Surface boundary layer of cattle feedlots: Implications for air emissions measurement

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Abstract

Air quality issues at cattle feedlots are a growing concern, and micrometeorological techniques have potential for measuring air emissions from these operations. However, eddy covariance and related methods rely on assumptions about the boundary layer that might not hold above the complex, non-uniform, and fetch-limited surface of a feedlot. The objective of this study was to characterize the surface boundary layer of an open-air cattle feedlot to provide insight into how micrometeorological techniques might be applied to these non-ideal sites. An open-path eddy covariance system was used to collect high-frequency time-series data of wind speed, CO\textsubscript{2}, and H\textsubscript{2}O above a large commercial feedlot in central Kansas in 2006 and 2007. This site, like many High Plains locations, was characterized by windy conditions with daytime average wind speed of 5 m s\textsuperscript{-1}, and near-neutral atmospheric stability was common, even at night. Using a modeled displacement height of 0.65 m, the roughness length ranged from 2 to 6 cm with a median of 3.6 cm. Ogives showed no signs of low-frequency transport (i.e. periods > 30 min). Eddy covariance measurements of CO\textsubscript{2} fluxes averaged 0.4 kg m\textsuperscript{-2} d\textsuperscript{-1} while H\textsubscript{2}O fluxes averaged 2.3 kg m\textsuperscript{-2} d\textsuperscript{-1}, both of which agreed with other studies measuring cattle respiration or water consumption. The tower was located along the north edge of a rectangular-shaped feedlot so the fetch was over 1600 m when winds were southerly. However, the length of fetch encompassed by feedlot pens decreased as winds became more southeasterly or southwesterly. Using the sharp contrast in CO\textsubscript{2} fluxes from the pens versus the surrounding fields, the outer edge of the sampling footprint could be determined by observing abrupt changes in CO\textsubscript{2} flux as wind directions shifted to the southeast or southwest. This provided a way to measure the footprint requirement using the respired CO\textsubscript{2} from the cattle as a tracer. Under neutral atmospheric stability the required fetch was about 360 m when the sensor height was 6 m. The fetch requirements and the source area were predicted with a footprint model. Results showed that, on average, the three pens directly south of the tower contributed 61% of the measured flux. Roads, feeding bunks, and transfer alleys (i.e. surfaces within the footprint other than pens) accounted for 21% of the total area. Thus, accounting for the diluting effect of these spaces in the source area was important when attempting to compute a flux per unit animal or per unit pen area.

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1. Introduction

Confined animal feeding operations (CAFOs) can affect air quality at local, regional, and global scales through emissions of trace gases (e.g. NH₃, N₂O, CH₄, and VOCs), particulates (PM₂.₅ and PM₁₀), and odors. However, field measurements are limited, and there is a need for more accurate quantification of gaseous and particulate emissions from different types of CAFOs in the United States (National Research Council, 2003; Steinfeld et al., 2006). Few studies have attempted to quantify emissions from open-air, earthen-surface cattle feedlots in the United States (Casey et al., 2006). Nearly 30 million cattle on feed are marketed from these feedlots every year, with around 60% coming from large-scale operations (capacity greater than 16,000 head), more than 80% of which are located in the High Plains states of Texas, Oklahoma, Kansas, Nebraska, and Colorado (National Agricultural Statistics Service, 2004). More than 9 million cattle are held at feedlots in this region throughout the year, and the feed nitrogen (N) for these animals, 0.23 kg animal⁻¹ d⁻¹ (Kissinger et al., 2007), totals more than 2 million kg of N per day. Preliminary estimates suggest up to 50% of feed N is lost to the atmosphere as ammonia (Flesch et al., 2007; Cole et al., 2007). Thus, emissions of ammonia (NH₃-N) from feedlots in the High Plains could be more than 2 million kg per day or 0.38 Tg annually—about 12% of total United States emissions (van Aardenne et al., 2001). Clearly, gaseous losses from feedlots are an important component of the anthropogenic emissions inventory. Data are needed to better understand the feedlot boundary layer and improve measurement and modeling of emissions from these CAFOs.

Quantifying emissions from cattle feedlots is challenging. A few studies have used the mass balance approach for quantifying total feedlot N emissions, but this method cannot distinguish between N species (e.g. N₂O versus NH₃) (Adams et al., 2004; Bierman et al., 1999; Erickson and Klopfenstein, 2001a,b; Farran et al., 2006). Kaharabata et al. (2000) applied a tracer ratio technique developed for natural gas facilities (Lamb et al., 1995) to estimate methane (CH₄) emissions from a dairy cow feedlot, but its accuracy depends on the tracer gas emissions having a source distribution similar to the CH₄ emissions. Various chamber techniques have been used to measure a number of emissions from either feedlot surfaces (Boadi et al., 2004; Ellis et al., 2001; Mieselbrook et al., 2001, 2006) or feedlot cattle (Beauchemin and McGinn, 2005, 2006; McGinn et al., 2004, 2006a), but these techniques alter the environment and can be unrepresentative of natural conditions (Cole et al., 2007). Flesch et al. (2007) and McGinn et al. (2006b, 2007) applied inverse dispersion techniques at feedlots to estimate NH₃ and CH₄ emissions using a backward Lagrangian stochastic dispersion model. As with any approach that involves modeling turbulent transport, accuracy of the results depends on the accuracy of both the model and model inputs.

Micrometeorological methods (e.g. eddy covariance (EC) and relaxed eddy accumulation) are often considered the best methods for measuring fluxes from CAFOs (Shah et al., 2006) and would be ideal in feedlot situations because they provide areally averaged flux measurements for large areas without disturbing the surface. The micrometeorological gradient method has already been used in a few feedlot studies (Hutchinson et al., 1982; Harper et al., 1999; Baek et al., 2006; Todd et al., 2007). However, gradient methods rely on strict assumptions including steady-state conditions, horizontally homogeneous sources and sinks of flux, and conformity to Monin–Obukhov similarity theory (Prueger and Kustas, 2005). Gradient methods are undesirable when the source area is heterogeneous because each sampling height has a different footprint. Single-height flux measurements such as eddy covariance, while still requiring certain assumptions, might be more appropriate when patchiness in the footprint is an issue. Regardless of the micrometeorological technique employed, unique characteristics of cattle feedlots, namely the various scales of surface heterogeneity and strong emissions of certain gases from the animals (i.e. moving and sometimes clustered point sources of gas) present a challenge. Assumptions underlying various micrometeorological measurement techniques might not hold true at feedlots when measuring specific compounds under certain circumstances. In these situations, fundamental knowledge of the surface boundary layer is needed to determine whether micrometeorological methods can be applied with confidence to these non-ideal, fetch-limited surfaces.

The goal of this study was to characterize the surface boundary layer of an open-air cattle feedlot. Specifically, objectives were to: (1) determine the distributions of wind speed, wind direction, and atmospheric stability; (2) calculate the roughness length and displacement height; (3) perform a spectral analysis of turbulence above the pens; (4) determine the effect of integration interval on flux calculations (i.e. ogive analysis); (5) develop composite curves of diurnal CO₂, latent heat, and sensible heat fluxes; (6) determine fetch requirements; (7) map the feedlot and determine the fraction of the surface covered by pens, roads, alleys, etc.; and (8) evaluate the source area footprint to account for the diluting effect of roads and other non-pen surfaces. These assessments provide some guidance on the use of eddy covariance and other micrometeorological techniques for measuring gaseous and aerosol emissions at cattle feedlots.

2. Materials and methods

2.1. Site description and field measurements

Research was conducted at a commercial cattle feedlot in western Kansas that has been in operation for more than 25 years. The area receives around 570 mm of precipitation annually and the terrain is level to gently sloping with slopes less than 5%. The feedlot has a one-time capacity of approximately 30,000 animals, with pens covering roughly 62 ha. Cattle enter the feedlot weighing an average of 300–350 kg. They are fed a high-concentrate finishing diet for around 180 days and leave the feedlot weighing an average of 550–600 kg. Stocking densities range from 15 to 18 m² animal⁻¹. Pens are scraped and manure is removed annually. Feedlot pens, roads, and other structures were measured with a survey grade RTK GPS rover and base station system (AgGPS 214, Trimble Navigation Limited, Sunnyvale, CA) and mapped using ArcGIS 9.0 software (ESRI, Redlands, CA). Feedlot layout is shown in Fig. 1.
Fluxes of sensible heat (H), latent heat (L), and CO2 (F) were measured with an EC system consisting of a 3D sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT) and an open-path infrared gas analyzer (LI-7500, LI-COR Biosciences, Lincoln, NE). These systems also provided component wind vectors (u, v, and w) and scalar measurements of temperature (T), water vapor (H2O) concentration, CO2 concentration, and atmospheric pressure. Data were collected from July 2006 through April 2007. The EC system was deployed at 6 m above the pen surface along the northern edge of the pens and the location of the tower along the north edge of the feedlot. (Fig. 1) of the feedlot showing configuration of the pens and the location of the tower along the north edge of the feedlot.

2.2. Data processing and filtering

All high-frequency EC data were post-processed with the EdiRe software package (version 1.4.3.1167, R. Clement, University of Edinburgh, UK) closely following the guidelines described in Lee et al. (2004) and Mauder et al. (2008). Eddy covariance fluxes were subject to the following corrections: despiking, lag removal, planar fit coordinate rotation (Wilczak et al., 2001; Lee et al., 2004), frequency response corrections (Moore, 1986), sonic-temperature sensible heat flux corrections (Schotanus et al., 1983), and density corrections for CO2 and H2O (Webb et al., 1980). Other calculations performed with EdiRe included calculation of friction velocity, u* (m s\(^{-1}\)); stability parameter, z/L, where L is the Obukhov length (m); stationarity tests, and iterative solutions for interdependent corrections. MATLAB (version 7.2.0.232, The Mathworks, Inc., Natick, MA) was used for any remaining calculations or post-processing.

Periods with questionable data were excluded using quality control filters similar to those described by Hammerle et al. (2007), which included stationarity and integral turbulence tests (ITT) (Foken and Wichura, 1996) and a footprint test. For the stationarity test, 30-min covariances between the vertical wind speed (w) and both the horizontal wind speed (u) and scalars (T, H2O and CO2) were compared with the average of six consecutive 5-min covariances for the same period. Periods where deviations, ΔST, were greater than 30% for any of the four were considered unstationary and were excluded from analysis:

\[
\Delta ST = \frac{100|w^s s_z - w^s s_0|}{w^s s_0}
\]

where s is the scalar of interest, and 5 and 30 are subscripts for the 5- and 30-min covariances. For the ITT, the deviation from Monin–Obukhov theory was determined by comparing the similarity function for vertical wind speed, \(\phi_w\), representing the ratio of the standard deviation of w (\(\sigma_w\)) and u* with modeled functions developed by Kaimal and Finnigan (1994):

\[
\phi_w = \frac{\sigma_w}{u^*} = \begin{cases} 
1.25(1 + 3z/L)^{-1.5}, & -2 \leq z/L < 0 \\
1.25(1 + 0.2z/L), & 0 \leq z/L < 1
\end{cases}
\]

where L is the Obukhov length (m) and z is measurement height (m). Any periods where the percent deviation between the observed and modeled similarity functions, ΔITT, was greater than 30% were excluded from analysis:

\[
\Delta ITT = \frac{100|\sigma_w/u^* - \phi_w|}{\phi_w}
\]

2.3. Footprint, roughness length, and spectral analysis methods

The size of the source area contributing to the flux measurement was approximated using an analytical footprint model developed by Hsieh et al. (2000). The distance upwind from the measurement location, Xf (m), representing a fraction (f) of the source area of the flux measurement was calculated as:

\[
X_f = -D_z(1 - P)\frac{z}{k^2 \ln(f)}
\]

with

\[
z_u = z_m \left( \ln \left( \frac{z_m}{z_0} \right) - 1 + \frac{z_0}{z_m} \right)
\]

where \(z_0\) is the roughness length (m), \(z_m\) is measurement height (m), k is von Karman's constant, and

\[
D = \begin{cases} 
0.28, & P = 0.59 \text{ for unstable conditions} \\
0.97, & P = 1.00 \text{ for neutral conditions (|z/L| < 0.02)} \\
2.44, & P = 1.33 \text{ for stable conditions}
\end{cases}
\]
Periods were excluded when the length of the footprint, $X_f$, computed using $f = 70\%$, extended beyond the boundary of the feedlot (i.e. pens). The rationale for using $X_{70\%}$ as the fetch requirement is discussed in Section 3.4.

Roughness lengths were calculated for each 30-min period by rearranging the wind profile equation as follows:

$$z_0 = \frac{z - d}{\exp \left( \frac{ku_z}{u^*} + \psi_m \right)}$$

(6)

where $d$ is the displacement height (m), $u_z$ is the wind speed at the measurement height (m s$^{-1}$), and $\psi_m$ is the diabatic correction factor for momentum computed from the Obukhov length following the approach of Businger et al. (1971) and Dyer (1974).

To evaluate turbulence in the frequency domain, the power spectra, $S_x(f)$, for CO$_2$ and $T$, and the cospectra, $C_x(f)$, of these scalars with vertical wind speed ($u$) were calculated from 20-Hz time series. Processing techniques were similar to those used by Blanken et al. (1998). Analyses are shown for eight 30-min segments collected between 1000 and 1400 LST on August 30, 2006, which was a typical summer day at the feedlot. Data from each 30-min segment were linearly detrended and the spectra and cospectra computed using Welch’s method in MATLAB (Mathworks Inc.). Values of $S_x$ and $C_x$ were normalized by the variance of $x$ and covariance of $x$ and $u$, respectively, and plotted with respect to normalized frequency, $f z_m / u$, where $z_m$ was measurement height less the displacement height and $u$ was the mean horizontal wind speed. To avoid cluttering the log–log plots with too many points, $S_x$ and $C_x$ were bin-averaged for 50 equally spaced intervals on the x-axis (i.e. log $f z_m / u$). Ogive functions were computed to determine if low-frequency transport processes (i.e. those with periods greater than 30 min) were affecting the eddy flux calculations (Moncrieff et al., 2004). Periods out to 2.0 h were evaluated to test for the effect of eddies of increasing larger periods.

3. Results and discussion

3.1. Wind speed, stability, and roughness

Distributions of wind speed and wind direction (Fig. 2a) clearly show that typical conditions at the feedlot are characterized by very high-speed southerly winds. In the dominant southerly wind direction, average 30-min wind speeds were greater than 6 m s$^{-1}$ more than 35% of the time, with an average daytime wind speed of 5 m s$^{-1}$, not uncommon for the cattle feeding region of the High Plains. The US National Climatic Data Center ranks Dodge City, KS and Amarillo, TX, cities in the heart of the prime feedlot region, as the fifth and sixth windiest cities, respectively, in the continental United States (National Climatic Data Center, 2006). Partially due to these high wind speeds, atmospheric stability (Fig. 2b) was near neutral 48% of the time with very few stable periods (around 25%). The other factor that helps sustain neutral stability, even under the often hot and dry feedlot conditions, is the significant amount of water deposited on the surface in the form of urine and fecal matter (Section 3.3).

Because cattle act like bluff-rough elements on the surface, the displacement height, $d$, was determined using a simplified empirical model developed by Raupach (1994) that is designed for sparse canopies (i.e. sparse shrublands, desert). The model is based on a physical parameter called the frontal area index, $\alpha$, defined as the frontal area of roughness elements per unit ground area:

$$\alpha = \frac{bh}{D} = \frac{nbh}{S}$$

(7)

where $b$ is the roughness element breadth (m), $h$ is the roughness element height (m), $D$ is the average distance between roughness elements (m), $n$ is the total number of roughness elements, and $S$ is the total surface area (m$^2$). This model is especially well suited for the feedlots, where cattle size and density per pen are known. Using the average weight of the cattle at the site (440 kg) $b$ and $h$ were estimated as 1.08 and 1.20 m, respectively, with regression equations developed by the American Society of Agricultural and Biological Engineers (ASABE, 2006). Displacement height was calculated using best-fit coefficients for $d$ found by Verhoef et al. (1997b), who
compared modeled estimates of $d$ with experimentally determined values of $d$ from a variety of sparse canopies:

$$d = h - \frac{h(1 - \exp(-\sqrt{42a}))}{\sqrt{42a}} \quad (8)$$

The displacement height for the feedlot, as computed using Eq. (8), was 0.65 m or about half the height of the cattle (i.e. $0.54 \times$ cattle height).

Calculations of $z_0$, typically ranged between 2 and 6 cm with a mean and standard deviation of $4.1 \pm 2.2$ cm and a median of 3.6 cm. Considering that the feedlot surface is fairly smooth – it is basically a bare soil surface interspersed with cattle and feed bunks acting as bluff-rough elements – it is not surprising that the roughness length is small, similar to bluff-rough desert shrublands or sparsely vegetated vineyards (Stewart et al., 1994; Verhoef et al., 1997a). The georeferenced map of the feedlot showed that pens accounted for 72% of the area while roads and alleys, which are also smooth, accounted for 21% of the area. Flesch et al. (2007) reported $z_0$ values between 4 and 11 cm at a feedlot, similar to but slightly larger than results of this study. Differences in roughness among different feedlots could be caused by the presence or absence of low-lying manure piles that are sometimes mounded up near the center of the pens.

3.2. Spectra, cospectra, sampling frequency, and integration interval

The majority of CO$_2$ emissions from feedlots originate from cattle respiration and ruminant digestion. The animals are essentially an arrangement of mobile bluff bodies and point sources of CO$_2$—sometimes clustered and sometimes distributed more uniformly in the pen. In contrast, sensible heat fluxes arise primarily from the pen surface, an areal source. Thus, it is possible that processes affecting turbulent fluctuations of CO$_2$ and $T$ may differ, especially at high and low frequencies. Power spectra and cospectra were similar and showed the expected $-2/3$ and $-4/3$ slopes, respectively, in the inertial subrange (Fig. 3). The cospectra slope was slightly less negative than $-4/3$, a feature commonly observed in other studies (Blanken et al., 1998). The spectra peak was near 0.01 for both scalars. There were no obvious differences between the CO$_2$ and $T$ curves indicating no cospectral distortion (Velasco et al., 2005). For $T$ and $H$, there was a slight upturn of both $S_T$ and $C_T$ at very high frequencies, a feature that could be the result of aliasing. Average wind speed was more than 6 m s$^{-1}$ and $H$ was more than 249 W m$^{-2}$, so temperature fluctuations of smaller, high-frequency eddies might not have been sampled adequately. The cospectra also were plotted on a semi-log scale so the area under sections of the curve was proportional to the covariance (i.e. flux) contributed by the corresponding frequencies for each section (Fig. 4). Again, good agreement between the $C_T$ curves indicates that the same size eddies and turbulent processes were transferring both CO$_2$ and $H$. Evaluation of the $C_T$ for ninety 30-min data periods at the feedlot during the summer of 2006 showed that 95% of the fluxes of both heat and mass were attributed to frequencies less than 5. Peak energy containing eddies were in the 0.2–0.3 band and the 0.04–0.06 band. Analysis of additional days showed that some had two peaks (Fig. 4) while others did not. Calculation of wavelength ($\lambda/f$) indicates there might be discontinuity on the order of 50–70 m under certain conditions, a feature likely caused by the presence of the north–south road or alley in the footprint during southeast and southwest winds (Fig. 1).

Integration of the different sections of the cospectra curve was used to determine how much of the total flux could be attributed to frequencies greater than 1 Hz. Fig. 5 shows the fraction of total flux accounted for by including progressively higher frequencies in the flux estimate; integration under the full 20 Hz cospectra was considered total flux. About two-thirds of the total flux resulted from turbulent fluctuations less than 1 Hz. Of the remaining third, only 1.7% of $H$ and 1.0% of $F_C$ resulted from frequencies greater than 10 Hz. The same calculations performed with data collected 3 m above a grassland showed that 3–5% of the flux was attributed to frequencies greater than 10 Hz during high wind speeds. Thus, if sonic anemometers like the CSAT3 (i.e. 10 cm sample path) are deployed at 3 m or less above a feedlot, sampling rates of 20 Hz or greater are advised to keep the uncertainty around the
flux estimate low. Bosveld and Beljaars (2001) showed that lower sampling frequencies do not impact the expected value of eddy flux measurements but do increase uncertainty (i.e. noise) surrounding the estimate. Ogive plots showed almost no effect of low-frequency eddies (Fig. 6). In most cases, integration intervals as low as 20 min were adequate to compute flux. However, the traditional 30-min integration interval for EC flux calculations appears acceptable. This is not surprising considering the relatively low height of the measurement (6 m) and prevalent high wind speeds at the shear-dominated site.

### 3.3. Carbon dioxide, latent and sensible heat fluxes

Composite curves were developed for diurnal $F_C$, $\lambda E$, and $H$ by averaging measurements of flux based on the time of day using only those periods where it could be assumed with reasonable confidence that fluxes originated within pen boundaries. Periods included in the calculations had at least a 100:1 fetch to height ratio (wind direction between 155$^\circ$ and 190$^\circ$) and atmospheric stability that was classified as either neutral or unstable. In this case, the cutoff for the stationarity filter was increased from 30 to 60% to include more data in the averages while still retaining periods of at least acceptable quality (Foken et al., 2004).

Fig. 7 shows diurnal composite curves of $F_C$ for different periods during 2006. Emissions of CO₂ were extremely high with a fairly sharp, steady increase in $F_C$ from around 3 mg m⁻² s⁻¹ at dawn to around 5–6 mg m⁻² s⁻¹ by late morning, roughly 10-15 times the maximum respiration rate observed with EC towers from agricultural crops or native ecosystems (e.g. Owensby et al., 2006). Fluxes remained fairly steady throughout the afternoon until early evening, when they began to slowly taper off to the predawn minimum, with the exception of a peak in flux just after dusk, likely due to increased cattle activity. Emissions from feedlot cattle vary, but assuming around 3000 L of CO₂ per day (Archibeque et al., 2007; Boadi et al., 2002), this would be an equivalent flux of about 4 mg m⁻² s⁻¹, assuming a stocking density of $17 \text{ m}^2 \text{hd}^{-1}$, which agrees with measured $F_C$. It is important to note that the EC measured $F_C$ includes both cattle and soil respiration. But, even under the most optimal conditions, soil respiration is typically less than 0.5 mg m⁻² s⁻¹, so $F_C$ from the feedlot was clearly dominated by cattle respiration. Kissinger et al. (2007) found that the average dry matter consumption of feedlot cattle was 10.3 kg animal⁻¹ d⁻¹, and of that total, 5.3 kg animal⁻¹ d⁻¹ was harvested as manure. This leaves 5 kg animal⁻¹ d⁻¹ of dry matter that must be accounted for in animal growth or respiration. Assuming the feed is 44% carbon and 20% of the animal growth is carbon (DeSutter and Ham, 2005), sample calculations showed expected CO₂ fluxes of about 4.4 mg m⁻² s⁻¹ on a pen surface basis. The footprint of the flux measurements was not all pen surface, so the
expected EC measured flux could be slightly less than this value in most cases. Again, the average $F_c$ in Fig. 7 was 4–5 mg m$^{-2}$ s$^{-1}$, which agreed closely with calculated values based on feeding data.

Fig. 8a shows the composite curves for $\lambda E$ for the same periods. Latent heat fluxes exhibited the typical diurnal pattern with peaks ranging from 80 to 320 W m$^{-2}$, depending on the time of year. This area receives low amounts of annual rainfall, typically in short duration, high intensity events. The soil surface is visibly dry much of the time, except for the urine patches, so $H_2O$ flux often is a reasonable estimate of cattle water consumption during dry periods. The exception would be immediately after precipitation or during the summer months when tanker trucks applied water to the feedlot to reduce dust emissions. The average daily $\lambda E$ for the fall period from September 1 to October 14 2007 was 7.9 MJ m$^{-2}$, equivalent to about 3.2 L m$^{-2}$ of water. Assuming a stocking density of 17 m$^2$ animal$^{-1}$, this is about 55 L of water per head per day. Winchester and Morris (1956) showed the range of water consumption for feedlot cattle was typically between 20 and 80 L animal$^{-1}$ day$^{-1}$, and was dependent upon both animal weight and air temperature. Fluxes of $H_2O$ were equivalent to 22.3 L animal$^{-1}$ day$^{-1}$ during the winter period and 84.7 L animal$^{-1}$ day$^{-1}$ during the summer period, consistent with ranges reported by Winchester and Morris (1956). Assuming the average annual rate of water consumption is 40 L animal$^{-1}$ d$^{-1}$, the amount of water deposited on the pen surface as urine and in fecal material would be, on average, 2.4 mm d$^{-1}$ or 876 mm annually. Thus, the equivalent depth of water in the animal waste is about 1.5 times that received as precipitation. In future studies, water meters will be added to the drinking troughs so rates of cattle water consumption can be compared directly to the eddy flux measurements of $\lambda E$.

Composite curves for $H$ show there is very little difference in $H$ between fall and summer periods (Fig. 8b), a sharp contrast with the differences seen in $\lambda E$. During the summer, $H$ is moderated by high $\lambda E$, predominantly due to the large increase in cattle water consumption. The average daytime (1000–1600 LST) Bowen ratio for the summer period was 0.7 versus 1.1 for the fall and winter periods. One would suspect that the quasi-constant input of moisture moderates daily and seasonal variations in the stability of the surface boundary layer and the Bowen ratio.

### 3.4. Determining fetch requirements

The tower was located on the north edge of a rectangular-shaped feedlot so the fetch was over 1600 m when wind direction was southerly. However, the length of fetch encompassed by feedlot pens decreased as winds became more southeasterly or southwesterly (Fig. 1). Because $F_c$ from the feedlot (3 to 6 mg m$^{-2}$ s$^{-1}$) contrasted sharply with that from surrounding fields (–1.0 to 0.6 mg m$^{-2}$ s$^{-1}$) a drastic change in $F_c$ was observed when the sampling footprint extended beyond the edge of the feedlot. When winds rotated too far to the southeast or southwest, the difference in magnitude between measured $F_c$ and expected $F_c$ (as defined by the composite $F_c$ curve, Fig. 7) showed when the EC tower was sampling outside the feedlot. Fig. 9 shows an example of $F_c$ measurements as wind direction changed from east to south; it was obvious when the sampling footprint started to

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$F_c$ measured flux could be slightly less than this value in most cases. Again, the average $F_c$ in Fig. 7 was 4–5 mg m$^{-2}$ s$^{-1}$, which agreed closely with calculated values based on feeding data.

Fig. 8a shows the composite curves for $\lambda E$ for the same periods. Latent heat fluxes exhibited the typical diurnal pattern with peaks ranging from 80 to 320 W m$^{-2}$, depending on the time of year. This area receives low amounts of annual rainfall, typically in short duration, high intensity events. The soil surface is visibly dry much of the time, except for the urine patches, so $H_2O$ flux often is a reasonable estimate of cattle water consumption during dry periods. The exception would be immediately after precipitation or during the summer months when tanker trucks applied water to the feedlot to reduce dust emissions. The average daily $\lambda E$ for the fall period from September 1 to October 14 2007 was 7.9 MJ m$^{-2}$, equivalent to about 3.2 L m$^{-2}$ of water. Assuming a stocking density of 17 m$^2$ animal$^{-1}$, this is about 55 L of water per head per day. Winchester and Morris (1956) showed the range of water consumption for feedlot cattle was typically between 20 and 80 L animal$^{-1}$ day$^{-1}$, and was dependent upon both animal weight and air temperature. Fluxes of $H_2O$ were equivalent to 22.3 L animal$^{-1}$ day$^{-1}$ during the winter period and 84.7 L animal$^{-1}$ day$^{-1}$ during the summer period, consistent with ranges reported by Winchester and Morris (1956). Assuming the average annual rate of water consumption is 40 L animal$^{-1}$ d$^{-1}$, the amount of water deposited on the pen surface as urine and in fecal material would be, on average, 2.4 mm d$^{-1}$ or 876 mm annually. Thus, the equivalent depth of water in the animal waste is about 1.5 times that received as precipitation. In future studies, water meters will be added to the drinking troughs so rates of cattle water consumption can be compared directly to the eddy flux measurements of $\lambda E$.

Composite curves for $H$ show there is very little difference in $H$ between fall and summer periods (Fig. 8b), a sharp contrast with the differences seen in $\lambda E$. During the summer, $H$ is moderated by high $\lambda E$, predominantly due to the large increase in cattle water consumption. The average daytime (1000–1600 LST) Bowen ratio for the summer period was 0.7 versus 1.1 for the fall and winter periods. One would suspect that the quasi-constant input of moisture moderates daily and seasonal variations in the stability of the surface boundary layer and the Bowen ratio.

### 3.4. Determining fetch requirements

The tower was located on the north edge of a rectangular-shaped feedlot so the fetch was over 1600 m when wind direction was southerly. However, the length of fetch encompassed by feedlot pens decreased as winds became more southeasterly or southwesterly (Fig. 1). Because $F_c$ from the feedlot (3 to 6 mg m$^{-2}$ s$^{-1}$) contrasted sharply with that from surrounding fields (–1.0 to 0.6 mg m$^{-2}$ s$^{-1}$) a drastic change in $F_c$ was observed when the sampling footprint extended beyond the edge of the feedlot. When winds rotated too far to the southeast or southwest, the difference in magnitude between measured $F_c$ and expected $F_c$ (as defined by the composite $F_c$ curve, Fig. 7) showed when the EC tower was sampling outside the feedlot. Fig. 9 shows an example of $F_c$ measurements as wind direction changed from east to south; it was obvious when the sampling footprint started to
include flux from the cattle on day 256. This analysis method was used as a basis to fine-tune use of the Hsieh et al. (2000) model (Eq. (4)) for footprint testing. We were able to compare the Hsieh modeled source area to the actual fetch requirements for the feedlot. For each 30-min period, fetch requirements were calculated using a form of the Hsieh footprint model (Eq. (4)) that predicted the distance from the tower representing a fraction of the source area of the flux measurement (i.e. distance from the tower representing 10, 20, ..., 90% of the source area, or $X_{10}$, $X_{20}$, ..., $X_{90}$). If this distance extended beyond the feedlot boundary, that period was excluded from analysis. Intuitively, it would seem that $X_{100}$ would best represent fetch requirements. However, as the distance from the tower increases, the contribution of the source area decreases and the uncertainty in the footprint model accuracy increases. So, for all practical purposes, the actual fetch requirements will be some distance less than $X_{100}$. Hammerle et al. (2007) used $X_{90}$ to represent fetch requirements, but in fetch-limited situations like the feedlot, it is especially important that this distance be optimized to be as short as possible to retain more data while still effectively identifying bad periods.

Fig. 10 shows measured $F_c$ plotted against wind direction with different colors representing data retained after various footprint filtering criteria. Even though there is considerable scatter in places, the $X_{50}$ and $X_{60}$ filters clearly did not adequately filter out poor data because in the 240–270° direction, points are being retained that are showing the effects of dilution from outside the footprint (i.e. $F_c < 2 \text{ mg m}^{-2} \text{s}^{-1}$). Conversely, the $X_{90}$ filter appeared to be too conservative, excluding a large number of points that represented fluxes from inside the boundaries of the feedlot. It seems that an $X_{70} - X_{80}$ footprint filtering criteria best filters the data and in the case of the feedlot (as would be the case in most fetch-limited situations), $X_{70}$ was chosen because it retained 25% more data than $X_{80}$ yet still appeared to adequately filter fluxes influenced by areas outside the feedlot (i.e. excluded almost all fluxes less than $2 \text{ mg m}^{-2} \text{s}^{-1}$). Under neutral conditions, $X_{70}$ was about 360 m, representing a fetch to measurement height ratio of about 65:1. This is significantly less than the 100:1 conventional rule of thumb, but consistent with other field observations reporting minimum fetch to height ratios ranging from 15:1 to 75:1 (Baldocchi and Rao, 1995; Gash, 1986; Heilman et al., 1989; Irvine et al., 1997).

Having a technique to determine the outer limit of the footprint is critical at a feedlot where almost every site will be fetch limited in certain wind directions.

3.5. Source area mapping

Fluxes measured with EC or other micrometeorological techniques will often need to be scaled to represent fluxes per unit animal or per unit pen area. Regulatory agencies want emissions factors expressed in these units so results can be scaled to regional levels using readily available data on cattle numbers. Also, fluxes per unit pen area are needed to compare the amount of nutrients delivered to the pens in the feed with the amount lost to the atmosphere. For example, if one could determine that 50% of the feed N was lost to the atmosphere as NH$_3$, it would be a useful scaling factor in determining bulk NH$_3$ contribution from feedlots over a large region. Finally, fluxes per unit area are needed by livestock producers and animal scientists so data can ultimately be expressed per animal, which is the experimental unit of interest when considering effects of diet and other aspects of CAFO management. Unfortunately, the footprint of a tower-based flux measurement contains surfaces other than pens (Fig. 1). The GPS map of the feedlot showed that 72% of the surface represents pen areas where the animals are confined; the rest was composed of alleys used to move the cattle, roads for trucks delivering feed, and feed bunks. These areas likely have negligible or very low emissions of CO$_2$, NH$_3$, and other compounds relative to the cattle. Lagoons, buildings, and various other structures also represented a large fraction when the entire property was considered. Further complicating this issue is the dynamic nature of the feedlot operation;
pens of cattle may vary by breed, weight, or sex; may be stocked at different densities; and can be fed different diets. In these situations, a thorough understanding of the source area footprint is needed to determine which pens are contributing to the flux signal or how the fluxes are being diluted by alleys and roads in the source area.

The footprint model of Hsieh et al. (2000) was used to examine the cumulative source area footprint for 6 months of measurements (i.e. the feedlot pen layout was overlaid with an EC source area map). The one-dimensional flux density distribution is calculated as a function of upwind distance (x) and L:

$$f(x, z_0) = \frac{1}{k^x} \frac{Dz_y[L^{1-f}]}{\exp\left(-1\frac{Dz_y[L^{1-f}]}{k^x}\right)}$$

For each 30-min period, flux densities were calculated over 10-min intervals upwind of the measurement location by integrating the modeled flux density distribution:

$$\int_{x-2}^{x+2} f(x, z_0) \, dx = \exp\left(-1\frac{Dz_y[L^{1-f}]}{k^x}\right) - \exp\left(-1\frac{Dz_y[L^{1-f}]}{k^{x-2}}\right)$$

A 1° by 4-m polar grid was created with the measurement location as the origin. The 30-min periods were sorted based on wind direction, and the integrated flux densities for each grid location were summed, resulting in a grid of x – y locations and corresponding cumulative flux densities.

Using the analytical model developed by Hsieh et al. (2000) as described in the methods section, a two-dimensional cumulative flux footprint was developed (Fig. 11) and clearly shows that EC flux measurement is dominated by a relatively small fraction of the feedlot. The three pens immediately south of the tower were responsible for 61% of the flux over a 6-month period, but represented less than 3% of the total feedlot area (Table 1). Thus, it would be especially important to know the characteristics of these pens. When fluxes were scaled to remove the diluting effect of the non-pen areas, the contribution of the same pens increased to 71%. The model showed that, on average, alleys and roads contributed 10 and 2% of the flux signal, respectively.

Carbon dioxide, and to a lesser extent H₂O fluxes, from the roads and alleys were likely very low compared with those from the pens, especially when the surface was dry. Thus, raw fluxes were scaled upward to estimate flux per unit pen area and, ultimately, flux per unit animal. The Hsieh et al. (2000) model was run for each 30-min period and mathematically projected over the feedlot map based on wind direction. Total flux was assumed to originate with X₀% as discussed in Section 3.4. The fraction of the weighted source area, S, that was attributed to pen surface could be determined. After assuming negligible flux from the non-pen surfaces, the flux per unit pen area, F₁₉₉, was calculated as:

$$F_{pen} = F_{raw} \frac{S_{total}}{S_{pen}}$$

Fig. 12 shows the fraction of the flux footprint originating from pen surfaces (as modeled with X₀% representing the total flux) versus wind direction. When it was assumed that all Fc originated from pens only and the raw EC fluxes were scaled up to pen area fluxes, results showed that, on average, F₁₉₉ were 11% greater than F₁₉₉, bringing average CO₂ flux per unit pen area up to 5.6 mg m⁻² s⁻¹. When winds were more easterly, more of the footprint was occupied by alleys (less pen area in the footprint) and fluxes per unit pen area were as much as 31% greater than F₁₉₉ in some cases. This approach for scaling flux measurement to account for non-pen surfaces in the footprint depends on the suitability of the Hsieh model and on the assumption of zero-flux in the non-pen areas. While simplistic, it represents an important first step in trying to scale results in a manner consistent with the nutrient balance of the pen and individual animals. This is crucial in a feedlot setting where EC measurements will likely be compared with feeding data. Inverse dispersion methods that inherently consider the geometry and patchiness of the source area would

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**Table 1 – Surface area and relative contribution to EC measurements from pens, alleys, and roads**

<table>
<thead>
<tr>
<th>Feedlot feature</th>
<th>Surface area (%)</th>
<th>Contribution to measured flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pen A</td>
<td>0.8</td>
<td>35.0</td>
</tr>
<tr>
<td>Pen B</td>
<td>0.8</td>
<td>18.8</td>
</tr>
<tr>
<td>Pen C</td>
<td>0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>Remaining pens</td>
<td>69.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Pen subtotal</td>
<td>71.9</td>
<td>86.8</td>
</tr>
<tr>
<td>Sediment basins and alleys</td>
<td>14.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Roads</td>
<td>7.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Other</td>
<td>6.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* Pens “A”, “B”, and “C” are the closest pens directly south of the tower (Fig. 11).
  * “Other” denotes structures, feed bunks, and otherwise unassigned areas.

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**Fig. 11 – Map of the Hsieh modeled source area of EC measurements of flux for the period from July 13 to December 31, 2006. Gray lines show the pen boundaries (see Fig. 1). Red indicates heavily sampled areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)**
not require this type of scaling and may have advantages. Combining inverse modeling techniques with direct flux measurements (eddy covariance and relaxed eddy accumulation) would be especially useful when measuring feedlot emissions.

4. Conclusions

Micrometeorological techniques are very useful tools for making emissions measurements, but the underlying theory behind these techniques necessitates a large homogeneous surface. The goal of this research was to assess the feasibility of using EC and other micrometeorological techniques for measuring emissions from a less than ideal surface—a cattle feedlot. To accomplish this, we characterized the surface boundary layer of a commercial feedlot in western Kansas. Typically, this feedlot experienced high wind speeds and near-neutral atmospheric stability, so extrapolating from measurements made under calm and/or stable conditions is not advised as they would be very unrepresentative of typical conditions at feedlots in this region. Data showed a roughness length of 3.6 cm and a modeled displacement height of 65 cm. Power spectra and cospectra showed the expected $-2/3$ and $-4/3$ slopes, respectively, in the inertial subrange, and there was no sign of turbulent features that would prohibit the use of EC or related techniques. In terms of daily emission rates per head, EC measurements of $F_E$ and $L_E$ agreed with other studies measuring cattle respiration or water consumption. The percentage of the Hsieh modeled source area that represented actual fetch requirements for the feedlot was about 70–80%. Under neutral conditions, $X_{70\%}$ was about 360 m, representing a fetch to measurement height ratio of about 65:1. Even with a 6-m measuring height, the source area of the EC flux measurements was dominated by a small portion of the feedlot, with 61% of the signal originating from the three pens immediately south of the tower. Therefore, it would be especially important to know the characteristics of those pens when relating flux measurements back to nutrient loading, cattle diets, or stocking density. Finally, for researchers interested in flux measurements in terms of pen surface, the effects of non-pen surfaces on the measurements could be significant. Raw EC fluxes were typically increased by 11% to represent pen area fluxes but were sometimes scaled up by as much as 31%. Indications are that micrometeorological techniques can be successfully applied to cattle feedlots in the High Plains. Results of this research provide guidance for applying these techniques to cattle feedlots and offer insight into challenges that must be faced in many fetch-limited, heterogeneous situations.

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REFERENCES


