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Statistical partitioning of a three-year time series of direct urban net CO_2 flux measurements into biogenic and anthropogenic components

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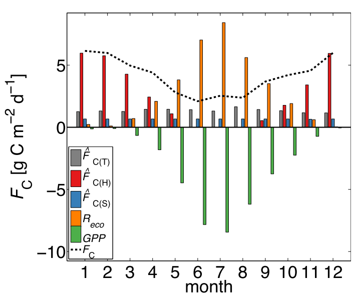
HIGHLIGHTS

- Vegetation and soil strongly impacted diurnal and seasonal cycles of urban CO_2 flux.
- *GPP* had largest magnitude and seasonal changes of any anthropogenic or biogenic flux.
- Growing-season peak *GPP* was similar to forests and prairies in the same climate zone.
- Subtracting R_{eco} from *GPP*, and a short growing season, reduced the net biogenic flux.
- Net biogenic flux was 1.5–4.5% of anthropogenic emission in residential area annually.

GRAPHICAL ABSTRACT



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ABSTRACT

Eddy covariance flux measurements are increasingly used to quantify the net carbon dioxide exchange (F_C) in urban areas. F_C represents the sum of anthropogenic emissions, biogenic carbon release from plant and soil respiration, and carbon uptake by plant photosynthesis. When F_C is measured in natural ecosystems, partitioning into respiration and photosynthesis is a well-established procedure. In contrast, few studies have partitioned F_C at urban flux tower sites due to the difficulty of accounting for the temporal and spatial variability of the multiple sources and sinks. Here, we partitioned a three-year time series of flux measurements from a suburban neighborhood of Minneapolis-Saint Paul, Minnesota, USA. We segregated F_C into one subset that captured fluxes from a residential neighborhood and into another subset that covered a golf course. For both land use types we modeled anthropogenic flux components based on winter data and extrapolated them to the growing season, to estimate gross primary production (*GPP*) and ecosystem respiration (R_{eco}) at half-hourly, daily, monthly and annual scales. During the growing season, *GPP* had the largest magnitude (up to $-$ 9.83 g C m^{-2} d^{-1}) of any component CO_2 flux, biogenic or anthropogenic, and both *GPP* and R_{eco} were more dynamic seasonally than anthropogenic fluxes. Owing to the balancing of R_{eco} against *GPP*, and the limitations of the growing season in a cold temperate climate zone, the net biogenic flux was only 1.5%–4.5% of the anthropogenic flux in the dominant residential land use type, and between 25%–31% of the anthropogenic flux in highly managed greenspace. Still, the vegetation sink at our site was stronger than net anthropogenic emissions on 16–20 days over the residential area and on 66–91 days over the recreational area. The reported carbon flux

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sums and dynamics are a critical step toward developing models of urban CO_2 fluxes within and across cities that differ in vegetation cover.

1. Introduction

Eddy covariance flux measurements have been shown to offer a feasible approach for validating CO_2 emissions inventories and to identify emissions mitigation potential of cities at neighborhood to local scales (Nemitz et al., 2002; Moriwaki and Kanda, 2004; Christen et al., 2011; Kotthaus and Grimmond, 2012; Kellett et al., 2013; Velasco et al., 2013, 2014). At the same time, multi-city synthesis studies have shown that variations in annual net CO_2 fluxes among different urban sites have a strong relationship to their fraction of vegetation cover (Velasco and Roth, 2010; Nordbo et al., 2012). However, to our knowledge only a few studies have attempted to partition the measured urban net CO_2 flux such that the biogenic fluxes from vegetation and soil could be isolated and quantified over time (Crawford and Christen, 2014; Weissert et al., 2014; Velasco et al., 2016; Bellucco et al., 2017). Importantly, this quantification of the CO_2 flux from urban vegetation and soil, and its separation into photosynthetic uptake and ecosystem respiration, allows for a prediction of the biogenic CO_2 fluxes and their comparison among different land use types within a city. Further, one can assess the similarity of CO_2 fluxes from urban vegetation to those of natural forest or grassland ecosystems surrounding the city, a critical step toward developing models of urban CO_2 exchange across cities that differ in vegetation cover.

Vegetated areas can have significant effects on the spatial and temporal variability of the urban carbon cycle and can even act as local sinks (e.g. Velasco and Roth, 2010; Christen et al., 2011; Crawford et al., 2011; Järvi et al., 2012; Peters and McFadden, 2012; Ward et al., 2013; Bellucco et al., 2017). Yet photosynthetic uptake and respiratory release of CO_2 from urban green spaces are seldom included in carbon budgets of urban areas (Nordbo et al., 2012), and few cities estimate the carbon sequestered by urban trees. Carbon uptake from trees is usually calculated based on biomass allometric equations and growth curves (McPherson et al., 2008; Nowak et al., 2008; Churkina et al., 2010; Weissert et al., 2014). More recently, high resolution remote sensing data and tree growth models have been used to estimate carbon stocks of the urban forest (Raciti et al., 2014; Alonzo et al., 2016).

The net CO_2 exchange between the atmosphere and the land surface (F_C) in natural ecosystems can be partitioned into two large fluxes of opposite sign, i.e., CO_2 uptake by photosynthesis (*GPP*) and CO_2 release from ecosystem respiration (R_{eco}) (Stoy et al., 2006; Desai et al., 2008). F_C is measured directly with the eddy covariance method, a micrometeorological technique that has been widely used in forest, grasslands and other ecosystems (e.g., Baldocchi, 2008). It is now increasingly used to quantify CO_2 fluxes in urban areas. Currently more than 30 active urban sites exist (Velasco and Roth, 2010), monitoring net carbon dioxide emissions at the neighborhood scale.

In natural ecosystems, separating the net CO_2 exchange into *GPP* and ecosystem respiration is accomplished using nonlinear statistical models that have been generally well established (Lasslop et al., 2010; Reichstein et al., 2005; van Gorsel et al., 2009). In contrast, partitioning of F_C in urban environments is more difficult due the large temporal and spatial variability of the multiple sources and sinks. In an urban environment, F_C represents the sum of anthropogenic emissions associated with e.g., transport or energy use in households and commercial buildings; biogenic carbon release from plant, soil and human respiration; and carbon uptake by plant photosynthesis. Only a few pilot studies have attempted to partition urban carbon dioxide fluxes and have relied on specialized additional measurements such as carbon isotopes (Christen et al., 2013), on surface fractions in the changing turbulent source areas as model input (Crawford and Christen, 2014), or light-response modeling (Bellucco et al., 2017).

The carbon exchange in urban environments exhibits diurnal and seasonal cycles that are driven by both anthropogenic and biogenic processes (Weissert et al., 2016). For example, in cold climates the vegetation is dormant during most of the winter. Deciduous trees do not photosynthesize then because they have no leaves and soil respiration is negligible when the ground is frozen. Hence, F_C is expected to comprise solely anthropogenic emission sources during this time. Similarly, for partitioning of F_C into ecosystem respiration and *GPP* in natural ecosystems, one of the first methods was developed on the notion that the net flux includes only ecosystem respiration during night (Reichstein et al., 2005).

The primary objective of this study was to separate the biogenic fluxes (*GPP* and R_{eco}) from the simultaneously occurring anthropogenic emissions of CO_2 in an urban landscape. Our aim was to partition all of the fluxes using an entirely "top-down" approach based on direct eddy covariance flux measurements of net CO_2 exchange over a suburban landscape without relying on external upscaled data or models of the urban landscape. This means that our time series of partitioned CO_2 fluxes did not depend on the use of a footprint model; therefore, our component CO_2 flux estimates were independent of the assumptions and uncertainties of flux footprint models. We followed this approach because the goal of our further work is to perform flux footprint analyses, similar to those made in natural ecosystems, of how *GPP* and R_{eco} are affected by variations in vegetation composition and ecosystem characteristics across the urban landscape.

In this study, we analyzed a three-year time series of net CO_2 flux measurements from an eddy covariance system mounted at 40 m above ground on a 150 m tall radio broadcast tower in Minneapolis-Saint Paul, Minnesota, USA. The cold climatic setting of the site provided an opportunity to partition net CO_2 fluxes into their sources and sinks by using dormant-season data to develop statistical models of the anthropogenic flux components, allowing us to estimate the net biogenic flux from vegetation and soil.

Our key scientific questions and objectives were the following: 1) How much do vegetation and soil contribute, relative to anthropogenic emissions, to the total net CO_2 exchange (F_C) over an urban ecosystem?; 2) Are the temporal variations of vegetation and soil CO_2 fluxes large enough to significantly modify the urban net CO_2 flux (F_C) over the seasonal cycle and from year to year? If so, which are the times and areas at which a possible modification is more pronounced than at others?; 3) How do urban biogenic CO_2 fluxes, and their components of photosynthetic uptake and ecosystem respiration, vary in magnitude and seasonality between land use types that differ in vegetation fractional cover?; 4) How do urban biogenic CO_2 fluxes differ in magnitude and seasonality in comparison to natural ecosystems in the same climate zone?