Estimation of in-canopy flux distributions of reactive nitrogen and sulfur within a mixed hardwood forest in southern Appalachia

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Introduction

Canopy-scale flux measurements and inferential models are useful for developing estimates of net emission or deposition of trace gases and aerosols above forests. However, more detailed measurements and models are needed to relate net fluxes to biological, physical, and chemical processes occurring within the air-canopy-soil system, which occur over multiple time scales. The objective of this work is to develop modeling tools that can be used to link atmosphere-biosphere fluxes of reactive compounds to specific ecosystem compartments (e.g., canopy, understory, ground).

Direct measurements of vertical source-sink profiles (fluxes) of most reactive nitrogen, carbon, and sulfur compounds are not possible, either due to limitation or absence of analytical methods capable of direct flux measurements, inability to measure fluxes at appropriate locations within the canopy, or both. However, measured concentration profiles can be used to infer the effective source-sink distribution if the flow field is known. **In this study, a combination of inverse source-sink modeling approaches are used to estimate vertical flux and source sink profiles in a forest canopy using measurements of air concentrations and the flow-field within and above a forest canopy.**

Study Site

- Coweeta Hydrologic Laboratory, North Carolina
- Mature southern Appalachian forest (~85 years since harvesting)
- Deciduous overstory (tulip poplar, sweet birch, red maple, oak), mean canopy height 30 m
- Evergreen understory (rhododendron, mountain laurel)
- Complex topography (base elevation 700 m)
- Mean annual temperature: 12.7 °C

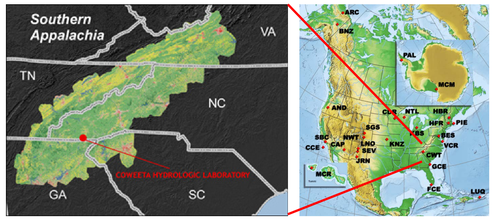


Fig. 1 Study area

Measurements

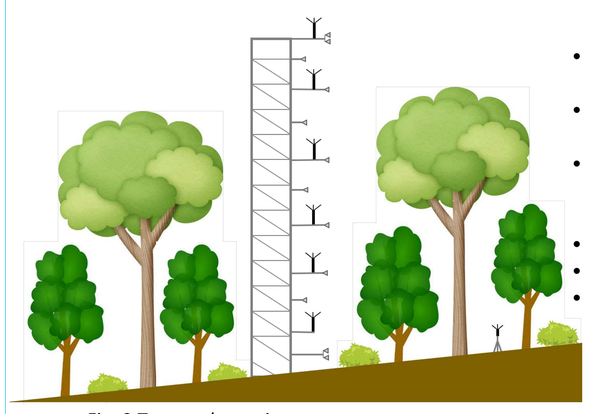


Fig. 2 Tower schematic

- Above canopy (43.5m) and sub canopy (2m) eddy covariance heat, CO_2, H_2O
- CO_2, H_2O concentration profile (7 heights)
- Air temperature profile (6 heights)
- Air concentrations of NH_3, HNO_3, SO_2, NH_4^+, NO_3^-, and SO_4^{2-} (10 heights)
- Daytime chemistry profiles
- URG annular denuder
- 3-4 hour sampling time
- Five seasonal intensives during 2015-16 Southern Appalachian Nitrogen Deposition Study (SANDS)

Modeling

1. Eulerian frame of reference

The effective source of sink (S) is estimate from the steady state mean scalar conservation equation:

$$-\frac{\mathrm{d}\overline{w'c'}}{\mathrm{d}z} + S = 0$$

where the flux $\overline{w'c'}$ is estimated from the corresponding flux budget equation:

$$\frac{\mathrm{d}\overline{w'c'}}{\mathrm{d}t} = -\overline{w'w'}\frac{\mathrm{d}C}{\mathrm{d}z} - \frac{\mathrm{d}\overline{w'c'c'}}{\mathrm{d}z} - \overline{c'\frac{\mathrm{d}p'}{\mathrm{d}z}}$$

with the following closures:

$$\overline{w'c'c'} = \frac{\tau}{C_8}\left[-\overline{w'w'w'}\frac{\mathrm{d}C}{\mathrm{d}z} - \overline{w'c'}\frac{\mathrm{d}\overline{w'w'}}{\mathrm{d}z} - 2\overline{w'w'}\frac{\mathrm{d}\overline{w'c'}}{\mathrm{d}z}\right], \overline{c'\frac{\mathrm{d}p'}{\mathrm{d}z}} = C_4\frac{\overline{w'c'}}{\tau}$$

This method requires the velocity variance ($\overline{w'w'}$), skewness ($\overline{w'w'w'}$), an Eularian time scale (τ), and the two constants (C4, C8).

2. Lagrangian localized near-field theory - LNF

A dispersion kernel is generated by dividing the canopy to n layers and calculating the concentration profiles for a uniformly distributed unit source from each of these layers resulting in a transformation matrix (D) that relates S to the mean concentration (C):

$$C - C_R = D\,S \quad \text{where } C_R \text{ is a reference concentration}$$

D is calculated by superimposing near- (C_n) and far- (C_f) field contributions, assuming vertical dispersion only, locally homogenous turbulence, and constant time scale. This method requires the velocity variance ($\overline{w'w'}$) and Lagrangian time scale (T_L).

Results

(1) Chemistry profiles

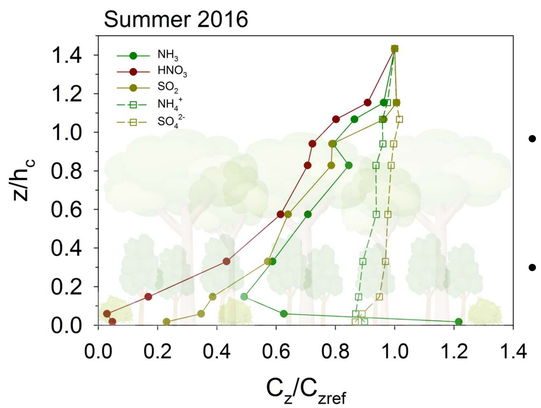
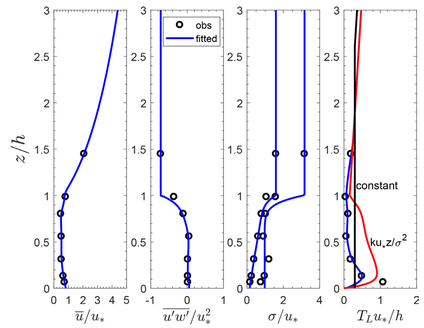


Fig. 3 Median vertical concentration profiles for summer 2016 campaign. Concentration at height z (C_z) is normalized by the reference concentration (C_{zref}) measured at z/hc = 1.4, where h_c is canopy height. Observations represent the median of n = 19 profiles.

- HNO_3 and SO_2 concentrations decrease by ≈ 95% and 80%, respectively, from the atmosphere to the forest floor.
- Aerosol profiles reflect much slower deposition than gases.
- NH_3 profiles indicate deposition to vegetation and emission from the forest floor.

(2) Flow field



- Wind speed decreased from above the canopy to the middle canopy then increased slightly within the trunk area above the forest floor.
- Reynolds stress and velocity variances followed typical patterns.

Fig. 4 Flow statistics used for source/sink estimation for an example profile on July 21, 2016. Statistics averaged over 4 hour (11:00-15:00) duration of chemical measurements. Three Lagrangian time scales (right hand panel) were considered, estimated from the auto-correlation of w′ (TL1, blue line), a far-field diffusion time scale (tau 1, red line), and a constant based on the canopy height and u_* (tau 3, black line).

(3) Source/Sink profiles

- Models predict a source of NH_3 above the forest floor, indicating emissions from litter or soil.
- The net flux of NH_3 over the canopy was downward.
- Uptake of HNO_3 and SO_2 mostly occurred just below the canopy top.
- Significant differences in the estimated source/sink can be found between different models and for different time scales.

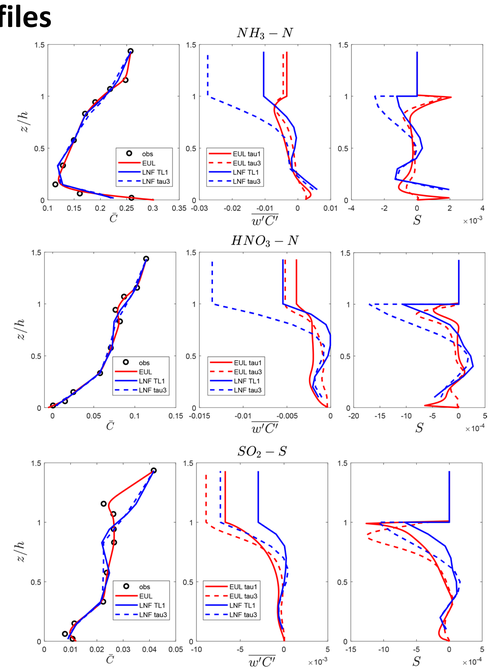


Fig. 5 Example measured (circles) and modeled (lines) concentration profiles (μg/m³) (left panel) along with modeled flux profiles (μg/m²/s) (middle panel) and source/sink distribution (μg/m³/s) for NH_3-N, HNO_3-N, and SO_2-S, respectively. Flow statistics in Fig. 4.

Next Steps

- Analysis of full data sets from five seasonal intensives.
- Evaluation and comparison of source-sink modeling approaches.
- Evaluation of source-sink models against measured fluxes of heat, CO_2, H_2O, and reactive nitrogen and sulfur compounds.
- Comparison of source-sink models to multilayer resistance based and big-leaf canopy scale models.

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