, SDOFT calculates the probability of the occurrence of odor annoyance. A greater distance between the farm and its neighbor(s) would result in a lower chance (frequency) of odor annoyance. Since in most counties of South Dakota odor annoyance is discussed and managed based on its occurrence frequency, the modeling results from SDOFT are expressed in setback (separation) distances required for a target frequency or frequencies.

What Assumptions are Used in SDOFT?

Again, the SDOFT by nature is an air dispersion model but deeply simplified and customized for establishing odor setback distances. For any dispersion models, they require three types of input data: source data, meteorological data, and receptor data. Here, receptors can be neighbors of a livestock farm or any spots near the farm where odor annoyance may take place. Meteorological data include wind speed, wind direction, temperature, solar radiation, etc. that influence odor dispersion in the outdoor air. Sources here are livestock facilities, including livestock barns, lots, and manure storages.

To simplify odor dispersion modeling, the SDOFT has adopted some major assumptions. For sources, it assumes that:

- Livestock barns/houses, lots, and manure storages are all area sources, that is, odor is emitted uniformly throughout the land area of a barn, lot, or storage. This assumption is used when we calculate the total odor emission rate from a livestock farm.
- Odor is emitted at the ground level.
- A livestock farm consisting of multiple houses, lots, and/or storages can however be considered as a point source when we conduct dispersion modeling.
- No high buildings or significant ground objects are located near the livestock farm (and therefore interfere with air movement).

For meteorology, the SDOFT assumes that:

- Historical weather conditions can be used to predict air movement including odor dispersion in the outdoor air.
- For a livestock farm, its historical weather conditions can be approximated by and acquired from the nearest local weather stations that run as part of the state's Mesonet climatology network.
- For counties with similar weather conditions,

they can be pooled together to share the same meteorological dataset.

For receptors, the SDOFT assumes that:

- All receptors are located at the ground level.
- All receptors and sources are located on flat terrain.

How is SDOFT Formulated?

As previously mentioned, the SDOFT involves a two-step procedure. Step 1 estimates the total odor emission rate from a farm site and Step 2 determines the distance and frequency of odor event through dispersion modeling. Our discussion about the tool formulation follows the two-step procedure as well.

Step 1 – Determining the total odor emission rate from a farm site

Emission rate and emission factor are among the most important concepts for air emissions management. They can be confusing to general readers. To clarify, an emission rate refers to the amount of an air pollutant emitted per unit of time. For example, the emission of carbon monoxide (CO) from a boiler is 1000 pounds over 10 days. In this case, the emission rate is 100 lbs CO/day. For dispersion models like the SDOFT, the total emission rate of an air pollutant must be determined before we run the models. An emission factor is a normalized emission rate. The normalization can be done based on material consumption, production, area, volume, etc. In the boiler example, if the boiler burns 20 tons of coals over the 10 days, the emission factor can be calculated by normalizing the CO emission rate (100 lbs CO/day) with the coal consumption rate (2 tons/day) and the result is 50 lbs CO/ton coal. The rationale of using the emission factor is that the emission rate can be highly variable whereas the emission factor is relatively constant. It is unnecessary to measure the CO emission rates from all individual boilers. Instead, we can select representative boilers and measure their average CO emission factors and use them, together with coal consumption records, to estimate the CO emission rates from other boilers. The same philosophy applies here to odor emission determination. Odor emission factors were derived from the measurement of farm sites typical of the Upper Midwest. These emission factors were odor emission rates per unit of land area occupied by a barn, lot, or storage. By multiplying the odor emission factor by the area of a facility, the odor emission rate from the facility can be determined.

With that being said, the total odor emission rate from a farm site is the sum of odor emission rates from all main odor sources on the site. An odor emission rate needs to be calculated for each odor source. If multiple facilities are of similar type (e.g., two swine finishing barns) on the site, the combined areas can be used to simplify the calculations. For each odor source, its odor emission rates (OER) can be calculated with the following equation:

$$\text{OER} = \frac{\text{Odor emission factor} \times \text{Plan area} \times \text{Odor control factor}}{10{,}000}$$

Odor emission factors

The SDOFT bases the odor emission factors on measured odor emissions obtained from measurements made on farms located in the Upper Midwest. In those measurements, odor levels were quantitated with the olfactometry method and presented in the unit of odor unit (OU)/ft^3. Correspondingly, the odor emission factors were in the unit of OU/ft^2-sec. Average values for a series of measurements from each odor source type are in Tables 1 and 2. Average values must be used since wide variation between sites with similar sources existed. Variation is related to such factors as farm management, animal diet, or such things as ambient temperature, humidity, and wind speed. Therefore, the actual odor from a given site may vary as compared to the results from this tool because of the same factors.

Plan area

Plan area is the ground area occupied by a livestock house, lot, or manure storage. To be consistent with other items in the equation, a unit of ft^2 (square foot) must be used. The plan area can be acquired from blueprints, field measurements, aerial or satellite images.

Odor control factors

Several technologies are currently available to control odor, although little testing and research have been done to document their effectiveness (Figure 1). The only technologies where sufficient information is available to determine likely reductions in odor emissions for field conditions are listed in Table 3. The factors vary from 0.1 to 1 and carry no unit; where 1 indicates no odor control and 0.1 indicates 90% odor reduction. Changes and additions to the odor control

Table 1. Odor emission factors for animal housing with an average management level.

Species	Type/Stage of Production	Type of Facility	Odor Emission Factor (OU/ft^2-sec)
Cattle	Beef	Dirt/concrete lot; Free stall, scrape	19
	Dairy	Free stall, deep pit; Loose housing, scrape	29
		Tie stall	10
Swine	Gestation	Deep pit, natural or mechanical	243
		Pull plug, natural or mechanical	146
	Farrowing	Pull plug, natural or mechanical	68
	Nursery	Deep pit or pull plug, natural or mechanical	204
	Finishing	Deep pit, natural or mechanical	165
		Pull plug, natural or mechanical	97
		Hoop barn, deep bedded, scrape	19
		Cargill/ open front, scrape Loose housing, scrape Open concrete lot, scrape	53
Poultry	Broiler	Litter	5
	Turkey	Litter	10

Table 2. Odor emission factors for manure handling facilities.

Type of Facility*			Odor Emission Factor (OU/ ft^2-sec)
Manure storage facility	Earthen basin		63
	Steel or concrete tank, above or below ground		136
	Crusted stockpile		9
Treatment facility	Anaerobic lagoon	Purple (phototrophic)	2
		Non-phototrophic (non-purple)	3

** Earthen basins are designed for manure storage without any treatment. Lagoons are anaerobic treatment systems.*

Table 3. Odor control factors.

Odor Control Technology		Odor Control Factor
No supplemental odor control implemented on the facility		1.0
Biofilters receiving 100% of air from all exhaust fans		0.1
Oil sprinkling used to control dust within building		0.5
Geotextile cover (at least 2.4 mm thick)		0.5
Straw or natural crust on manure	2″ thick	0.5
	4″ thick	0.4
	6″ thick	0.3
	8″ thick	0.2
Impermeable cover		0.1

factors (Table 3) will be made as more research is conducted and more technologies are developed. Currently, there is no standard procedure for getting odor control technologies listed in Table 3, nor is it required by the SDOFT to allow only odor control technologies listed in Table 3. However, estimated reductions in odor emissions should be based on sound scientific research.

Figure 1. Odor control is critical for reducing the frequency of annoying odor events. Shown in this picture is a horizontal biofilter that treats exhaust air from pit fans.

The relative impacts of various odorous sources can be assessed by comparing the size of individual odor emission rates. For example, if a manure storage facility has an odor emission rate of 150 × 10^4 OU/sec compared to 100 × 10^4 OU/sec for the housing facility, then the manure storage facility can be projected to have 50% greater influence than the housing facility on the minimum desired setback distance and the resulting overall odor impact on neighbors. The relative size of the odor emission rates also is a good indicator of where odor control would be most beneficial. Generally, you want to spend resources where they will have the greatest benefit overall – on the sources with the largest odor emission rate.

Once the odor emission rates (in the unit of 10^4 OU/sec) from all individual odor sources on a farm site are calculated, they are added together to estimate the total odor emission rate (in the unit of 10^4 OU/sec) from the site. As previously mentioned, the entire farm is assumed as a point source (i.e. a single point on a map) when we move to the next step–odor dispersion modeling. This assumption creates uncertainties and we address this uncertainty issue in the Data Interpretation section in Part 2 of this fact sheet.

Step 2 – Determining distance and frequency of odor events through dispersion modeling

Once the total odor emission rate is calculated, the frequency of odor occurrences at various distances from the farm site can be estimated using Figures S1-S12. The horizontal axis is the total odor emission rate calculated from Step 1. The vertical axis is the distance from the farm site. There are three sets of figures with each set containing 4 figures. Each set is devoted to an area in South Dakota (Figure 2). The four figures in a set provide setback annoyance-free distances for each direction from the odor emitting site. All these figures were generated from AERMOD modeling.

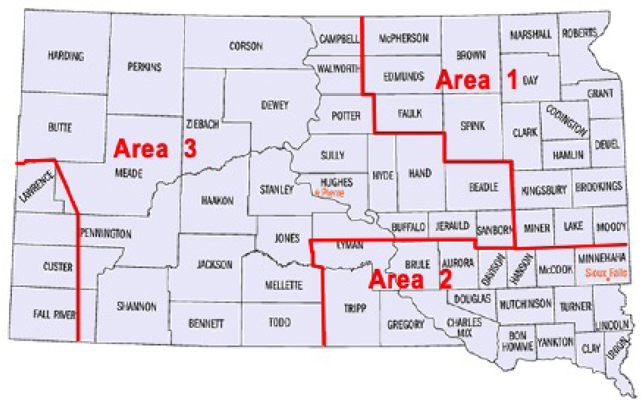

Figure 2. Three areas adopted by the SDOFT.

Annoyance-free frequency

The curves in Figures S1-S12 are known as odor annoyance-free frequency curves. These curves represent different frequencies of time when odors will not be at levels considered "annoying." Options include 91%, 94%, 96%, 97%, 98%, and 99%, and these numbers represent the percent of time during the spring-through-fall period where odors are possibly detected but at a level that is NOT typically considered annoying. An odor intensity level less than 2 on an intensity scale of 0 to 5 is defined as not annoying. Odors with an intensity of less than 2 are weak or mild odors that are not likely to be annoying. A small percentage of the population is highly sensitive to odors. These individuals may detect odors at very low levels and be annoyed at intensities less than 2.

To further clarify, the AERMOD model uses the odor emission rate in the unit of OU/sec as its model input. OU is the odor unit determined using the olfactometry method and it is a different measure than odor intensity. Correspondingly, the AERMOD model output is also based on OU. To translate the model-predicted odor concentration (in the unit of OU/m³ air) to odor intensity, a relationship (75 OU/m³ equivalent to the odor intensity level of 2) established from a previous study is used in the SDOFT. Thus, an odor concentration of less than 75 OU/m³ is interpreted as not annoying.

The curve selected represents the minimum proportion of hours during which a residence situated at or beyond the setback distance should not be exposed to annoying levels of odor coming from the particular livestock site. Odor annoyance-free frequencies of 99%, 98%, 97%, 96%, 94%, and 91% correspond to 7, 15, 22, 29, 44, and 66 hours/month of annoying odors during April through October. These are the warmer months when odor annoyance is of particular concern. Odor is usually not an issue during winter when the activity of odor-producing microbes is suppressed by low temperatures. Since these predicted frequencies are based on "average" weather conditions, actual frequencies of odor events may be significantly different.

To find the setback distance for a specific frequency curve and total odor emission rate, simply find the total odor emission rate on the horizontal axis, then move vertically to the desired annoyance-free frequency curve, and then move horizontally to the vertical axis. The number on the vertical axis is the separation distance (in feet) needed to achieve the desired frequency of odors. For example, if the 96% curve is chosen, odors at a location within the setback distance would be expected to be at annoying levels more than 4% (100% - 96%) of the time, while odors at a location beyond the setback distance would be expected to be at annoying levels less than 4% of the time.

Different odor annoyance-free frequencies result in different setback distances for the same total odor emission rate. For example, to achieve an odor annoyance-free frequency of 99% for a facility with a total odor emission rate of 150 requires a separation distance of 1.5 miles. (This separation distance is measured from the edge of the nearest odor source.) During the rest of the time (1% or 7 hours per month), annoying odors will be detected at this distance. Reducing the frequency of annoyance-free odors to 96% would require a separation distance of less than 0.5 miles. At this distance, annoying odors would be experienced 4% of the time or 29 hours per month.

Meteorological data – Why three areas?

As a regulatory air dispersion model, AERMOD requires two meteorological data files to simulate the transport of air pollutants including odor in the outdoor air: surface meteorological data and upper air meteorological data. The surface meteorological data characterize the meteorological conditions at the ground level, including temperature, humidity, wind speed, wind direction, etc. The upper air meteorological data characterize the vertical profile of atmospheric conditions, e.g., changes in temperature and wind speed with altitude. For the surface data, they are available through the state and local weather stations. In South Dakota, nearly every county has at least one such station. Some counties have multiple weather stations. For the upper air data, their measurements require the use of balloons or other airborne devices. Thus, only a limited number of stations can do such measurements. In South Dakota, only two stations (Aberdeen and Rapid City) provide upper air data.

An important step for AERMOD modeling is to decide the surface and upper air data sets applicable to a given site. A general rule is that one should use the data acquired from the nearest weather stations with land use and topographic conditions similar to the farm site. Following this rule, the Aberdeen upper air data were selected during the SDOFT formulation. For surface data, the situation is more complicated given a large number of weather stations in the state. Theoretically, the data from all these stations can be utilized. However, this would make the SDOFT too bulky to use. For simplicity, the 66 counties (and county sections) of South Dakota were combined into four areas based on their similar surface meteorological conditions. The area at the southwestern corner is largely covered by the Black Hills, with little livestock production. Thus, it is excluded from the SDOFT. The rest areas were designated as Areas 1, 2, and 3. AERMOD modeling was done for each area to develop the odor annoyance-free curves (four charts/figures for each area).

Since there is considerable variability in meteorological conditions for any location, the SDOFT could over- or underestimate an odor event in any given month. It is also noteworthy that only the meteorological data from April through October were used to develop the annoyance-free curves. These archived historical data (1996-2005) were retrieved from the federal and state meteorological databases such as NOAA NDCD and NOAA/ESRL Radiosonde databases.

Wind roses

Wind roses were used to study the similarity of surface meteorological conditions in different locations. A wind rose (Figure 3) shows the information about the distribution of wind speeds and the frequency of the varying wind directions. Wind roses vary from one location to another but neighboring areas are often fairly similar. For more information about South Dakota wind roses, visit the website at https://climate.sdstate.edu/tools/windrose/windrose.shtm.

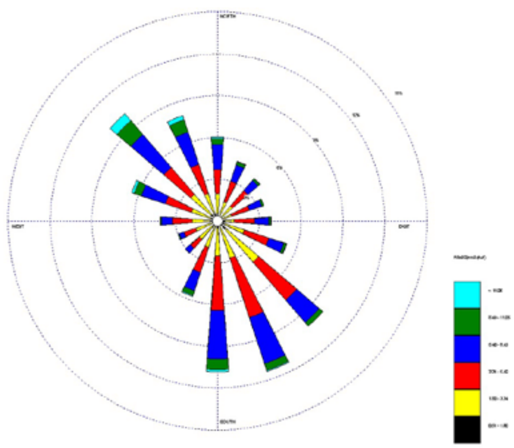

Figure 3. A yearly wind rose for Brookings, SD.

Topography

The odor annoyance-free curves given in Figure S1-S12 were obtained assuming flat terrain with no obstructions. However, the impact of topography (e.g., hills and valleys) on odor dispersion is significant and complicated. For example, winds are the primary factor governing the dispersion of air pollutants including odor in the outdoor air. Wind speeds and directions can be influenced by topography. In general, the residence situated on wind facing slopes would be more prone to odor annoyance caused by upwind livestock farms, as relative to the communities on a flatland; while those on lee slopes are less prone to odor annoyance. However, it is noteworthy that this general rule does not always stand. When winds are strong, the turbulence (i.e., air vortexes) over lee slopes could pull down odor-laden air from higher altitudes, causing a nuisance.

The SDOFT was developed based on AERMOD, a regulatory air dispersion model frequently used for air permitting purposes. For livestock farms, no air permitting is currently required. But if a permit is required in the future, we anticipate that AERMOD will be the tool to use. Complex terrain, such as rolling hills, can be handled by AERMOD through its terrain preprocessor AERMAP. Thus, it is feasible to include the impact of topography in the future SDOFT but this would require significant time and effort. The current SDOFT should be sufficient for most zoning and planning purposes. For scenarios where the impact of terrains must be considered, several suggestions are given in the Data Interpretation section in Part 2 of this fact sheet.

Cumulative Impact

The SDOFT may have the ability to consider the cumulative odor impact of multiple farm sites. However, to do this accurately would require site-specific information, e.g., the relative locations of farm sites. A general idea of cumulative impact on a specific location could be demonstrated by adding the annoyance-free frequencies from the surrounding farm sites. For example, if a residence is located beyond the 97% odor annoyance-free line of site 1 and the 96% annoyance-free line of site 2, the residence would experience odor annoyance in less than 7% (3% + 4%) of time from April through October.

Acknowledgments

The authors acknowledge the research done at the University of Minnesota for developing the basis for this model and compiling the odor emission database. Also, acknowledgment is noted for the work done at the University of Nebraska – Lincoln in running the AERMOD dispersion model. The funding to develop the SDOFT was provided by the South Dakota Pork Producers.

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Appendix

Area 1

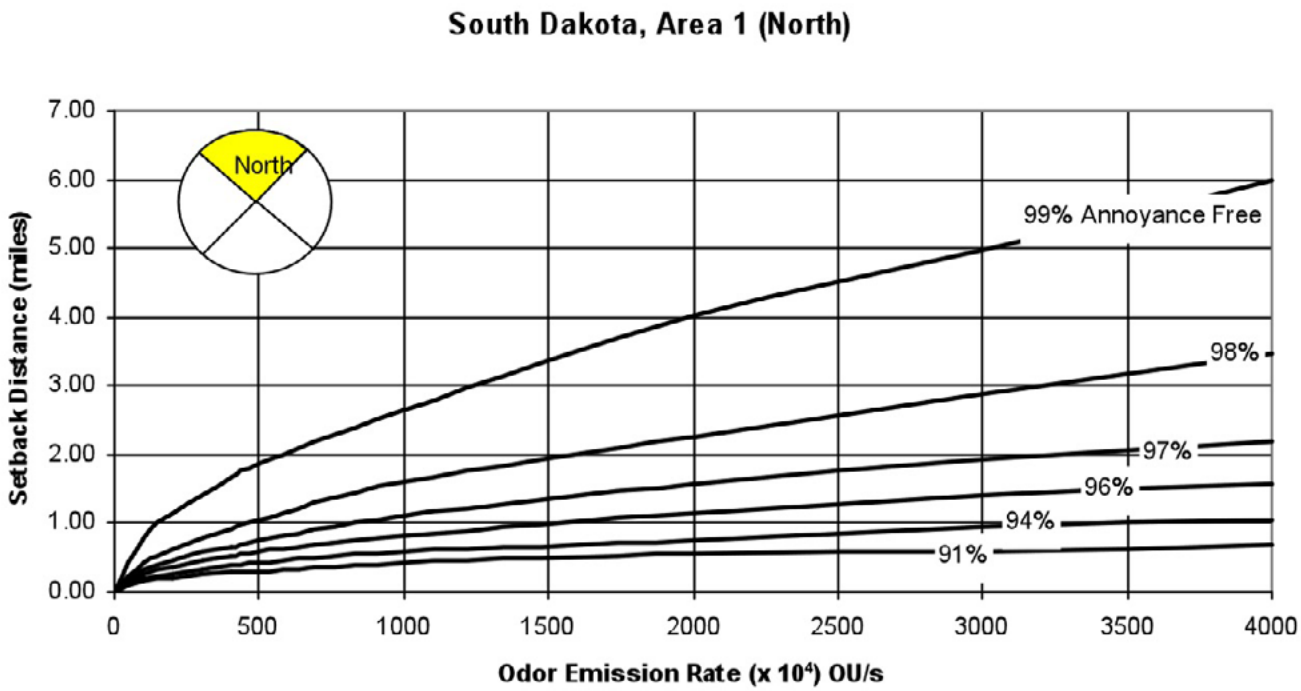

Figure S1. Estimated setback distances (miles) in Northeast South Dakota to the north of a farm at different odor annoyance-free frequency requirement.

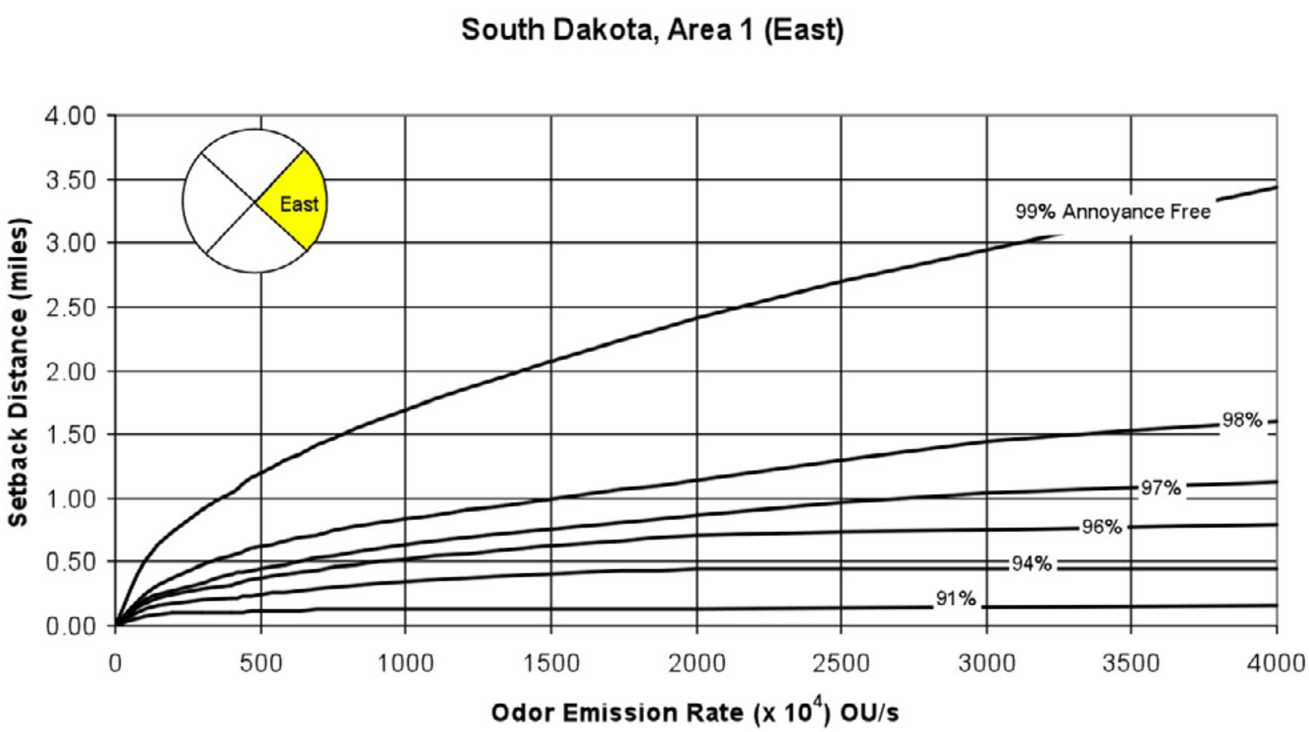

Figure S2. Estimated setback distances (miles) in Northeast South Dakota to the east of a farm at different odor annoyance-free frequency requirement.

Area 1

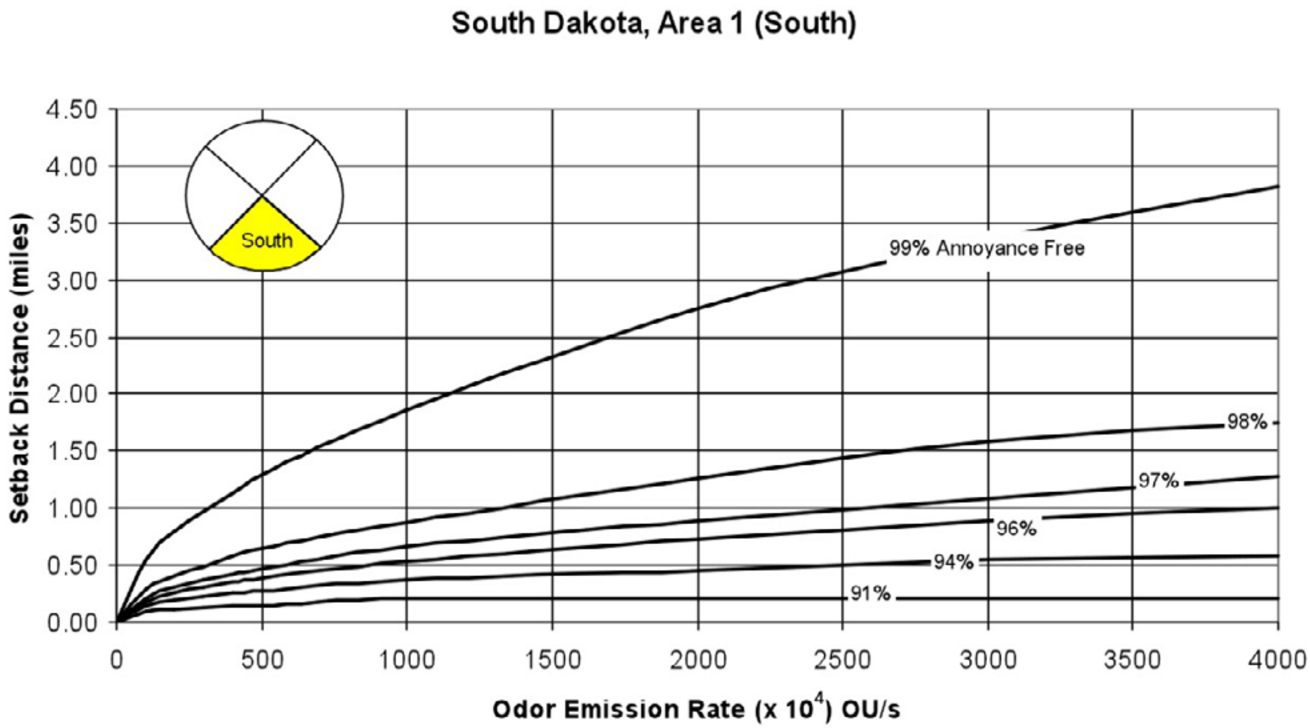

Figure S3. Estimated setback distances (miles) in Northeast South Dakota to the south of a farm at different odor annoyance-free frequency requirement.

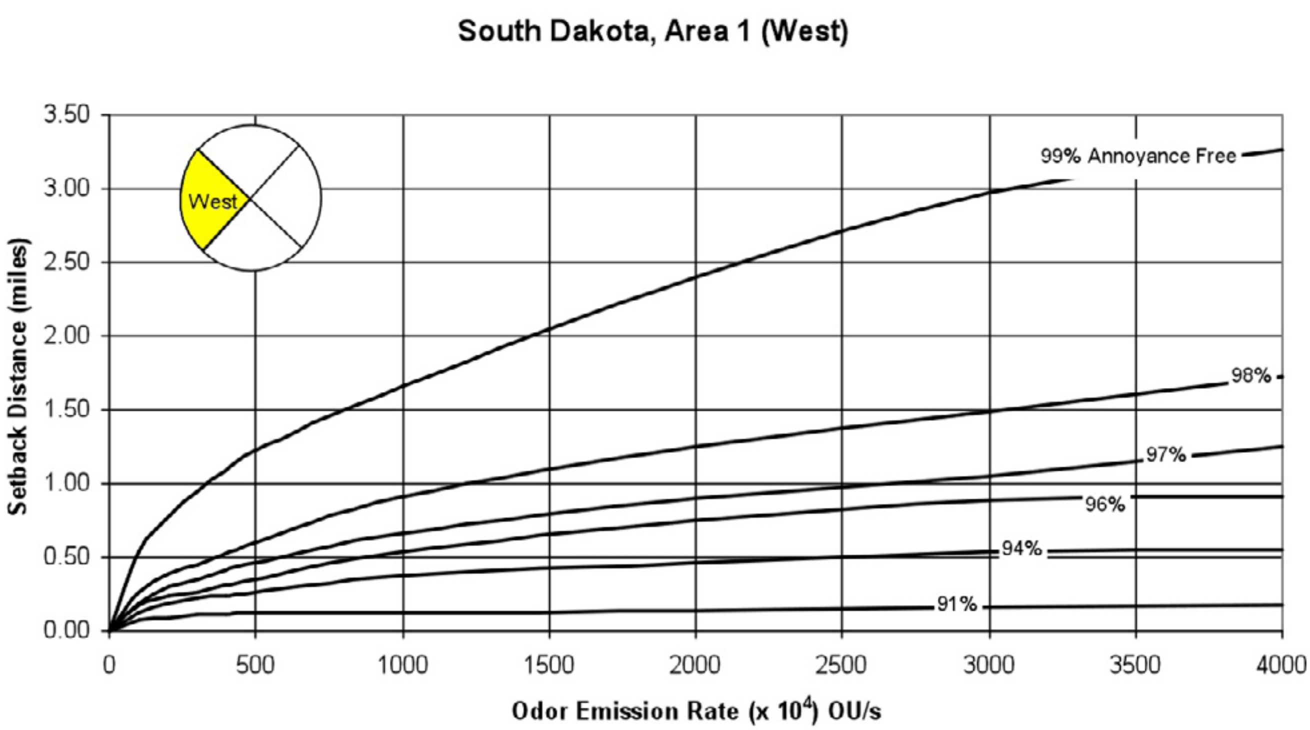

Figure S4. Estimated setback distances (miles) in Northeast South Dakota to the west of a farm at different odor annoyance-free frequency requirement.

Area 2

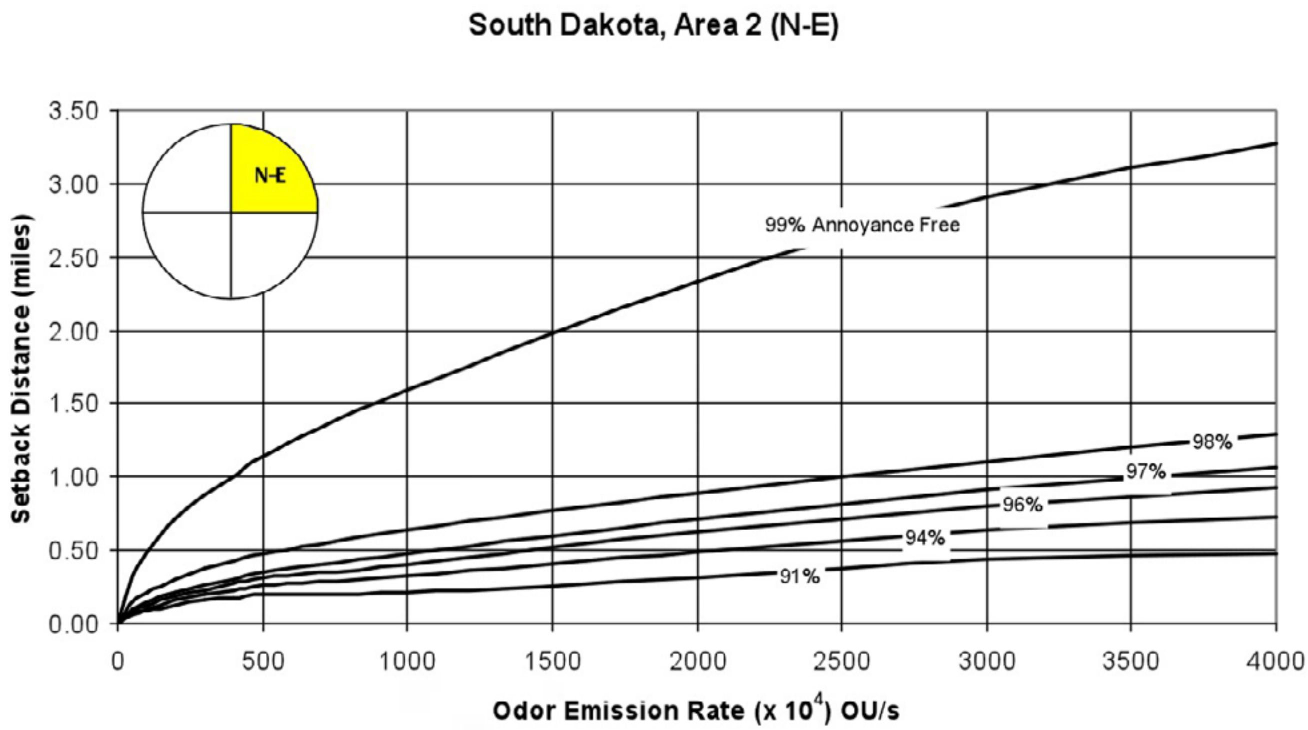

Figure S5. Estimated setback distances (miles) in Southeast South Dakota to the northeast of a farm at different odor annoyance-free frequency requirement.

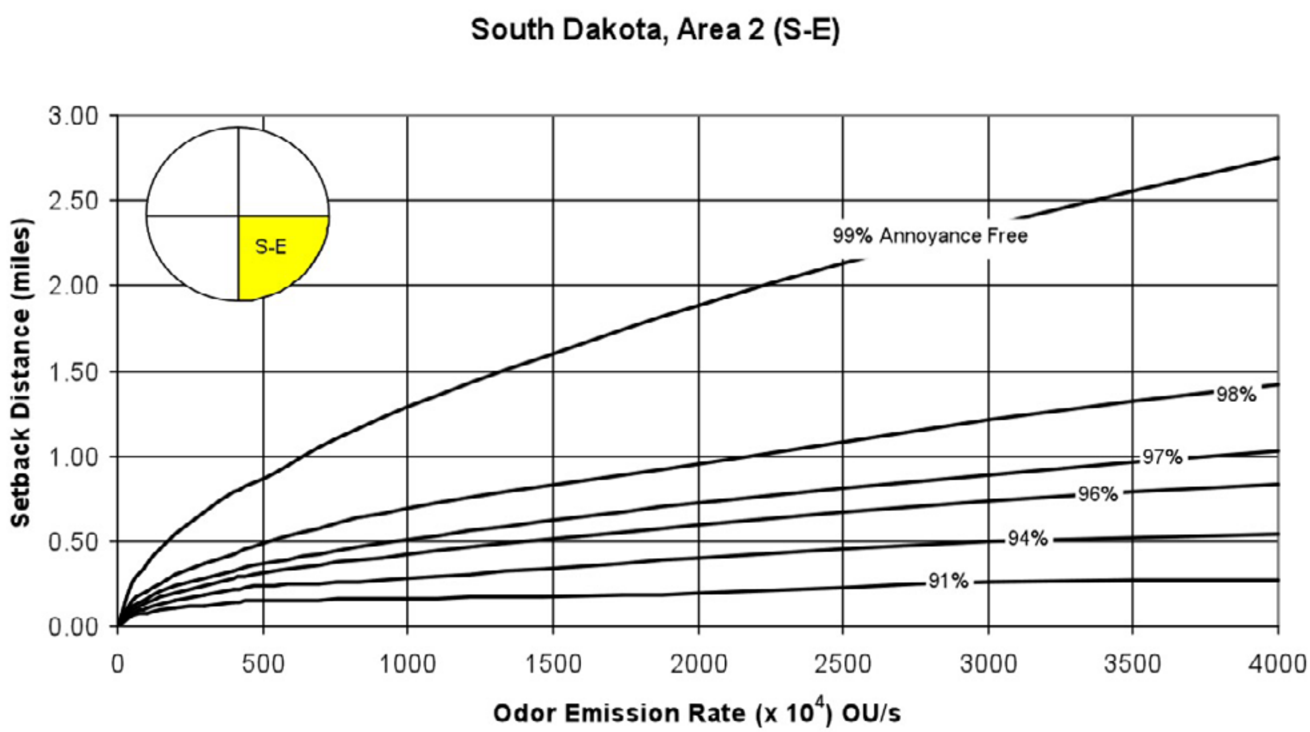

Figure S6. Estimated setback distances (miles) in Southeast South Dakota to the southeast of a farm at different odor annoyance-free frequency requirement.

Area 2

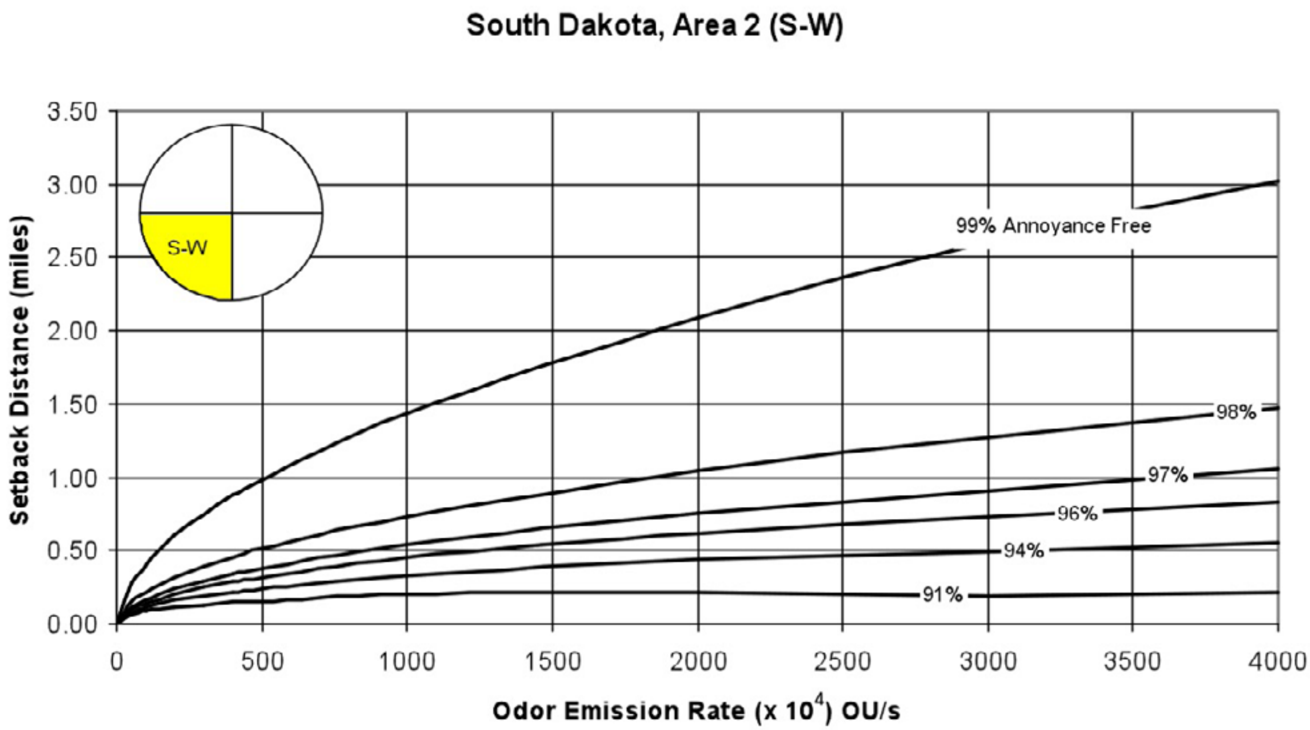

Figure S7. Estimated setback distances (miles) in Southeast South Dakota to the southwest of a farm at different odor annoyance-free frequency requirement.

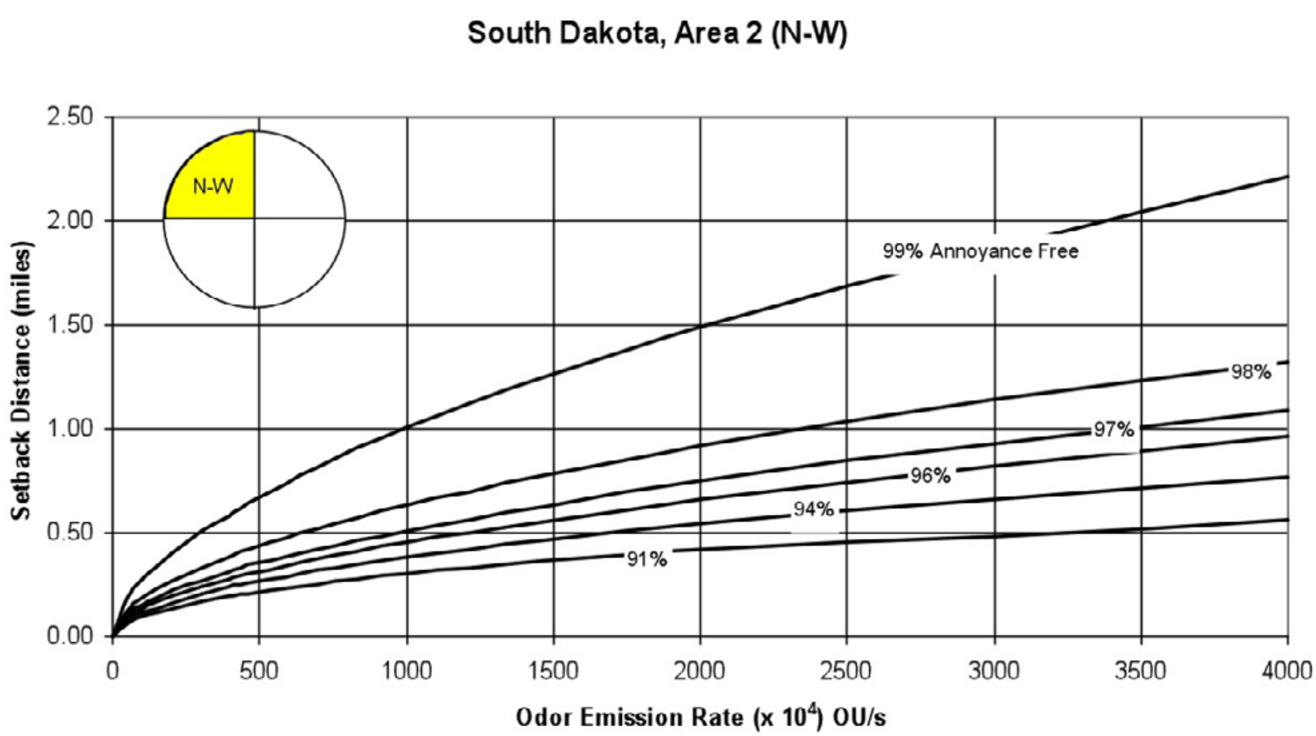

Figure S8. Estimated setback distances (miles) in Southeast South Dakota to the northwest of a farm at different odor annoyance-free frequency requirement.

Area 3

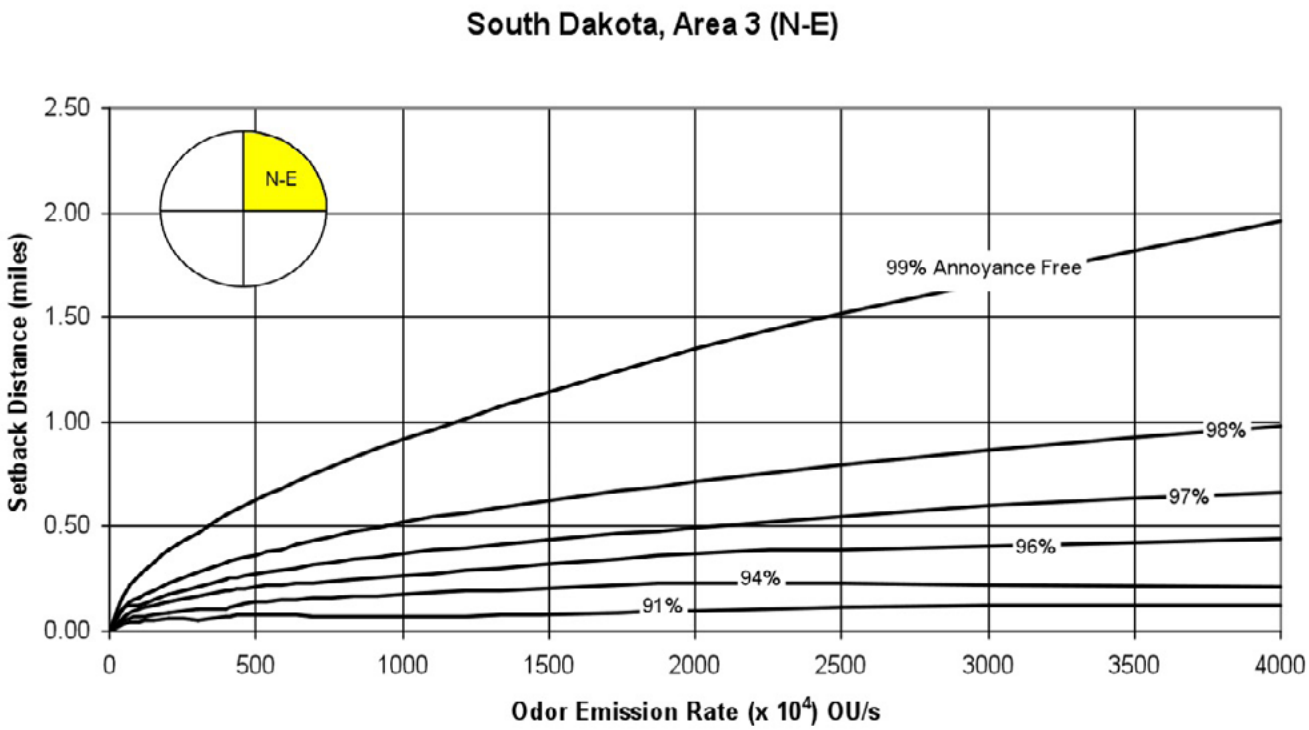

Figure S9. Estimated setback distances (miles) in western South Dakota to the northeast of a farm at different odor annoyance-free frequency requirement.

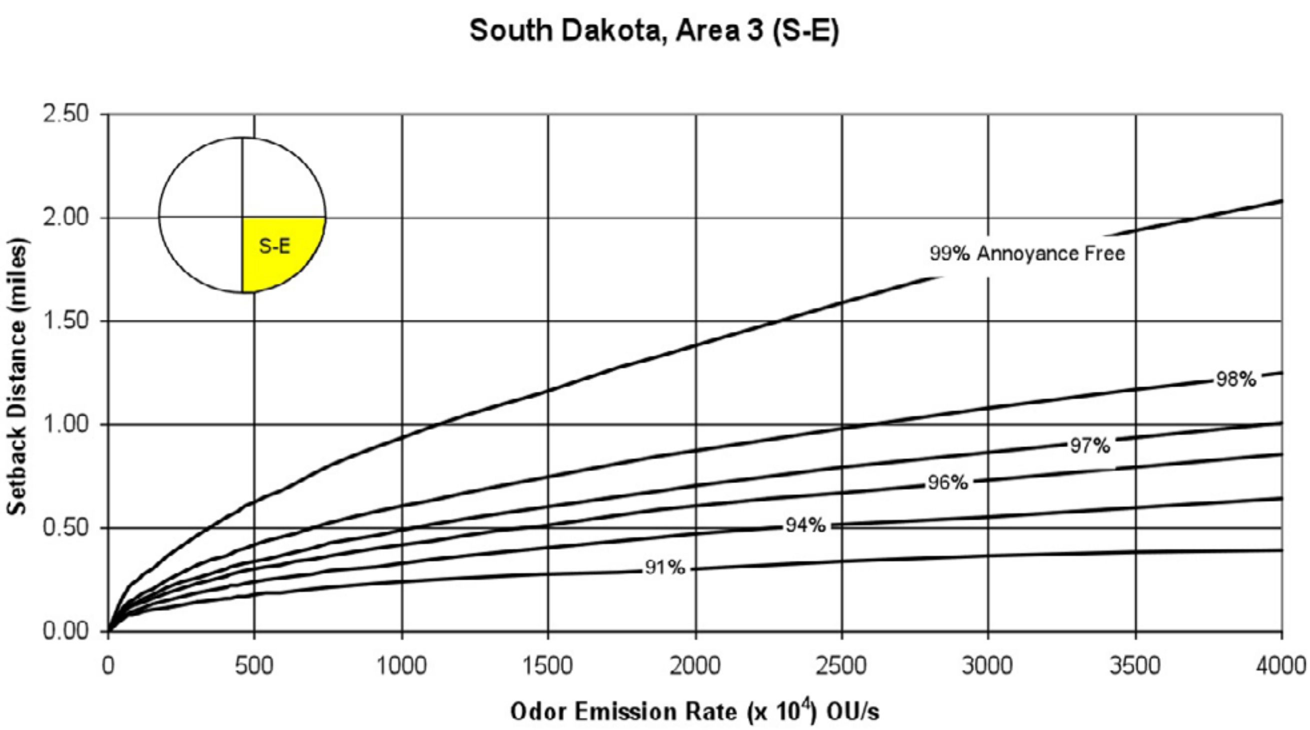

Figure S10. Estimated setback distances (miles) in western South Dakota to the southeast of a farm at different odor annoyance-free frequency requirement.

Area 3

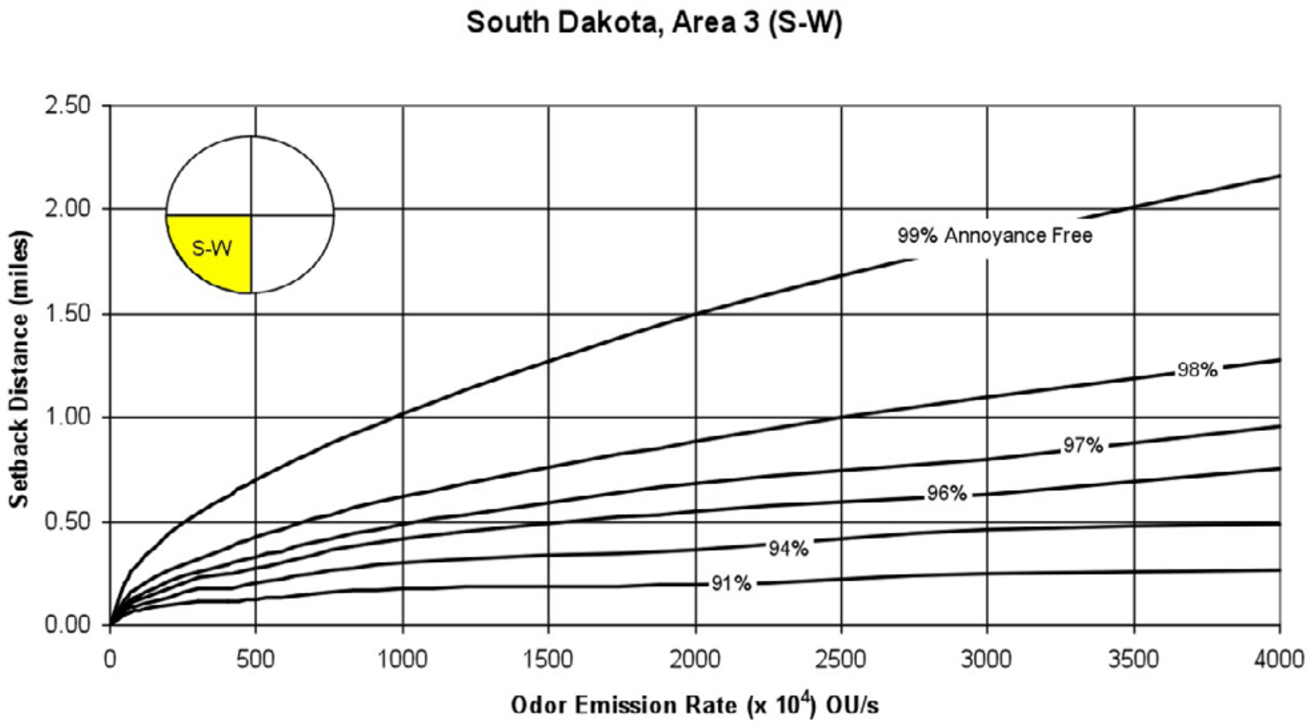

Figure S11. Estimated setback distances (miles) in western South Dakota to the southwest of a farm at different odor annoyance-free frequency requirement.

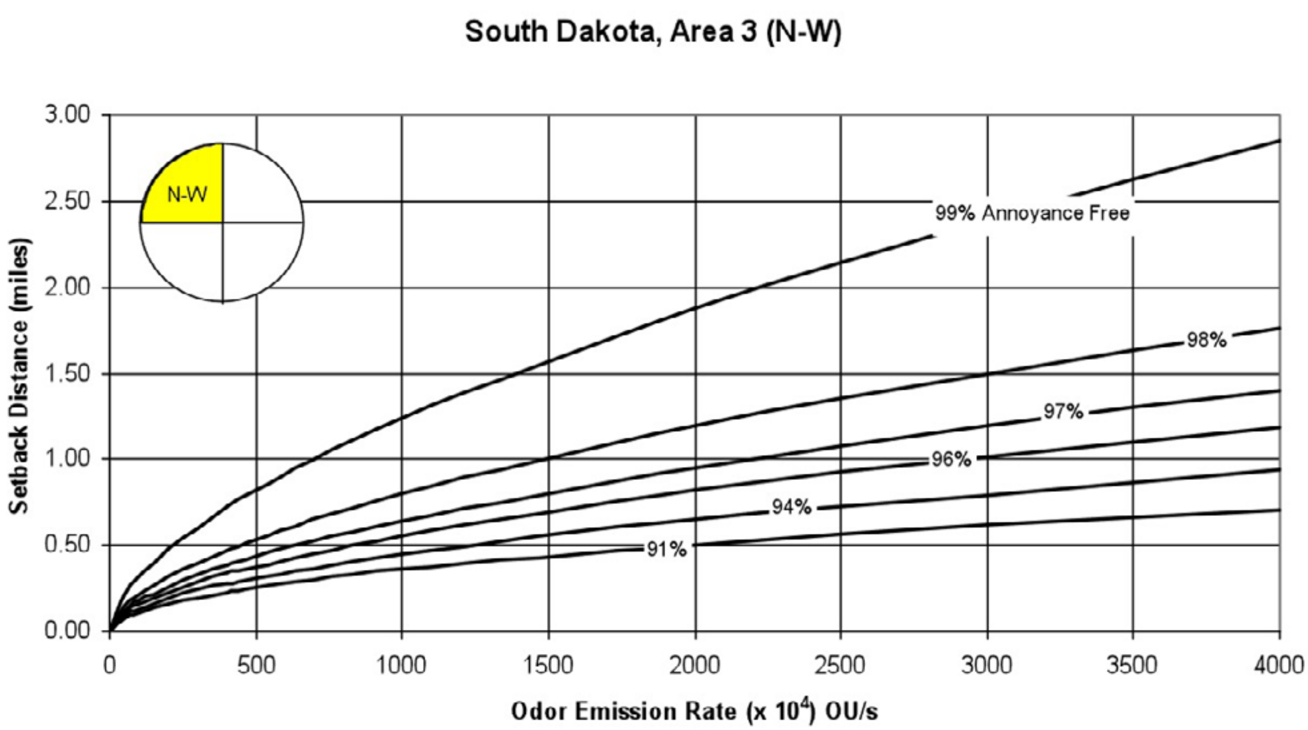

Figure S12. Estimated setback distances (miles) in western South Dakota to the northwest of a farm at different odor annoyance-free frequency requirement.