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Ammonia emissions from a beef feedlot: Comparison of inverse modeling techniques using long-path and point measurements of fenceline NH_3

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ABSTRACT

Nitrogen (N) deposition in Rocky Mountain National Park, USA (RMNP) and adjacent alpine ecosystems has led to increased focus on ammonia (NH_3) emissions from livestock operations in this region. A study was conducted at a commercial beef feedlot in Northern Colorado, USA to quantify NH_3 fluxes, estimate emission factors (EFs), and evaluate measurement methodologies. Point and line-integrated fenceline NH_3 measurements were taken over a 78-day study at a large feedlot east of RMNP focusing on transport towards the park. Ammonia fluxes were estimated using two inverse models, a backward Lagrangian stochastic approach (WindTrax) and a simpler inverse dispersion approach (FIDES) using input data from both NH_3 datasets. Line-integrated NH_3 concentrations were obtained from a long-path laser and single-point concentrations were collected with a cavity ring-down analyzer, both positioned on the downwind fenceline. Mean feedlot NH_3 concentration ($\pm$ 1 standard deviation, σ) was 601 $\pm$ 246 $\mu g\, m^{-3}$ (1013 $\pm$ 421 ppb_v), where peak values often exceeded several ppm_v. Concentrations from the long-path sensor were slightly higher than the point sensor when winds were from the feedlot ($p = 0.0005$), but 2.5 times less data were collected with the long-path instrument due to dust or laser-reflector alignment issues. Regardless of the model used, fluxes showed a diel pattern peaking in the afternoon with early morning minimums. Emissions varied more by inverse model than by sensor, with WindTrax emissions 25% higher than FIDES. Composite 24-h mean emissions ($\pm$ 1σ) from FIDES were 48 $\pm$ 24 $\mu g\, m^{-2}\, s^{-1}$ (EF = 71 $\pm$ 35 $g\, hd^{-1}\, d^{-1}$), while WindTrax averaged 60 $\pm$ 30 $\mu g\, m^{-2}\, s^{-1}$ (EF = 89 $\pm$ 44 $g\, hd^{-1}\, d^{-1}$) ($p << 0.0001$). Overall 24-h mean EF for the summer (across both models) was 80 $\pm$ 39 $g\, hd^{-1}\, d^{-1}$. When dietary N was considered (13.25% crude protein), based on 24-h composites FIDES estimated NH_3-N released to the atmosphere to be 35.6% of fed-N, while WindTrax showed 44.6% fed-N. The overall mean across models was 40.0% fed-N.

1. Introduction

Animal agriculture is the largest global source of atmospheric ammonia (NH_3), comprising 50–64% of all anthropogenic emissions (FAO, 2006; NRC, 2003). Concentrated animal feeding operations (CAFOs) such as beef feedlots are considered NH_3 "hotspots" due to continual excretion of urea nitrogen (N) in waste within confined areas (e.g., cattle pens). Once airborne, volatilized NH_3 can travel downwind and have environmental impacts through N deposition at tens to hundreds of kilometers from the feedlot. Ecological consequences of NH_3 include eutrophication, biodiversity changes, and influences on water chemistry and the soil microbiome (Galloway et al., 2004; Vitousek et al., 1997), while also contributing to increased regional haze (Bauer et al., 2016; Behara et al., 2013).

Ammonia also enhances formation of particulate matter (Arogo et al., 2006), whereby NH_3 gas converts to ammonium (NH_4^+) aerosols that have longer atmospheric lifetimes, making long-distance transport/deposition possible (Aneja et al., 2008). Additionally, NH_3 has an indirect effect on climate change after deposition, being a precursor to formation of strong greenhouse gases such as nitrous oxide and odd oxides of N (NO_x) (Erisman et al., 2011).

The implications of such issues are important for the northern part of Colorado's *Front Range*; a heavily urbanized region coinciding with intensive crop, livestock, and industrial activities directly adjacent to sensitive mountain ecosystems. Year-round, regional upslope wind events can transport pollutants from this mixed-use corridor westward to sensitive alpine biomes along the eastern flank of the scenic Rocky Mountains where deposition of NO_x- and NH_3-containing compounds have been shown to have measurable effects on the ecosystem (Baron et al., 2000; Bowman et al., 2012; Burns, 2004; Lieb et al., 2011; Wolfe

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Nomenclature

AGWS	Acid-gas washing samplers
bLs	Backward Lagrangian stochasic
CAFO	Concentrated animal feeding operation
CP	Crude protein
CRDS	Cavity ring-down spectroscopy analyzer
DOY	Day of year (calendar day)
EF	Emission factor
FIDES	Flux interpretation by dispersion and exchange over short range
FG	Flux gradient method
LP	Long-path laser
LST	Local standard time
LVL	Light value level
MDV	Mean diurnal variation
mMDV	Modified MDV
MOST	Monin-Obukhov stability theory
NH_3	Ammonia gas
NH_4^+	Aqueous ammonium ion
N	Nitrogen
NO_x	Odd oxides of nitrogen
QA/QC	Quality assurance/quality control
PM_{10}	Particulate matter less than 10 μm in diameter
PTFE	Polytetrafluoroethylene
RMNP	Rocky Mountain National Park
STP	Standard temperature and pressure
TDR	Touchdown ratio
WT	WindTrax

Symbols

σ	Standard deviation
$U_{u,v,w}$	Components of the mean wind ($m\ s^{-1}$)
u*	Friction velocity ($m\ s^{-1}$)
θ	Wind direction (degrees, °)
L	Obukhov length (m)
RH	Relative humidity (%)
T	Temperature (°C)
z_0	Roughness length (cm)
C_{NH3}	NH_3 concentration ($\mu g\ m^{-3}$ or ppb_v)
C_{bgd}	Background NH_3 concentration ($\mu g\ m^{-3}$ or ppb_v)
$\sigma_{u,v,w}/u^*$	Component wind statistics (dimensionless)
x, z	Location of concentration sensors in FIDES (m)
x_s, z_s	Upwind source location in FIDES (m)
R^2	Regression goodness of fit (dimensionless)

et al., 2001, 2003). A land use map of the Northern Front Range is shown in Fig. 1 which identifies Rocky Mountain National Park (RMNP) in addition to nearby CAFOs. There are over 500,000 head of cattle within 8 counties east of RMNP in 2014 (~150 km radius), with cattle in beef feedlots accounting for about 75% of the total (CDPHE, 2014). July wind roses in Fig. 1 for Greeley and Fort Morgan show that easterly (i.e., upslope) summertime winds are common. It follows that NH_3 emissions from CAFOs have been implicated as significant source of N impacting the park (Malm et al., 2013).

While livestock emissions on the eastern plains of Colorado are significant, determining source apportionments (i.e., finding the origin of deposited N) for RMNP is very complex and fraught with uncertainty (Gebhart et al., 2011; Malm et al., 2013; Rodriguez et al., 2011; Thompson et al., 2015). Apportionments are determined via atmospheric modeling, of which a major input parameter are CAFO NH_3 emissions (to constrain simulations). Unfortunately, most in-situ NH_3 emissions studies to date are from CAFO-heavy areas other than Colorado (such as Canada, Australia, and especially the Texas Panhandle, USA). Considering regional differences (climate, population, and proximity to RMNP) between the Texas Panhandle and Northern Front Range, more measurements of NH_3 fluxes from representative Colorado feedlots would improve the NH_3 inventory for the state and reduce uncertainty when modeling nitrogen deposition in RMNP.

Emissions factors (EFs) for NH_3 are usually determined from field

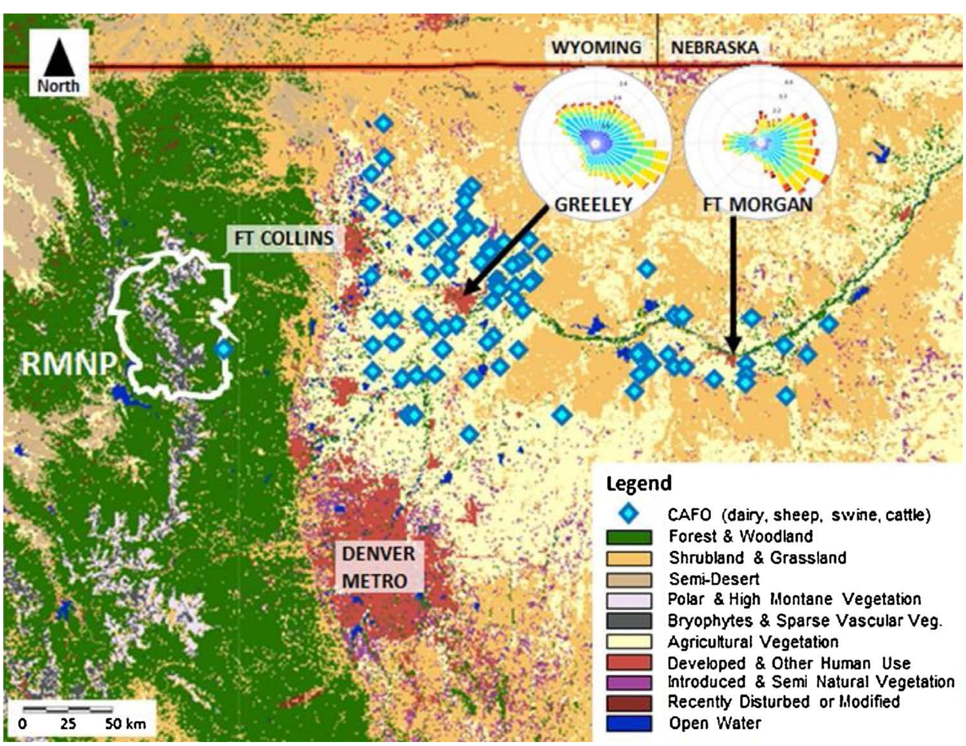

Fig. 1. Land use map for Colorado Front Range (USGS, 2017), with major cities and known large CAFOs (beef and some sheep feedlots with 1000+ head or dairies with 700+ head). July 5-year wind roses (for cities Greeley and Fort Morgan, locations designated by black arrows) show summertime winds near areas of high CAFO concentration tend to have a significant upslope component. Note proximity of urban (reds/purple) to forest/woodland (green) and high instances of agricultural vegetation (light yellow) amidst grassland (orange), where most CAFOs reside. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)