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Mitigating swine odor with strategically designed shelterbelt systems: a review

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Abstract Recent reports clearly indicate that odor emitted from concentrated livestock production facilities in the Midwest of the US is a significant social problem that negatively impacts rural and state economies, human health, and the quality of rural life. A potential incremental approach to dealing with livestock odor is the use of shelterbelts arranged in strategic designs near and within livestock facilities. This review outlines the various ways that shelterbelts can be effective technology which bio-physically mitigates odor thereby reducing social conflict from odor nuisance. The biophysical potential of shelterbelts to mitigate livestock odor arises from the tree/shrub impacts on the central characteristics and physical behavior of livestock odor. As the majority of odors generated in animal facilities that are detectable at appreciable distances travel as particulates, there is compelling evidence that shelterbelts can ameliorate livestock odor by impeding the movement of these particulates. Because the odor source is near the ground and the tendency of livestock odor is to travel along the ground, shelterbelts of modest heights (i.e. 20–30 ft) may be ideal for odor interception, disruption, and dilution. Shelterbelts can be adapted to fit almost any production situation. Depending on shelterbelt health, these trees can provide long term, year round odor interception, with increasing effectiveness over time. Additionally, more is becoming known about how landscape aesthetics affect how people might perceive livestock odor, suggesting that landscape elements such as shelterbelts can lead to aesthetic improvements and perhaps more positive opinions of livestock odor and the farm systems that create them.

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Introduction

The Natural Resource Conservation Service of the USA defines air quality as a measure of the concentration of particulates and gases relative to an accepted standard that limits the use of the air for a designated purpose at a specific location (Vining and Allen 1993). Unfortunately for many people living, working, enjoying, or passing through parts of rural America, the quality of the air is often below accepted standards (Huang and Miller 2006). Recent reports clearly indicate that odor emitted from concentrated livestock production facilities in the Midwest of the US, particularly from pork production, is a significant social problem that negatively impacts rural and state economies, human health, and the quality of rural life (Iowa CAFO Air Quality Study 2002; Wing and Wolf 2000; Thu and Durrenberger 1998). Whereas livestock derived odors are ubiquitous with animal agriculture, four factors are thought to cause an increase in odor nuisance and a need for additional technological and management creativity. First, larger-scale livestock confinement production has led to increased concentrations of manure being stored and utilized in relatively small geographic locations. Second, urban/suburban expansion into the agricultural landscape has put many more people with limited agricultural experience into closer proximity to livestock production. Third, the current livestock odor problem is characterized by high concentrations of odorous emissions that travel across highly modified landscapes relatively devoid of any significant natural barriers that can impede, alter, absorb, or dissipate the odor plumes prior to contact with people (e.g. Iowa has about 93% of its natural landscape converted to fairly homogeneous agricultural uses). Fourth, market economics and regulatory policy of livestock production create limited producer incentives to control water and air pollution beyond minimum regulatory requirements—to do more may put producers at a financial disadvantage. Livestock production, communities, and the environment in which people live, work and enjoy life will continue to be at risk if creative and effective solutions are not forthcoming.

A potential incremental approach to dealing with livestock odor is the use of shelterbelts (trees and shrubs) arranged in strategic designs near and within livestock facilities. This review outlines the various ways that shelterbelts can be an effective technology which bio-physically mitigates odor in a socio-economically responsible way thereby reducing social conflict from odor nuisance (Lin et al. 2006; Midwest Plan Service 2002; Tyndall and Colletti 2001). Several sources (Koelsch 1999; WED 1999; National Pork Producer Council 1995; Lorimor 1998; OCTF 1998; Jacobson et al. 1998) list shelterbelts as odor control devices, but provide little physical, biological, or economic quantification as to effectiveness. The National Center for Manure and Animal Waste Management listed the lack of quantification regarding the impact of vegetative barriers on livestock production emissions as a ''major research gap'' (National Center MAWM 2001). Still, the USDA's National Animal Health Monitoring System Swine 2000 report noted that 33% of respondents across 17 states use shelterbelts/windbreaks specifically for air quality management (Vansickle 2002). A recent Iowa swine producer survey indicates that 38% of the respondents (n = 562) use shelterbelts for odor mitigation purposes and 64% of that group are satisfied with their effectiveness and management—only 0.9% were unsatisfied with the practice (Lorimor and Kliebenstein 2004).

This review will focus only on swine odor mitigation, as swine production has historically been associated with the most frequent odor nuisance complaints (Hardwick 1985). However it should be noted that the use of shelterbelts for odor mitigation is theoretically amenable to all livestock and poultry species.

Defining shelterbelts and swine odor

Shelterbelts

Shelterbelts are vegetation systems that typically use trees and shrubs arranged in row or group configurations to redirect wind and reduce wind speeds, thereby modifying environmental conditions within the upwind and downwind sheltered zones. Wind flow modification is useful in controlling wind erosion, controlling blowing snow, increasing crop yields, protecting farm buildings and other structures, protecting livestock, improving working conditions in the field, or any combination of these effects (Brandle et al. 2004). Trees and shrubs can also provide visual diversity within agricultural landscapes, improve biodiversity, provide wildlife habitat and can improve the private recreation potential of many farms (Brandle et al. 2004; Ronneberg 1992).

The magnitude of wind dynamic and microclimate changes will vary within and between shelterbelt systems depending upon the internal, external, and managerial characteristics of the system (J. Brandle pers. comm. 1999). The internal and external structures of a shelterbelt are very important. In terms of the internal structure, porosity is the most commonly used descriptor. It is a simple ratio of perforated area to total area (Heisler and DeWalle 1988). Shelterbelts with a porosity of 40–60% provide the greatest reduction in wind speed over the greatest distance (Brandle and Finch 1991). External structure can be described as the height, width, and number of rows, species composition, length, orientation, continuity, and overall design of plantings or natural configurations. Management characteristics can include: the goals of the shelterbelt (e.g. crop protection/enhancement, wildlife habitat, etc.); species selection, planting technique and planting design; manipulation of porosity; and maintenance (J. Brandle pers. comm. 1999).

Constituents of swine odor

To have a better understanding of the shelterbelt—livestock odor dynamics, an examination of the physico-chemical characteristics of livestock odor is a good place to start. Swine manure odor is a product of a complex interaction and intermingling of individual odorous and non-odorous components that are produced during anaerobic decomposition of animal manure (Bottcher 2001; Zahn et al. 1997; Melvin 1996). Anaerobic decomposition of animal manure involves a complex series of digestive reactions by diverse populations of bacteria that metabolize the nutrients contained within the manure and subsequently convert these chemicals to various odorous compounds (Williams 1996). Researchers have identified upwards of 330 specific chemicals and compounds in animal manure odor that are end products and intermediates of the anaerobic decomposition process (Schiffman et al. 2001; Zahn et al. 1997). In the US more than 75% of the swine production systems handle manure anaerobically (Zahn et al. 1997). Included in this collection of odorous compounds and chemicals are a few key gases. Gases refer to the specific gaseous compounds that are produced and emitted from a manure source—primarily ammonia (NH_3), hydrogen sulfide (H_2S), methane (CH_4), and carbon dioxide (CO_2). Some gases, particularly highly volatile compounds like ammonia and methane, have potentially chronic effects associated with long-term environmental degradation (i.e. acid rain and other NO_x related problems, eutrophication) rather than short-term odor nuisance (Jacobson 1997). Collectively, the chemicals that make up swine odor are referred to as volatile organic compounds (VOCs).

Of particular importance, the majority of odorous chemicals and compounds are easily absorbed onto, concentrated by, and carried on aerosols (particulates) generated in animal facilities (such as animal houses and manure storage) and from land application (Bottcher 2001; Hammond and Smith 1981). An aerosol is a suspension of solid or liquid particles in a gas with particle size ranging from 0.002 μm to more than 100 μm, this includes such things as dust, clouds, fumes, mist, fog, smog, smoke and sprays (Hinds 1999). Depending on ambient weather conditions, odorous particulates have been known to travel upwards of two miles from their source (Hammond et al. 1981). Thernilius (1997), Laird (1997), and Hammond and Smith (1981) all conclude that by removing and/or controlling these particulates, animal houses, lagoons, and feedlots may become less odorous. Eby and Willson (1969) report that most of the odor from poultry houses can be eliminated by removal of air borne dust. Hartung (1986) concluded that up to 65% reductions in odor emissions are possible by filtering air dust from the animal houses' exhaust systems. However, the complex relationship between VOCs and particulate matter and the association between particulate reduction and odor reduction are far from conclusive and are subjects of continuing research (Cai et al. 2006; Bottcher 2001).

Shelterbelt and swine odor interactions: odor mitigation

Many odor control management technologies are available. They generally fall into one of three strategic categories. The first deals with the prevention of odor and involves technologies such as manure and feed additives. The second strategy attempts to capture and destroy odors before they are released into the atmosphere and involve techniques such as chemical scrubbers and biofilters. The third technique uses innovations that attempt to disperse and/or dilute odors before they can accumulate and become a nuisance to neighboring areas and involve manipulating air movement using obstructions made of both constructed materials (e.g. screening) and living barriers of trees and shrubs (Schmidt and Jacobson 1995).

The potential of shelterbelts to mitigate livestock odor arises from the tree/shrub impacts on the central characteristics and physical behavior of livestock odor. These characteristics are:

- most livestock odor sources are at ground level;
- there is often limited odor plume rise due to common weather conditions (i.e. temperature inversions) and limited mechanical landscape turbulence (Takle 1983; Takle et al. 1976);
- odor plumes have spatial and temporal variability (Guo et al. 2001; Zhu et al. 2000);
- odor plumes may be very extensive covering large land areas (Smith 1993);
- there is often a close proximity of people to odor sources;
- the odors generated in animal facilities that are intense and detectable at appreciable distances often concentrate and travel on particulates (Cai et al. 2006; Bottcher 2001; Hammond et al. 1981);
- there appears to be a major socio-psychological component to the perception of odor being a nuisance (Mikesell et al. 2001; Kreis 1978).

Because the odor source is near the ground and the tendency of the plume is to travel along the ground, shelterbelts of even modest heights (i.e. 20–40 ft) may be ideal for plume interception, disruption, and dilution (Lin et al. 2006; Bottcher 2001; Heisler and DeWalle 1988; Laird 1997; Thernelius 1997; Takle 1983). Shelterbelts can be adapted to fit the production situation and expected/experienced odor plume shape and timing. Depending on the shelterbelt design and tree/shrub species used, it can deal with the temporal changes to provide long term, year round plume interception, with increasing effectiveness over time. More is also becoming known about how landscape aesthetics affect how people might perceive livestock odor, suggesting that landscape elements such as shelterbelts can lead to improvements and perhaps more positive opinions of livestock odor and the farm systems that create them (Mikesell et al. 2001; Kreis 1978).

It should be emphasized that shelterbelts are amenable to use with the three main sources of livestock odor: animal buildings, manure storage systems, and agricultural land that has manure applied. Most other odor mitigation technology is very often source specific and not adaptable throughout the farm. Shelterbelts can be used throughout the entire farm and agricultural landscape. It is a technology that is not limited to producer use only. In fact, properly designed shelterbelts, may be the only odor technological approach that can be effectively used by the public, as well as producers.

Based on evidence available in research literature, there are five primary, interacting, ways that shelterbelts can mitigate livestock odors by

- physical interception and capture of dust and other aerosols as well as gases by trees and shrubs;
- dilution and dispersion of downwind concentrations of odor;
- land deposition of dust and other aerosol from reduced wind speeds;
- acting as a biological sink for the chemical constituents of odor after interception;
- enhancing the aesthetics of pork production sites and rural landscapes.

Physical interception of dust, gases and other aerosols

Swine confinement buildings are generally ventilated in one of three primary ways: ventilation by way of natural, open-air methods and by way of mechanical ventilation, or a combination of the two-hybrid systems. Regardless of the ventilation process utilized, this exhaust air contains significant quantities of odorous dust particles and gases. This air is in most cases exhausted without prior treatment. Once outside the confinement, depending on the current climatic conditions, these ‘‘plumes’’ can travel significant distances.

Vegetation can and does filter airstreams of particulates. As air moves across vegetative surfaces, leaves and other aerial plant surfaces remove some of the dust, gas, and microbial constituents of airstreams. It is also generally accepted that trees and other woody vegetation (i.e. shrubs) are among the most efficient natural filtering structures in a landscape in part due to the very large total surface area of leafy plants (Bolund and Hunhammer 1999).

Direct filtering occurs when particles are removed from air streams due to interception by and deposition onto plant surfaces. Small, turbulent eddy currents occur when laminar airflow is disrupted by aerodynamically rough surfaces such as leaves and branches (Beckett et al. 1998, 2000a, b). These eddy currents that form in turbulent airflows around plant surfaces reduce the resistance of the protective boundary layer of these surfaces allowing much of the particulate load to be impacted (lodged) onto plant surfaces. And once impacted, it often takes very high winds for particles to become re-suspended (Ould-Dada and Baghini 2001; Beckett et al. 1998). Interception and impaction by tree laminar (leaf) surfaces typically involves particulates with diameters between 0.1 μm and 10 μm (the so called PM_{10} range) (Beckett et al. 2000b). For particles of dimensions 1–5 μm, interception by fine hairs on leaf surfaces and non-laminar surfaces (stems, petioles, bark) may be the most important retentive mechanism (Smith 1984). In a study of aerial dust in commercial swine finishing houses, it was noted that 93.3% of the particles sampled were 5.2 μm and smaller (Stroik and Heber 1986). Also, particles from swine facilities are often irregular in shape, generally classified as flakes, fibers, spheres or cubes (Dawson 1990), and as noted by Freer-Smith et al. (1997) such shapes are advantageous for particulate retention on leaf surfaces. Quantification of this process, however, has been limited.

Recent wind tunnel experiments and field studies have quantified the capture efficiency (ratio of particulates hitting and being retained by tree surfaces to the amount of particulates in the air stream) of several different tree species as well as under conditions of different total particulate loads (Beckett et al. 2000a). Beckett et al. (2000b) exposed five tree species—Corsican pine (*Pinus nigra* var. *maritima*Aiton), Leyland cypress (× *Cupressocyparis lelyandii* Dallimore & Jackson), hedge maple (*Acer campestre*L.), Swedish whitebeam (*Sorbus intermedia* L.), and hybrid eastern poplar (*Populus deltoides* × *trichocarpa* Beaubre)—to 1 μm diameter droplets of NaCl over a range of air speeds (from 0.7 ms^{-1} to 10 ms^{-1}) within a wind tunnel. At 10 ms^{-1} they found the particle trapping efficiency of *Corsican pine* (2.8%) and *Leyland cypress* (1.22 %) to be significantly greater than that of *Swedish whitebeam* (0.21%), *hybrid eastern poplar* (0.12 %), and *hedge maple* (0.06%). Such results seem to confirm greater capture efficiency for species with more complex shoot structures, and with small but complex surface area (e.g. conifer needles) or hairier leaves (e.g. *whitebeam*). They also indicated a functional relationship between trapping efficiency and windspeed—that is the greater the particle inertia as it encounters a solid object, the greater likelihood of impaction onto that surface.

In a parallel study, Beckett et al. (2000c) examined the actual accumulations (weight) of particles (PM10, PM2.5, and soluble ions—coarse, fine, and ultra fine grain particles) within four of the same tree species as above in urban settings in the UK—a fifth species, Common Whitebeam (*Sorbus aria* L.), was also examined . They found that all five tree species captured the three size ranges of particulates with similar efficiency at both urban sites studied (one a small urban park, the other an agricultural research site on the campus of the University of Sussex). That is, the same pattern of particulate capture can be seen for each particle size range at each site. And just as with the wind tunnel simulations, Corsican pine was by far the most efficient particulate filter with Leyland cypress ranked second. Among the broadleaf species observed, the Common Whitebeam accumulated a significant amount of the coarse fraction particulates, which may be explained by this species' rough and hairy abaxial (lower) leaf surfaces (Beckett et al. 2000c). In contrast, poplar, with comparatively smooth and leathery leaves, was the least effective particle collector.

Ucar and Hall (2001) reviewed research of shelterbelts mitigating pesticide drift and concluded that the spray droplet capture efficiency of tree species is among the most important variables (along with toxicity tolerance and micro-climate suitability) when developing a drift-mitigating strategy. They also noted the general superiority of conifers for particulate capture and suggest that because conifers are ''in leaf'' year round they may also be more effective temporally. This is an important factor with regard to odor because even though odor nuisance increases in warmer weather, odor events do happen year-round. Nevertheless, studies have shown that non-laminar (stems, petioles, bark) particulate capture can be significant. For example, Ucar and Hall (1998) cite a study by Porskamp et al. (1994) that observed alder (*Alnus* spp.) windbreaks reducing pesticide drift up to 90% when in leaf, and still up to 70% when leaves were absent. Wind tunnel tests have shown non-laminar particulate capture contributing upwards of 37% of the total particulate load (particle size = 2.75 μm) to European beech (*Fagus sylvatica* L.) trees, and upwards of 47% of the total load (particle size = 5.0 μm) to White poplar *(Populus alba* L. trees (Little 1977).

Another factor influencing particle capture is a trees' roughness on a larger scale as defined by the overall canopy structure of individual trees or grouping of trees. A highly complex canopy (i.e. the pinnate structure of ash *Fraxinus* spp.) creates more opportunity for wind obstruction in the through-flow and therefore more internal turbulence (Beckett et al. 2000a). Interestingly it was noted, that younger, smaller trees of species that are efficient particle filters are also highly effective at removing particulates due to their greater foliage densities compared to much larger, mature specimens (Beckett et al. 2000a).

It is difficult to get an understanding of just how much particulate matter is accumulated. Some studies indicate actual amounts such as Steubing and Klee (1970), who measured the considerable filtering capacity of Mugo pine (*Pinus mugo* Turra) along the roadsides in Frankfurt, Germany. These researchers found that Mugo pine can have a capture effect of at least up to 0.18 mg cm^{-2} (1,800 mg m^{-2}) of dust on leaf surfaces (Farmer 1993), or Beckett et al. (2000b) who noted particulate weights of 488 mg m^{-2} and a total foliar surface area (ab- and ad-axial surfaces) of 341 m^2 on a single juvenile European linden tree (*Tilia* × *europaea* L.) within a shelterbelt in Fulmer, East Sussex, UK.

To assess the importance of these capture quantities, an example from Takai et al. (1998) assumes that the inhalable dust emission rate is 88 g h^{-1} for a mechanically ventilated hog farm with 500 pig fatteners, or an emission rate of roughly 2100 g of inhalable particulates per day. A single, 20 ft European linden tree may at least have the capacity of holding about 166 g of particulates at any time in dry weather (note that this includes only insoluble particles). This also does not include particulates captured by any of the woody parts of the tree (stems and bole). Linden shelterbelts placed within and around this hypothetical farm, depending on overall length and number of rows could have anywhere from 100 to 400 trees (or even more) with a potential total particulate load of around 16,000–66,400 g of particulates. However, some important questions still remain such as the load limit in which particulate capture efficiency becomes significantly reduced, the maximum duration of particulate holding, and the ultimate fate of the particulate matter held by the vegetation.

It must also be emphasized that the calculation of actual capacity, or total particulate loads within individual trees or grouping of trees is confounded by the ambient conditions of each site. Precipitation, which can effectively wash both soluble and insoluble particulates from tree surfaces (Beckett et al. 2000c), ambient humidity, diurnal weather patterns, variable wind speeds and wind direction, topography, the complex daily variability in emissions of the various particulate sources, and even the positioning of the plant material (natural vs. designed planting) collectively create an ecosystem context that make published total particulate loads site-specific and of limited generalizability, except to the extent that they can show that the particulate capture capacity exists and, in some cases, is likely to be substantial.

Perhaps additional filtration evidence can be found in overall patterns of particulate deposition. The total particulate capture of trees is dependent not only on the species-specific morphological capacity for particulate capture, but also upon the particle loads in the airstreams. That is, the higher the particulate load in the wind stream, the more particulates are found to be captured and held by these plants. Freer-Smith et al. (1997), show a filtering effect within a small urban woodlot near a major highway in Surrey, UK, since the number of particles counted on leaf surfaces decreased significantly as distance from the highway (the particulate source) increased. This result, however could be partially explained by dispersion of the particulate stream as well as by particulate capture. Still, this capture pattern was also evident with the filtering of coal-mine dust within a 15 m-wide mixed-age (24–50-year-old trees) greenbelt consisting mostly of European White Birch (*Betula pendula* Roth.) in Kansk, Siberia (Spitsyna and Skripal'shchikova 1991). Both suggest that the airstream is becoming ‘‘cleaner'' as it travels through the trees. For information regarding total particulate capture, Beckett et al. (1998) provide a more extensive review, particularly with reference to urban trees.

Based on the literature there are some general conclusions that can be made regarding the particulate filtering capacity of trees (Beckett et al. 2000a, b, c; Spitsyna and Skripal'shchikova 1991; Smith 1984):

- There is a high correlation (i.e. Pearson *r* values from 0.7 ± 0.19 to 0.98 ± 0.02) between leaf surface area and the quantity of dust accumulation.
- The greater the surface roughness of the leaf, the greater the particulate capture efficiency for particles 5 μm and less. Surface roughness increases with the presence of leaf hairs and pronounced veination.
- Smaller leaves are generally more efficient than larger leaves in collecting particulates.
- Leaves with complex shapes and large circumference-to-area ratios (i.e. conifers) appear to capture particulates most efficiently.
- Conifers are generally more efficient in capturing particulates than broadleaf species.
- Non-laminar surfaces (petioles, stems, bark) also accumulate significant amounts of particulates in the PM_{10}range.
- The more irregular in shape the particulates are, the greater the capture and retention on tree surfaces.

Dilution and dispersion of downwind concentrations of odor

The conditions leading to pollutant trapping by the atmosphere are well known (Takle 1983; Takle et al. 1976). Low wind velocity, radiational inversions and lack of physical landscape features that create turbulence all contribute to pollutants being trapped at ground level (Jacobson et al. 2001; Guo et al. 2001; Takle et al. 1976). Odor has a tendency to be most severe during stable, night-time conditions with low to moderate wind speeds, at which times odors emitted near the surface will not diffuse upward but remain near the surface and travel by way of near laminar flow that will meander over the terrain (OCTF 1998; SOTF 1995; Takle undated). Most odor events are recorded between 5 AM and 7 AM and between 7 PM and 10 PM, both relatively high residential activity hours and stable atmospheric conditions (Jacobson et al. 2001). Air temperature is also a major factor. At higher temperatures, the conditions for anaerobic decomposition can improve and greater volatility of odorous compounds may occur (NPPC 1995; SOTF 1995). When these weather conditions occur singly or simultaneously, it has been noted that odor can be transported over distances greater than two miles (NPPC 1995). Shelterbelt systems may be of value in dealing with these situations.

Shelterbelts have the ability to lift part of the odor plume into the lower atmosphere aiding in the dilution and dispersion process. When wind approaches a row of trees, a portion of the air stream will pass through the vegetation, some will pass around it, with the remaining wind being lifted up and over the vegetation. The lifting aspect will begin at some distance on the windward side, typically a distance equal to 2–5 times the height (referred to as 2–5 H) of the shelterbelt (McNaughton 1988). As studies in the distribution of windblown pollution indicate, the properties of the underlying surface (terrain) are important in deflecting the airstream or in modifying the rate of mixing and consequent dilution of the material carried with it (Pasquill 1974). Within the near vicinity of shelterbelts, heat, vapors, CO_2 and other scalar quantities (including odor plumes) are transported along streamlines by the prevailing winds and only across streamlines by mechanical turbulence (McNaughton 1988). McNaughton (1988) further notes that as the air streams top the obstacle, the stream is redirected, becomes compressed and increases in speed. This is commonly referred to as wind shear. This affected zone above the shelterbelts has been noted at heights of 1.5 H (that is 1.5 times the height of the barrier) to 1.7 H. Therefore, for a shelterbelt that is about 20 ft tall, this effected zone may extend roughly 30–34 ft above ground level. This zone then downturns to follow the air stream downwind and acts as a source of turbulent kinetic energy. Thus shelterbelt height is a significant variable: the taller the barrier the higher air will be pushed into the lower atmosphere. It should be noted, however, that this dynamic has yet to be quantified.

Both field and wind tunnel studies that have examined the dynamics of shelterbelts cite a somewhat triangular ''quiet'' zone (zone of low speed, providing maximum wind protection) that extends from the top of the shelterbelt down to a distance of about 8 H. Immediately above this quiet zone the longitudinal turbulent fluctuations are more energetic and larger in scale (Cleugh 1998). It is within this turbulent zone that much of the dilution of the odor plume into other air layers may take place (Fig. 1 below is a schematic of these processes). This dilution effect comes not only from that part of the odor plume which is mixing with other ''higher-off-the-ground'' air layers but also from a slower release of odorous particulates and gases into the airstreams that continue downwind. Therefore, the concentration of odorants within the plume that does continue downwind is reduced. Based on computer simulation studies, the plume also appears to become more uniform in terms of concentration, which is beneficial with regards to how the human olfactory system processes exposure to odors (Lammers 2002). High odorant variability within an exposure often leads to higher perceptions of an odor event being considered offensive (P. Lammers pers. comm. 2002).

Recent wind tunnel and field studies performed by North Carolina State University personnel have shown that artificial wind break walls deflect building exhaust air so that air flows higher above the ground or the surface of downwind lagoons improving potential dilution of odors to the point of noticeable odor reduction downwind (OCTF 1998; Bottcher et al. 1999). By examining the behavior of smoke emissions, researchers have observed enhanced vertical mixing of swine building exhaust plumes due to the presence of artificial, non-porous windbreak walls (Bottcher et al. 2000, 2001).

Odor plume modeling has also indicated this vertical mixing in simulations. Using three-dimensional fluid dynamic algorithms with simultaneous diffusion calculations, Lammers et al. (2001) observed that an odor emission from a livestock building would experience an elevated mainstream that is distributed by turbulent eddies in the lee of a solid flow barrier such as an adjacent building. The impact of a diffuser type barrier such as a shelterbelt with an unspecified level of porosity shows a slightly different plume pattern in that there is still an elevated mainstream but the dispersion is more uniform, and therefore,

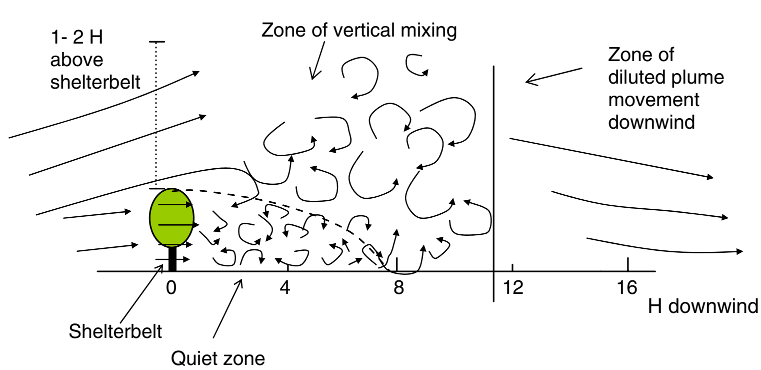

Fig. 1 Schematic representation of turbulence and zone of potential odor dilution. Adapted from McNaughton (1988). The term ''H'' means ''multiplication by height of shelterbelt''

diluted in the downwind stream (Lammers et al. 2001; P.S. Lammers pers. comm. 2002).

Lammers et al. (2001) note that shelterbelts could become a temporary zone of increased odor trapping and perhaps zones of increased on-site odor (e.g. concentrated odor). However, it is not yet known if there are any on-farm implications because of this. Bottcher et al. (2001) warns that smoke simulations indicate that dilution benefits are reduced during periods of stable wind flows.

Buildings are not the only odor source that can benefit from air stream manipulation by shelterbelts. Anaerobic manure lagoons and other uncovered manure storage facilities are also major sources of swine odor. Liu et al. (1996) numerically simulated the effects of tall barriers around manure lagoons and predicted reductions in downwind malodorous lagoon emissions of 26–92% for a range of barrier distance to height ratio from 8 to 0.6. This reduction is largely due to the prevention of particulates (generated elsewhere on the site) from passing over the lagoon surface. Thereby limiting the concentration of odorous VOCs convecting off of the lagoon surface onto ambient particulates and then subsequently moving downwind.

In a recent Canadian pilot study, Lin et al. (2006) used a mobile odor generator to simulate swine odor and quantify the odor dispersion effects of various configurations of field shelterbelts (e.g. differing species, optical porosity, distance from odor source). Two single row deciduous and two single row conifer shelterbelts where compared to a control site that lacked landscape vegetation. Using trained odor panelists (individuals trained in differentiating odor intensity) in the field there were recorded reductions in odor concentration with downwind distance from the source. The reductions are believed to be caused by the presence of the tree row leading to enhanced odor dispersion in the field. In general, Lin et al. (2006) concluded that: (1) windbreaks of low optical porosity (≈35%; optical porosity being a two dimensional measure of porosity) showed a more pronounced odor reduction effect; (2) a conifer tree row (species not defined) at 15 m from the odor source showed greater odor dispersion than a deciduous tree row (*Populus* spp.) at the same distance; (3) a tree row located closer to the odor source recorded more odor dispersion than one located further downwind (15 m vs. 60 m). See Lin et al. (2006) for details regarding analytical protocols and full results.

Land deposition of dust and other aerosol due to reduced wind speeds

Much progress has been made in understanding turbulent transport of air over, around, and through windbreak structures as well as quantifying wind speed alterations (Wang and Takle 1995; Zhang et al. 1993; McNaughton 1988; Heisler and DeWalle 1988; Kort 1988). Measured reductions in wind speed on the lee (downwind) side of a shelterbelt have been varied, with reductions being recorded as far as 50 H of the shelterbelt (Heisler and DeWalle 1988). Measurable wind speed reductions to about 30 H are more typical (Cleugh 1998). The air turbulence changes and wind speed reduction creates situations where wind borne particles can be deposited at much shorter downwind distances than would occur without the shelterbelt. For example, a barrier effect has been noted in the hedgerow systems in Britain as downwind spatial deposition patterns of various propagules (e.g. seeds, pollen, or spores) have been identified (Burel 1996). Ucar and Hall (1998), investigating windbreaks and agrochemical drift mitigation, discussed the exponential trends of drifted spray deposits. They suggest that even a simple vegetative barrier such as a single row of trees would reduce potential chemical drift significantly due to reduced wind speed, though they pointed out that that does not mean reduction to significant levels in all cases. Ucar and Hall (2001) also conclude that pesticide drift reduction offered by shelterbelts evidently arises from two main causes. The first cause is the shelterbelt induced reduction of wind speed over and around the targeted crops; the second cause is due to interception of fugitive pesticide aerosols within the shelterbelt itself.

Laird (1997) and Thernelius (1997) both modeled the potential of windbreaks to deal with odor carrying particulates using an open circuit wind tunnel and a small-scale model of an open-air ventilated hog confinement building and a simulated shelterbelt. The hog house particulate matter was simulated with highly ground walnut shells positioned within the model hog house. Digital imaging was used to examine the brightness of the wind tunnel floor as a measure of dust deposition behavior. Multiple scenarios were tested examining differences in particle deposition due to the number of parallel shelterbelts of various heights as well as different wind speeds and angles. The objective was to minimize the total particulate mass that leaves the farm boundaries. Table 1 below displays some results of modeled particulate reduction due to shelterbelts.

Based on the results, wind velocity, angle of wind, and the height of the shelterbelts are important variables, with wind velocity being the most important. Successful reduction in mass transport far downstream ranged from 35% to 56%, with the conclusion that this reduction would provide a substantial reduction in the effects of offensive odors in surrounding areas (Laird 1997). Both researchers, however, noted that in order for the information they gathered to be useful in full-scale applications, it remains necessary to perform field-testing. Vegetation type was not a variable nor was windbreak porosity, which has been noted as possibly the most influential factor in reducing wind speed (Ucar and Hall 1998; Brandle and Finch 1991; Heisler and Dewalle 1988). Dust interception by the vegetative barriers was loosely considered as it was noted that ''part'' of the total dust mass was retained by the model shelterbelts.

Acting as a sink for the chemical constituents of the odorous pollution

Not much is known about the ability of trees and other plants to ameliorate odor by way of intake or absorption of odorous chemicals or the managerial use of vegetation for this purpose. There is, however, indirect evidence that suggests this is possible. In the last few decades there has been tremendous interest in the ability of plants to remove various pollutants from the air, and several reviews have addressed the capability of plants to act as a sink for air contaminants (Kwiecien 1997; Smith 1984; Bennett and Hill 1973; Hill 1971).

Aerosol chemicals can enter the plant in three ways: (1) gaseous diffusion through open stomata, (2) if chemicals are soluble, they can enter through the stomata in dissolved form, and (3) chemicals can be adsorbed onto and absorbed into plant tissues (Landolt and Keller 1985; Smith 1984). The rate of pollutant transfer is regulated by a series of resistances (Saxe 1990; Smith 1984). It has been emphasized that other than pollutant concentration and exposure time, stomatal resistance is the most important factor determining the uptake of pollutants by plants (Landolt and Keller 1985). Diffusion through open stomata is considered the route of least resistance. This is regulated first by the plant surface boundary layer (the perfectly still layer of air surrounding all surfaces) and then by the concentration gradient between the ambient air and the sorptive surfaces of a plant's interior (Kimmins 1997; Treshow and

Table 1 Downwind particulate reduction associated with different wind parameters as modeled in a wind tunnel using a simulated 3 row shelterbelt

Wind speed(m/s)	Angle of wind (°) (oblique to the shelterbelt)	Height of shelterbelt (m)	Distance from building(m)	Percent of particulates lost without shelterbelt	Percent of particulates lost with shelterbelt	Percent change in particulate retention with shelterbelt
4	0	5.00	19.11	57.4	29.1	50.7
4	30	5.00	19.11	75.3	32.8	43.6
5	15	3.75	19.11	80.0	51.7	64.6
6	0	5.00	19.11	81.9	49.3	60.2
6	30	5.00	19.11	96.4	63.0	65.4

Shelterbelt heights and distance from building translated from 1:50 scale. The percentage of particulates lost with or with out shelterbelts means the percentage of on-farm particulates that are blown off the farm and, theoretically, ''downwind''

Source: Laird (1997) and Thernelius (1997)

Anderson 1989). Diffusability and solubility of pollutants are the main factors that affect the rate of boundary layer penetration.

Once the boundary layer is penetrated and contact is made with the leaf surface, a pollutant may enter by two routes: absorbed by way of passive diffusion through the stomata (if soluble, pollutants will often enter in solution) or absorbed through the tissues (Waring and Schlesinger 1985). One study of interest examined different sorption rates of sulfur dioxide and ozone between conifers and deciduous trees during a fumigation study and determined that sorption rates were higher in conifers (Elkiey et al. 1982).

A waxy, lipophilic cuticle resists adsorption of pollutants into plant tissues. The cuticle does offer significant resistance to the movement of water and solutes but it is not impermeable, as evidenced by the fact that most agricultural chemicals are applied as foliar sprays and many of those chemicals, such as herbicides and systematic insecticides, must penetrate the cuticle to be effective (Schonherr and Riederer 1989). Interestingly, lipophilic substances (i.e. organic fatty compounds) actively accumulate in lipids on plant surfaces (the cuticle is composed of cutin, which is a lipid-based polymer) (Taiz and Zeiger 1991). The leaves of trees are highly lipophilic and due to lipophilic affinity, they are excellent accumulators of lipophilic foreign substances such as VOCs (Reischl et al. 1987, 1989). For example, as measured in field experiments, nitrogen based chemicals and compounds have shown high affinities for leaf cuticles and other plant surfaces (Asman et al. 1998). This affinity of nitrogen-based chemicals to leaf cuticles is enhanced with increased relative humidity and decreased vapor pressures (Asman et al. 1998). Both typically occur within the leeward quiet zone of shelterbelts. Depending on the porosity of the shelterbelt, relative humidity is typically 2–4% higher and temperature is several degrees higher in sheltered areas than in open areas (Brandle and Finch 1991). Asman et al. (1998) suggested that reductions in NH_x might be achieved indirectly by modifying local scale atmospheric transport and because a relatively large percentage of the emission is dry deposited close to the source, benefits might be achieved by planting a managed farm woodland system around known sources to increase dry deposition and reduce deposition to more critical areas downwind.

Research also suggests that trees can be used as bio-indicators for pollution emission location and prediction (Reischl et al. 1987, 1989; Gaggi et al. 1985). Reischl et al. (1989), using gas chromatography tests, recorded accumulations of chlorinated hydrocarbons (anthropogenic VOCs) in the foliage of 15-year-old Norway spruce (*Picea abies*). Foliage samples were taken at different locations in the proximity of different pollution centers such as an industrial area, an urban area, and a hazardous waste landfill and were then compared to samples from a ‘‘clean air’’ site (an area of considerable distance from a pollution source). The study found much higher concentrations of pollutants from the samples located in the polluted areas as compared to the levels recorded for the clean area.

Another potential air pollution sink exists on and within the microorganisms that coexist on plant surfaces. The surfaces of plants, depending on such factors as plant species, humidity, temperature, season, leaf age and health are usually covered with micro-organisms of all kinds; various forms of fungi, bacteria, and yeasts dominate (Schreiber and Schonherr 1993; Dickinson and Preece 1976; Preece and Dickinson 1971). In an early review, Smith (1976) hypothesized that since epiphytic organisms have been exposed to many compounds now considered as pollutants for millennia and that this exposure occurs at the atmospheric–plant interface, these microbes may behave as sinks for certain particulates and gaseous pollutants. Schreiber and Schonherr (1992, 1993) determined that microorganisms often influence and affect the quantification of foliage uptake of chemicals to the point where care must be made to separate the mechanism during related research.

It is known that many different microorganisms are capable of metabolizing and/or breaking down chemical pollutants such as anthropogenic VOCs (Baker and Herson 1994; Muller 1992; Fry et al. 1992) and this process is used in many different types of bioremediation techniques (Baker and Herson 1994). It is not, however, currently known how effective epiphytic microorganisms are at metabolizing and/or degrading odorous VOCs or if such a process could be effective in mitigating ambient and downwind odorous conditions.

Smith (1984) and Abbasi and Khan (2000) listed some generalizations regarding gaseous/aerosol pollutant interception and/or uptake into plants that can be made based on controlled experiments and with seedlings. Among the most important were:

- Plant uptake rates increase as solubility of the pollutant in water increases. Ammonia in particular is highly soluble in water.
- When the plant surfaces are wet, the pollutant removal rate may increase up to 10-fold. When conditions are damp, the entire aerial plant surface is available for uptake.
- Moisture stress and limitations on solar radiation act to limit stomatal openings and can hinder pollutant uptake significantly.
- Pollutants are absorbed most efficiently by plant foliage near the canopy surface, where light-mediated metabolic and pollutant diffusivity rates are greatest.
- Because numerous forces and conditions regulate the rate of pollutant uptake, the rate of removal under field conditions will be highly variable.
- However, the rate of pollutant removal can increase linearly as the concentration of the pollutant increases.

Aesthetics

Socio-psychological factors play a role in livestock odor being perceived as a nuisance. Researchers have documented that perceptions of odor differ from individual to individual and are characterized by personal preferences, experiences, opinions, imagination, cultural associations, visual images, and variability in our olfactory systems (Distel and Hudson 2001; Williams 1996). In an early review regarding the minimization of livestock odor impacts, Kreis (1978) made several observations in this regard. It is explained that avoiding nuisance complaints is difficult, in part, because of interactions of the social and psychological background and the individual preferences. Kreis (1978) points out that psychologists have stressed that *a priori* bias either positive or negative towards an odor source often influences emotional responses to that odor source. It is further suggested that additional ‘‘aesthetic insult’’ from that odor source, be it other pollutants (such as water pollution), or other more cosmetic factors such as yard disorderliness or objectionable architecture may negate many odor amelioration attempts. Additionally, visual cues have been noted to be associated with higher incidences of odor nuisance complaints (Kreis 1978 citing Eugene 1971 and Waller 1970).

Mikesell et al. (2001) interviewed all the neighbors within a variable radius (≤ 1 mile) of seven large swine farms in Pennsylvania and recorded an inverse relationship between the ‘‘attractiveness’’ of a farm and reported negative odor intensity ratings. That is, those farms that appeared to be more subjectively attractive were perceived to be less odorous. However, quantification of actual odor emission rates at each farm was not attempted, and the characteristics of what constitutes ‘‘attractiveness’’ were not defined.

The specific aesthetic appeal of shelterbelts within agricultural landscapes has been examined. Cook and Cable (1995) find by way of a photo elicitation (slide show) survey of Kansas State University undergraduates that photos of Great Plains shelterbelts (both single belts and systems) rate very high on scenic quality indices whereas open and barren agricultural landscapes rate very low on scenic quality indices. They conclude that (1) shelterbelts add quite positively to the scenic beauty of Great Plains landscapes and (2) that observer background characteristics appear to have little to do with scenic quality evaluations of shelterbelt landscapes, therefore suggesting a loosely generalizable appreciation of the landscape aesthetics of shelterbelts. Also, Ronneberg (1992) listed improved aesthetics as a major benefit of general shelterbelt use, stating that studies have shown ‘‘Visual diversity...(is) preferred to open landscape’’.

Kliebenstein and Hurley (1999) conducted a general public survey regarding environmental impacts and other farm issues, and found that

68% ($n = 329$) of the respondents agreed that "filtration" (in a general sense) of swine building air for odor reduction is somewhat to very acceptable. There was also a general high social approval of technology that is considered "natural" (which it could be argued includes shelterbelts), as opposed to technology which is mechanical or chemical in nature.

Professionals involved with livestock agriculture generally accept that a well-landscaped operation, which is visually pleasing or screened from view by landscaping is much more acceptable to the public than one which is not (Lorimor 1998; NPPC 1995; Melvin 1996). It is this notion of visual screening that has made landscaping and shelterbelts a common suggestion from agricultural engineers with regard to minimizing odor problems. If it is made known to neighbors and local communities that a shelterbelt is being used as a pollution (air or water) control tool, it may serve as very visible proof that a livestock producer is making an extra effort to control odor.

General shelterbelt design considerations

Shelterbelts designed for the purpose of particulate capture and plume dilution/dispersion can be located on the production site wherever particulate emissions occur. Main on-site locations of particulate emissions are swine buildings, agricultural fields that receive land applications of manure, heavily used roads, and any outdoor animal systems (i.e. feedlots or hauling lots). For plantings near buildings it was noted that they should extend high enough to fully intercept the plumes of airflow issuing from the fans (e.g. 4 m high for typical buildings) (Bottcher et al. 2000). Care must also be taken so as not to compromise building ventilation. If naturally ventilated, trees and/or shrubs must not impede necessary wind patterns. For mechanically ventilated buildings, vegetation must not be close enough to impede ventilation intakes and outlets or maintenance alleys. Based on examinations of artificial windbreak walls (Ford and Riskowski 2003; Bottcher et al. 2000), a distance of at least four fan diameters downwind from the fans are sufficient to prevent back pressures, however the eventual crown width of the tree species must be factored in. Thus some suggest that shelterbelts should be located at a minimum distance of five times the diameter of the fans (Malone and Abbot-Donnelly 2001). If shelterbelts are to be planted near or around manure lagoons or earthen manure pits, the rooting habits of the tree species used should be known to prevent tree roots from compromising the protective lining of the lagoon that prevents leaching of pollutants into the soil and ground water sources.

In general, care always needs to be taken when vegetation is planted to avoid creating any negative on-farm situations. The mature size of vegetation must be known so that trees and/or shrubs will not grow to become hazards. If used near roads or feedlots, trees should not be planted in ways that impede sight lines and create snow deposition problems in the wintertime. Likewise, if planted as a perimeter around agricultural fields, expected snow deposition patterns are critical so as to prevent excessive moisture problems in the spring and/or as a benefit to possibly enhance moisture in dryer areas.

Shelterbelt structure is of prime concern when it comes to particulate interception. Aspects such as height, length, width, and porosity (density) all have important implications. For interception, shelterbelt height is important to the degree that the odor plume is intercepted as much as possible. A shelterbelt that is shorter than the plume will only intercept that portion that comes into contact with the trees. Because the odor source is near the ground and due to typical weather patterns in agricultural areas, the tendency of the plume is to travel along the ground with limited rising and mixing (Takle 1983), therefore shelterbelts of even modest heights (i.e. 15–30 ft) may provide adequate plume interception. Shelterbelt length needs to be considered with regard to the width of the plume, again for proper plume interception. An initial rule of thumb may be to size the shelterbelt length at least as wide as the width of a building ventilation system, the width of a manure lagoon, or the width of an agriculture field that has received a manure application. Odor plumes start out at least as wide as the emission source and may expand with distance downwind from that source depending on ambient weather and landscape conditions.

Shelterbelt porosity is also of significant concern for particulate capture as there needs to be adequate air flow through a shelterbelt so that particulates have an opportunity to make contact with tree surfaces and create instances of internal turbulence. A shelterbelt that is too dense simply pushes most of the wind up and over and particulate capture efficiency diminishes significantly (Ucar and Hall 2001). Total deposition of particulates to a shelterbelt is determined by a trade-off between enough porosity promoting throughflow of particulate-laden airstreams and enough density to promote particulate contact with tree surfaces, implying there exists an optimum value for porosity (Raupach et al. 2001). Dorr et al. (1998) (as cited in Ucar and Hall 2001) suggested a theoretical optimum porosity of 40–50% for capturing windborne pesticide droplets. It was also suggested by Dorr et al. (1998) that a system of shelterbelts consisting of multiple rows of belts with this level of porosity, provide increased surface area for particulate capture. Thus the widths of the shelterbelt and the number of rows involved are important factors for particulate interception and capture.

With regard to promoting odor plume dilution, species considerations for this particular dynamic can be different than those of particulate capture. Here height and overall shelterbelt porosity is of critical concern. Some species, which may not be the best for particulate capture, may be more appropriate here. Species such as *Populus* grow quite quickly (1–4 ft per year has been observed in the Midwest US), and may be used as nurse trees—trees that can provide early height while other slower growing species (i.e. conifers) take more time. As shelterbelt porosities of $< 40\%$ may be needed to achieve desired turbulence, the overall crowning habit of species should be understood, as some species maintain a fuller crown even as they grow taller. There is also limited empirical evidence that suggests a wedge-shaped belt (e.g. multiple rows of different heights), with shortest row facing into the prevailing wind, can ''ramp'' (push) airstreams higher into the atmosphere (J. Brandle pers. comm. 1999).

Generic shelterbelt system demonstration

Below is basic diagram of a shelterbelt design associated with a hypothetical hoop house swine production facility. The shelterbelt design shown is very generic. This generic design provides ''buffering'' around the major sources of livestock odor for a hoop house of this design located in central Iowa. The design can easily be adapted to fit other livestock confinement and /or feedlot systems. The wind in Iowa primarily comes from the south, southwest, and southeast during the summer months and the north and west during the winter. The orientation of shelterbelts reflects this. Also note that there are no trees or shrubs located on southern end of this facility. This facility would be naturally ventilated and there is a need to limit the risk of negatively impacting the necessary flow of cooling winds into the buildings open southern walls.

Shelterbelt impact on odor perception

The primary goal of odor mitigation is to *minimize* perceived odors, not necessarily eliminate them. Williams (1996) and Melvin (1996) suggest that the achievement of this goal can be measured by reductions in: (1) odor concentrations reaching populated areas, (2) the number of people affected by objectionable odors, (3) the duration of exposure to odors, and (4) the number of occurrences of odor events. Legally defined separation distances aid in the dispersion of odors. In Iowa, for example, this distance is between 1,250 and 3,000 ft depending on the size of the facility and number of animals (Lorimor 1999). Because most of these distances are determined based on protection of water sources, the distance is often not enough to reduce odor concentrations to levels that eliminate odor nuisance. As the evidence above suggests, shelterbelts have the ability to reduce odor concentrations significantly at or very near the source, which greatly enhances the effectiveness of that separation distance. Appropriate shelterbelt designs, through the combined effects of each dynamic—particulate capture, plume dilution, particulate drop out, and biological attraction of odorous chemicals to vegetation—should be able to decrease the concentration levels of odor plumes leaving production sites and, therefore, contribute incrementally to the physical decrease of odorous chemicals moving through an airshed. This, in combination with legal separation distances should significantly limit odor plumes reaching populated areas, reduce the total number of people affected downwind, reduce the duration of exposure to odors, and allow for reductions in the number of occurrences of odor events. And any aesthetic landscape improvements may contribute to a more positive response to odor that does reach critical receptors—people.

However, key to that assessment is the notion of 'appropriate'. If a shelterbelt is planted without the consideration of ecological, biochemical, and engineering principles and knowledge, shelterbelts can be inefficiently utilized or worse they could be ineffective (Khan and Abbasi 2001). Ucar and Hall (2001) also stress that existing shelterbelts and other vegetation may work quite well for their original purpose (i.e. erosion control, crop/animal protection, riparian buffer zones), but in establishing shelterbelts for other goals (such as odor mitigation) careful design is imperative. Moreover, as shelterbelts likely provide site specific incremental mitigation benefits, they should not be considered as outright substitutes for separation distance or used in decisions regarding the setting of legal distances. They also should not be considered as an alternative to standard best management practices (Ucar and Hall 2001). Ideally shelterbelts are to be used with other proven odor mitigating technologies and/or suitable manure management practices for the additive benefits of incremental odor amelioration.

Overall discussion on shelterbelts as technology

Despite the promise of shelterbelts as a beneficial technology there are some potential drawbacks that are common to tree based technologies. There is the time needed for the vegetation to grow. This is a difficult technological drawback when dealing with acute odor problems and retrofitting plant material is the management option. It is likely that trees need to be at least 3–5 years old before any noticeable benefits occur (though aesthetically, benefits may occur sooner). Shelterbelts also have space needs. Some livestock systems are more space limited than others. And several rows of trees throughout a production site can add up to hundreds of trees. Furthermore, facility land space may be limited because of maintenance and access roads. Trees need to be located so as to not hinder the use of those roads. Of particular concern is that for optimal use some shelterbelts may best be planted on land that is not part of the production site, particularly around fields where manure is spread. This may require coordination across property ownerships and the planting of trees on edges of active agricultural land. Government assistance programs such as the Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP) may provide some financial support but multiple landowner coordination is often difficult to manage.

Knowledge of tree growth and maintenance to maximize tree health and prevent unnecessary tree mortality (e.g. avoiding certain herbicides, proper mowing procedures, and providing suitable moisture levels) is required. Many land management professionals typically have expertise in trees/forestry or in farm systems but rarely expertise in both (Schaefer 1989). Such situations have led to on-farm failures of tree systems.

There are also time requirements for maintenance that may include: mowing, spraying, irrigation, and occasional tree replacement—5% to 10% tree mortality is common over the first 10 years for many otherwise healthy shelterbelts (G. Horvath pers. comm. 2002). Some concern has been expressed regarding the notion that shelterbelts may provide habitat for on-farm pests such as rats and other mammals as well as undesirable insects. Research on this topic is limited. But there has been very little evidence that this has been a serious problem with crop field shelterbelts. Undoubtedly more research is needed to fully answer this question.

Because empirical evidence is lacking it is difficult to assess the effectiveness of this technology at this point. However it is likely that there is a continuum of effectiveness. The lower the overall level of odorous emissions emanating from a production site, the more effectual shelterbelts are likely to be. It is likely that there is a threshold at which shelterbelts (and other technologies) are simply overwhelmed and a nuisance situation may continue to exist. Field and laboratory tests are needed for a better understanding of this threshold.

There are some very real barriers to appropriately using shelterbelts within and near livestock production sites. Though shelterbelts are comparatively inexpensive to establish and maintain as an odor control technology, they do represent a cost to livestock producers both up front (i.e. site preparation, plant stock, and shelterbelt establishment) and over time (i.e. management). Recent research, however, has shown that total costs are significantly below what swine producers have been reported to be willing to pay for odor control. For example an economic analysis of the shelterbelt design shown in Fig. 2 revealed total costs to be between \$0.45 and \$0.59/per pig (marketed) *below* producer willingness to pay for odor control (Tyndall 2003; USDA 1996).

It is known that livestock odor has site-specific idiosyncrasies in its biophysical behavior and also idiosyncrasies in the social reaction to it, yet many current advances in odor mitigation seem to ignore this fact. Odor nuisance complaints are on the rise in the Midwest of the US, so it seems clear that there is something missing in management approaches currently used. Indeed, Person et al. (1995) call attention to this by suggesting the status quo in managing odor nuisance is not at all adequate in the face of the changes in livestock agriculture. Furthermore they state that the "appropriateness of recommendations for new technology and management practices will depend upon their being simultaneously compatible in an extensive interactive system that functions

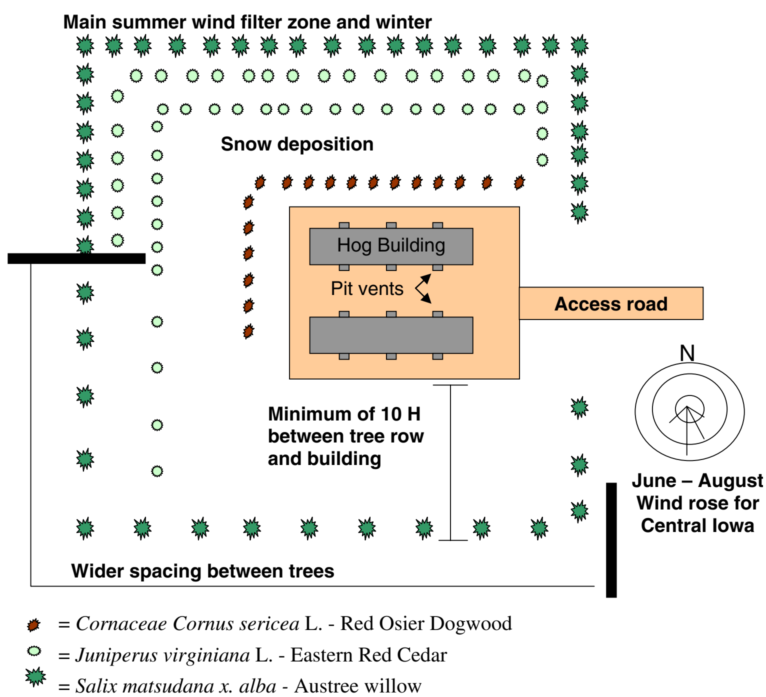

Fig. 2 Diagram of a shelterbelt system planted around a hypothetical naturally ventilated (side curtain) 2,100 head wean to finish hog facility. Planting orientation is guided by the summer wind patterns for Central Iowa—predominant summer winds originate from south to slightly south-east. Plantings to the south and south-west/east show wider spacing between trees and a minimum distance of 10 H from tree row to buildings; this is to allow for adequate summer wind to vent the buildings. The shelterbelts along the north-west and north show three rows and tighter spacing (8–10′ between trees; 12 ft between rows) to provide a zone of filtering surface area and turbulence to aid in dilution of odor plume. Three species are shown here for visual and biodiversity

in a community, natural (resource), economic, (and environmental) context all of which are tightly coupled'' (Person et al. 1995).

It is for these reasons that there is a distinct advantage in the use of shelterbelts in that there is evidence that they are quite adaptable to the ecosystem and production variability of livestock production sites and production regions. There is also information that the presence of trees in agricultural landscapes has socio-aesthetic advantages that most other odor mitigation technology lacks completely. Shelterbelts are also a technology that can be considered production technology neutral, in that producers who raise hogs in a variety of facilities—confinement, modified confinement, hoop house, pasture—can plant designed shelterbelt systems. Shelterbelt systems are also a size neutral odor mitigation technology. Shelterbelts, very uniquely, offer a technology that both producers and rural residents and communities can appropriately use, suggesting ''user neutrality''. Further, as opposed to other odor mitigating technologies that typically depreciate over time, shelterbelts may be the only odor control technology that theoretically increases in effectiveness over time. As with other tree based technologies used in agriculture, the effectiveness of shelterbelts in mitigating odor comes from providing complex ecological infrastructure within an otherwise ecologically simplified system (Schultz et al. 2000). As the trees grow larger, and more morphologically complex their ability to mitigate odors should become increasingly efficient. Of course, this implied improvement over time is contingent upon the long term health and maintenance of the shelterbelt systems and the continuance of hog production best management practices.

Conclusion

Clearly, the published information on the ability of shelterbelts to mitigate on-and off-farm livestock odor is limited and further bio-physical, economic, and social qualification and quantification of this technology is needed. Yet the existing evidence indicates that shelterbelts, when planted in strategic designs (e.g. on-farm location, species selection), can help incrementally to reduce odor pollution. There are several key studies currently underway that will begin to answer questions of quantification, design, and producer and societal acceptance (Adrizal et al. 2006; Malone et al. 2006; Colletti et al. 2006). In the mean time it seems prudent to approach the design of shelterbelts for odor mitigation from a ''prevent hazards'' point if view and plant in a way so as to not cause snow deposition problems and/or impediment to needed natural wind flow.

It has been said that the sustainability of industries within agriculture will be shaped by its collective ability to improve environmental impact technologies (Kliebenstein 1998). This review suggests that shelterbelts can make an incremental, yet likely beneficial, contribution to that end.

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References

Abbasi SA, Khan FI (2000) Greenbelts for pollution abatement: concepts, design, applications. Discovery Publishing House, New Delhi, 246 pp

Adrizal, Patterson P, Hulet R, Bates R (2006) Foliar nitrogen status and growth of plants exposed to atmospheric ammonia (NH_3). In: Aneja VP et al (eds) Proceedings: Workshop on Agricultural Air Quality: State of the Science, Potomac, Maryland, June 5–8, 2006, pp 442–452

Asman WAH, Sutton MA, Schjorring JK (1998) Ammonia: emission, atmospheric transport and deposition. New Phytol 139(1):27–48

Baker KH, Herson DS (1994) Bioremediation. McGraw-Hill Inc., New York, 375 pp

Beckett KP, Freer- Smith PH, Taylor G (1998) Urban woodlands: their role in reducing the effects of particulate pollution. Environ Pollut 99:347–360

Beckett KP, Freer- Smith PH, Taylor G (2000a) The capture of particulate pollution by trees at five contrasting UK urban sites. Arboricult J 24:1–21

Beckett KP, Freer- Smith PH, Taylor G (2000b) Particulate pollution capture by urban trees: effect of species and wind speed. Global Change Biol 6:995–1003

Beckett KP, Freer- Smith PH, Taylor G (2000c) Effective tree species for local air quality management. J Arboricult 26(1):12–19

Bennett JH, Hill AC (1973) Absorption of gaseous air pollutants by a standardized canopy. J Air Pollut Control Assoc 23:203–206

Bolund P, Hunhammer S (1999) Ecosystem services in urban areas. Ecol Econ 29:293–301

Bottcher RE (2001) An environmental nuisance: Odor concentrated and transported by dust. Chem Senses 26:327–331

Bottcher RE, Munilla RD, Baughman GR (1999) Controlling dust and odor from buildings using windbreak walls. Proceedings: 1999 Animal Waste Management Symposium. Raleigh, North Carolina. January 27–28, 1999

Bottcher RW, Munilla RD, Baughman GR, Keener KM (2000) Designs for windbreak walls for mitigating dust and odor emissions from tunnel ventilated swine buildings. In: Swine Housing, Proc. of the 1st International Conference, Oct. 9–11, 2000, Des Moines, Iowa. American Society of Agricultural Engineers, St. Joseph, MI 49085-9659, pp 174–181

Bottcher RW, Munilla RD, Keener K, Gates RS (2001) Dispersion of livestock building ventilation using windbreaks and ducts. Presentation at the 2001 ASAE Annual International Meeting, Sponsored by ASAE Sacramento Convention Center, Sacramento, California, USA July 30–August 1, 2001

Brandle JR, Finch S (1991) How windbreaks work. University of Nebraska Extension EC 91-1763-B

Brandle JR, Hodges L, Zhou XH (2004) Windbreaks in North American agricultural systems. Agroforest Syst 61:65–78

Burel F (1996) Hedgerows and their role in agricultural landscapes. Crit Rev Plant Sci 15(2):169–190. CRC Press, Inc.

Cai L, Koziel JA, Lo YC, Hoff SJ (2006) Characterization of VOCs and odorants associated with swine barn particulate matter using SPME and Gas Chromatography–Mass Spectrometry-Olfactometry. J Chromatogr A 1102(1–2):60–72

Cleugh HA (1998) Effects of windbreaks on airflow, microclimates and crop yields. Agroforest Syst 41:55–84

Cook PS, Cable TT (1995) The scenic beauty of shelterbelts on the Great Plains. Landscape Urban Plan 32:63–69

Colletti JP, Hoff S, Thompson J, Tyndall J (2006) Vegetative environmental buffers to mitigate odor and aerosol pollutants emitted from poultry production sites. In: Aneja VP et al (eds) Proceedings: Workshop on Agricultural Air Quality: State of the Science, Potomac, Maryland, June 5–8, 2006

Dawson JR (1990) Minimizing dust in livestock buildings: possible alternatives to mechanical separation. J Eng Res 47:235–248

Dickinson CH, Preece TF (1976) Microbiology of aerial plant surfaces. Academic Press, London and New York, 669 pp

Distel H, Hudson R (2001) Judgment of odor intensity is influenced by subject's knowledge of the odor source. Chem Senses 26:247–251

Dorr G, Woods N, Craig I (1998) Buffer zones for reducing drift from the application of pesticides. International Conference on Engineering in Agriculture. September 27–30, 1998. Paper No. SEAg 98/008. The University of Western Australia, Perth

Eby HJ, Willson GB (1969) Poultry house dust, odor and their mechanical removal. In: Animal waste management. Proceedings, Cornell university Conference on agricultural waste management. Cornell University, Ithaca, NY, pp 303–309

Elkiey T, Ormrod DP, Marie B (1982) Foliar sorption of sulfur dioxide, nitrogen dioxide, and ozone by ornamental plants atmospheric pollutants. Horticult Sci 17(3):358–360

Eugene T (1971) The effect of expectation of judgments of odors. U.S. Public Health Service, Washington, DC

Farmer A (1993) The effects of dust on vegetation—a review. Environ Pollut 79:63–75

Ford SE, Riskowski GL (2003) Effect of windbreak wall location on ventilation fan performance. Appl Eng Agricult 19(3):343–346

Freer-Smith PH, Holloway S, Goodman A (1997) The uptake of particulates by an urban woodland: Site description and particulate composition. Environ Pollut 95(1):27–35

Fry JC, Gadd GM, Herbert RA, Jones CW, Watson-Craik IA (eds) (1992) Microbial control of pollution. 48th Symposium of the Society for General Microbiology held at the University of Cardiff

Gaggi C, Bacci E, Calamari D, Fanelli R (1985) Chlorinated hydrocarbons on plant foliage: an indication of the troposheric contamination level. Chemosphere 14(11/12):1673–1686

Guo H, Jacobson LD, Schmidt DR, Janni KA (2001) Simulation of odor dispersions as impacted by weather conditions. In: Stowell RR, Bucklin R, Bottcher RW (eds) Livestock environment VI: Proceedings of the 6th International Symposium, 21–23 May 2001, Louisville, Kentucky, USA, 701P0201, pp 687–695

Hammond EG, Smith RJ (1981) Survey of some molecularly dispersed odorous constituents in Swine house air. Iowa State J Res 55(4):393–399

Hammond EG, Fedler C, Smith RJ (1981) Analysis of particle bourne swine house odors. Agricult Environ 6:395–401

Hardwick DC (1985) Agricultural problems related to odour prevention and control. In: Nielsen VC, Voorburg JH, L'Hermite P (eds) Odour prevention and control of organic sludge and livestock farming. Elsevier Applied Science Publishers, New York, pp 21–26

Hartung J (1986) Dust in livestock buildings as a carrier of odours. In: Odour prevention and control of organic sludge and livestock farming. Elsevier Applied Science Publishers, New York, pp 321–332

Heisler GM, Dewalle DR (1988) Effects of windbreak structure on wind flow. Elsevier Science Publishers B.V., Amsterdam. Agricult, Ecosyst Environ 22/23:41–69

Hill AC (1971) Vegetation: a sink for atmospheric pollutants. J Air Pollut Control Assoc 21:341–346

Hinds WC (1999) Aerosol technology: properties, behavior, and measurement of airborne particles, 2nd edition. John Wiley and Sons, New York, NY, pp 483

Huang H, Miller GY (2006) Citizen complaints, regulatory violations, and their implications for swine operations in Illinois. Rev Agricult Econ 28(1):89–110

Iowa (CAFO) Concentrated Animal Feeding Operations Air Quality Study. ISU/UI Study Group, University of Iowa College of Public Health, Iowa City, IA, 2002

Jacobson LD (1997) Monitoring odor and air quality. Presented at the 13th Minnesota Poultry Service Workshop (Sept 23, 1997) St. Paul, MN.

Jacobson L, Schmidt D, Nicolai R, Bicudo J (1998) Odor control for animal agriculture. BAEU-17. University of Minnesota Extension Service, Department of Biosystems and Agricultural engineering. http://www.bae.umn.edu/extens/aeu/baue17.html

Jacobson LD, Guo H, Schmidt DR, Nicolai RE (2001) Influence of weather condition on field evaluation of odor dispersions from animal production sites. In: Stowell RR, Bucklin R, Bottcher RW (eds)Livestock environment VI: Proceedings of the 6th International Symposium, 21–23 May 2001, Louisville, Kentucky, USA, pp. 679–686

Khan FI, Abbasi SA (2001) Effective design of greenbelts using mathematical models. J Hazard Mater B81:33–65

Kimmins JP (1997) Forest ecology : a foundation for sustainable management, 2nd ed. Upper Saddle River, NJ: Prentice Hall, c1997. xii, 596 pp

Kliebenstein JB (1998) Economic and associated social and environmental issues with large-scale livestock production systems. Concept Paper for the World Bank Workshop on Sustainable Intensification of Agricultural Systems: Linking Policy, Institutions and Technology. July 5–10, 1998. Iowa State University, Ames, Ia

Kliebenstein JB, Hurley SP (1999) Determining the benefits of environmental improvements in pork production and their sustainability: a community-based study of Iowa's pork industry. Leopold Center Progress Report. Volume 8, March 1999

Koelsch R (1999) Animal housing odor control options. Manure matters. Vol. 5, Number 1. University of Nebraska Livestock Environmental Issues Committee. http://www.ianrwww.unl.edu/manure/v5n1_99.html

Kort J (1988) Benefits of windbreaks to field and forage crops. Agricult, Ecosyst Environ 22/23:165–190

Kreis RD (1978) Limiting the environmental impact of animal production odors. Environ Int 1:247–275

Kwiecien M (1997) Deposition of inorganic particulate aerosols to vegetation—a new method of estimating. Environ Monitor Assess 46:191–207

Laird DJ (1997) Wind tunnel testing of shelterbelt effects on dust emissions from swine production facilities. Thesis (M.S.)–Iowa State University, Parks Library, Ames. 128 pp

Lammers PS, Wallenfang O, Boeker P (2001) Computer modelling for assessing means to reduce odour emissions. Presented at 2001 ASAE Annual International Meeting, Sponsored by the ASAE, Sacramento, California, USA, July 30–August 1, 2001. Paper Number:01-4042

Landolt W, Keller T (1985) Uptake and effects of air pollutants on woody plants. Experientia 41, Birkhauser Verlag, CH-4010, pp 301–310

Lin XJ, Barrington S, Nicell J, Choiniere D, Vezina A (2006) Influence of windbreaks on livestock odor dispersion plumes in the field. Agricult Ecosyst Environ 116(3–4):263–272

Little P (1977) Deposition of 2.75,5.0 and 8.5um particles to plant and soil surfaces. Environ Pollut 12:293–305

Liu Q, Bundy DS, Hoff SJ (1996) The effectiveness of using tall barriers to reduce odor emission. Proceedings of the International Conference on Air Pollution from Agricultural Operations, Midwest Plan Service, Ames, Ia, pp 403–407

Lorimor J (1998) Iowa Odor Control Demonstration Project: Landscaping. Cooperative Extension Service. Iowa State University Extension. Pm-1754h. http://www.extension.iastate.edu/Publications/PM1754h.pdf. (Last accessed 2/1/06)

Lorimor J (1999) A short summary of 1998 Manure Law Amendments. ISU Ag & Biosystems Engineering. July 7, 1999. http://www.ae.iastate.edu/manurelaw1998.pdf

Lorimor J, Kliebenstein J (2004) Odor control methods used by Iowa pork producers. Iowa State University Extension. PM 1964. http://www.extension.iastate.edu/Publications/PM1964.pdf (Last accessed 2/1/06)

Malone GW, Abbott-Donnelly D (2001) The benefits of planting trees around poultry farms. University of Delaware, College of Agriculture and Natural Resources, Extension Bulletin #159, December 2001

Malone GW, VanWicklen G, Collier S, Hansen D (2006) Efficacy of vegetative environmental buffers to capture emissions from tunnel ventilated poultry houses. In: Aneja VP et al. (eds) Proceedings: Workshop on Agricultural Air Quality: State of the Science, Potomac, Maryland, June 5–8, 2006, pp. 875–878

McNaughton KG (1988) Effects of windbreaks on turbulent transport and microclimate. Agricult, Ecosyst Environ 22/23:17–40

Melvin SW (1996) Swine odor measurement and control issues reviewed. Feedstuffs 68(22):12–14

Midwest Plan Service (2002) Outdoor air quality. Manure Management Systems Series. MWPS—18, Section 3.

Mikesell RE, Kephart KB, Ressler LJ, Willits FK (2001) Comparison of neighbor and non-neighbor perceptions of large-scale animal agriculture. International Symposium on Animal Production & Environmental Issues. Oct. 3–5, 2001. Research Triangle Park, NC

Muller R (1992) Bacterial degradation of xenobiotics. In: Fry JC, Gadd GM, Herbert RA, Jones CW, Watson-Craik IA (eds) Microbial control of pollution. 48th Symposium of the Society for General Microbiology held at the University of Cardiff, pp 35–58

The National Center for Manure and Animal Waste Management (2001) Particulate matter emissions from confined animal feeding operations: management and control measures. The National Center for Manure and Animal Waste Management White Paper Summaries, pp 13–16. http://www.cals.ncsu.edu:8050/waste_mgt/natlcenter/summary.pdf (1/11/05)

National Pork Producers Council (1995) An executive summary: a review of literature on nature and control of odors from pork production facilities. A report prepared by Miner JR, Bioresource Engineering Department Oregon State University for the subcommittee of the National Pork Producers Council

Odor Control Task Force (OCTF) (1998) Board of Governors of the University of North Carolina. Control of odor emissions from animal operations. http://www.cals.ncsu.edu/waste_mgt/control.htm (3/31/99)

Ould-Dada Z, Baghini NM (2001) Resuspension of small particles from tree surfaces. Atmos Environ 35:3799–3809

Pasquill F (1974) Atmospheric diffusion: the dispersion of windborne material from industrial and other sources, 2nd Edition. John Wiley & Sons, New York, 429 pp

Person H, Aronoff M, Alocilja E, Vigmostad K (1995) Recommended human relation management practice within a technological and social system involving livestock odor issues. International Livestock Odor Conference, October 16–17, 1995, Iowa State university

Porskamp HAJ, Michielsen JMPG, Huijmans JFM (1994) The reduction of the drift of pesticides in fruit growing by a wind-break. Dienst Landbouwkundig Onderzoek, Instituut voorMilieu-en Agritechniek, Rapport 94-29. Wageningen, 27 pp

Preece TF, Dickinson CH (1971) Ecology of leaf surface micro-organisms. Proceedings of an International Symposium held at the University of Newcastle Upon the Tyne. September (1970) Academic Press, London

Raupach MR, Woods N, Dorr G, Leys JF, Cleugh HA (2001) The entrapment of particles by windbreaks. Atmos Environ 35:3373–3383

Reischl A, Reissinger M, Hutzinger O (1987) Occurrence and distribution of atmospheric organic micropollutants in conifer needles. Chemosphere 16(10–12):2647–2652

Reischl A, Reissinger M, Thoma H, Hutzinger O (1989) Accumulation of organic air constituents by plant surfaces. Chemosphere 18(1–6):561–568

Ronneberg E (1992) The Hedgerow Project: a review of literature. Hedgerow Foundation, Chicago, i, 43 p.: ill.; 28 cm.

Saxe H (1990) Air pollution, primary plant physiological responses, and diagnostic tools. Other title: Luftforurening, primaere plantefysiologiske reaktioner og diagnostiske metoder. Thesis (doctoral)—Department of Plant Physiology, Royal Veterinary & Agricultural University. Frederiksberg C, Denmark, 1990

Schaefer P (1989) Trees and sustainable agriculture. Am J Alternat Agricult 4:(3–4)173

Schiffman SS, Bennett JL, Raymer JH (2001) Quantification of odors and odorants from swine operations in North Carolina. Agricult For Meteorol 108:213–240

Schmidt D, Jacobson L (1995) Odor and odor policy criteria. University of Minnesota Extension Service—Department of Biosystems and Agricultural Engineering. AEU-11 http://www.bae.umn.edu/extens/aeu/aeu11.html (3/15/99)

Schonherr J, Riederer M (1989) Foliar penetration and accumulation of organic chemicals in plant cuticles. Reviews of environmental contamination and toxicology, vol 108. Springer-Verlag, New York

Schreiber L, Schonherr J (1992) Leaf surface microflora may significantly affect studies on foliar uptake of chemicals. Bot Acta 105:345–347

Schreiber L, Schonherr J (1993) Determination of foliar uptake of chemicals: influence of leaf surface microflora. Plant, Cell, Environ 16:743–748

Schultze RC, Colletti JP, Isenhart TM, Marquez CO, Simpkins WW, Ball CJ (2000) Riparian forest buffer practices. In: Garrett, Rietveld, Fisher (eds) North American agroforestry: an integrated science and practice. American Society on Agronomy, Inc. Madison, Wisconsin, USA, 2000, pp 189–282, 402 pp

Smith RJ (1993) Dispersion of odours from ground level agricultural sources. J Agric Eng Res 54:187–200

Smith WH (1976) Air pollution-effects on the structure and function of plant: surface microbial ecosystems. In: Dickinson CH, Preece TF (eds) Microbiology of aerial plant surfaces. Academic Press, London and New York, pp 75–106

Smith WH (1984) Pollutant uptake by plants. In: Treshow M (ed) Air pollution and plant life. Wiley & Sons, New York, pp 417–450

Spitsyna NT, Skripal'shchikova LN (1991) (translation of Ekologiya July 1992). Phytomass and dust accumulation of Birch forests near open-pit mines. Soviet J Ecol 22(6):354–359

Steubing L, Klee R (1970) Comparative investigations into the dust filtering effects of broad leaved and coniferous woody vegetation. Agnew Bot 4:73–85. Listed in: Farmer, A. 1993. The effects of dust on vegetation—a review. Environ Pollut 79:63–75

Stroik M, Heber AH (1986) Characteristics of aerial dust in swine finishing houses. ASAE paper 86-4027. American Society of Agricultural Engineers, St. Joseph, MI, 17 pp

Swine Odor Task Force (SOTF) (1995) Options for managing odor. North Carolina University, http://www.ces.ncsu.edu/whpaper/SwineOdor.html

Taiz L, Zeiger E (1991) Plant physiology. Benjamin/Cummings series in the life series. Benjamin/Cummings Publishing Co. xxxii, 559 pp

Takai H, Pedersen S, Johnsen JO, Metz JHM, Groot Koerkamp PWG, Uenk GH, Phillips VR, Holden MR, Sneath RW, Short JL, White RP, Hartung J, Seedorf J, Schroder M, Linkert KH, Wathes CM (1998) Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. J agric Engng Res 70:59–77

Takle ES (1983) Climatology of superadiabatic conditions for a rural area. J Climate Appl Meteorol 22:1129–1132

Takle ES (Unknown Date) A numerical model feasibility study of managing swine odor by manipulation of atmospheric flow. A research proposal. Department of Agronomy, Iowa State University

Takle ES, Shaw RH, Vaughan HC (1976) Low-level stability and pollutant trapping potential for a rural area. J Appl Meteorol 15:36–42

Thernelius SM (1997) Wind tunnel testing of odor transportation from swine production facilities. Thesis (M.S.)—Iowa State University, Parks Library, Ames. 111 pp

Thu KM, Durrenberger EP (eds) (1998) Pigs, profits, and rural communities. State University of New York Press, New York

Treshow M, Anderson FK (1989) Plant stress from air pollution. John Wiley and Sons, Chichester, 283 pp

Tyndall JC (2003) A biophysical and socio-economic examination of the use of shelterbelts for swine odor mitigation. Thesis (Ph.D.)—Iowa State University, Parks Library, Ames. 133 pp

Tyndall JC, Colletti JP (2001) Air quality and shelterbelts: odor mitigation and livestock production. A literature review. Final Report. United States Department of Agriculture, National Agroforestry Center, Lincoln, Nebraska. Project Number: 4124-4521-48-3209. http://www.unl.edu/nac/reports/finalreport.pdf. (1/1/06)

Ucar T, Hall F (1998) Windbreak technology for agrochemical drift mitigation. Progress Report 1 for the Laboratory for Pest Control Application Technology and the USDA-NRCS

Ucar T, Hall FR (2001) Windbreaks as a pesticide drift mitigation strategy: a review. Pest Manage Sci 57:663–675

United States Department of Agriculture (USDA) (1996) Economic Research Service, Natural Resources and Environment Division. Manure Management by U.S. Pork Producers in (1992) AREI UPDATES, no. 7, Aug. 1996

Vansickle J (2002) Production practices vary widely by region. National Hog Farmer, Feb 15, 2002

Vining RC, Allen M (1993) Consideration of the air resource through total resource management. In: Mitchell JK (ed) Integrated resource management & landscape modification fro environmental protection. Proceedings of the International Symposium for the American Society of Agricultural Engineers. Chicago, Il. 13–14 December, 1993, pp 20–28

Waller RA (1970) Environmental quality, its measurement and control. Regulat Studies 4:177–191

Wang H, Takle ES (1995) Numerical simulations of shelterbelt effects on wind direction. J Appl Meteorol 34(13):2206–2219

Waring RH, Schlesinger WH (1985) Forest ecosystems: concepts and management. Academic Press Inc., San Diego, California, 340 pp

WED Western Economic Diversification (1999) Hog Manure Management Strategic Initiative: New Technology Demonstration sites for Hog Manure Management. Western Canada Initiative. http://www.cetac-west.ca/hmm/hmm-content.html (3/17/99)

Williams CM (1996) Nuisance concerns with animal agriculture—the case of odors. Animal and Poultry Waste Management Center. North Carolina State University, Raleigh, NC

Wing S, Wolf S (2000) Intensive livestock operations, health, and quality of life among Eastern North Carolina Residents. Environ Health Perspect 108(3):233–238

Zahn JA, Hatfield JL, Do YS, DiSpirito AA, Laird DA, Pfeiffer RL (1997) Characterization of volatile organic emissions and wastes from a swine production facility. J Environ Quality 26:1687–1696

Zhang H, Brandle JR, Meyer GE (1993) A model to evaluate windbreak protection efficiency. Proc. Third North American Agroforestry Conf., 16–18 Aug. 1993, pp 145–151

Zhu J, Jacobson L, Schmidt D, Nicolai R (2000) Daily variations in odor and gas emissions from animal facilities. Appl Eng Agricult 16(2):153–158