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Modelling the biogenic CO_2 exchange in urban and non-urban ecosystems through the assessment of light-response curve parameters

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ABSTRACT

The biogenic CO_2 surface–atmosphere exchange is investigated and linked to vegetation cover fraction for seven sites (three urban and four non-urban) in the northern hemisphere. The non-rectangular hyperbola (NRH) is used to analyse the light-response curves during period of maximum ecophysiological processes, and to develop two models to simulate biogenic vertical CO_2 fluxes. First, a generalised set of NRH coefficients is calculated after linear regression analysis across urban and non-urban ecosystems. Second, site-specific NRH coefficients are calculated for a suburban area in Helsinki, Finland. The model includes a temperature driven equation to estimate ecosystem respiration, and variation of leaf area index to modulate emissions across the year. Eddy covariance measured CO_2 fluxes are used to evaluate the two models at the suburban Helsinki site and the generalised model also in Mediterranean ecosystem.

Both models can simulate the mean daily trend at monthly and seasonal scales. Modelled data typically fall within the range of variability of the observations (differences of the order of 10%). Additional information improves the models performance, notably the selection of the most vegetated wind direction in Helsinki. The *general* model performs reasonably well during daytime but it tends to underestimate CO_2 emissions at night. This reflects the model capability to catch photosynthesis processes occurring during the day, and the importance of the gross primary production (GPP) in modifying the net ecosystem exchange (NEE) of urban sites with different vegetation cover fraction. Therefore, the *general* model does not capture the differences in ecosystem respiration that skew nocturnal fluxes. The relation between the generalised NRH plateau parameter and vegetation cover improves (R^2 from 0.7 to 0.9) when only summer weekends with wind coming from the most vegetated sector in Helsinki and well-watered conditions for Mediterranean sites are included in the analysis. In the *local* model, the inclusion of a temperature driven equation for estimating the ecosystem respiration instead of a constant value, does not improve the long-term simulations. In conclusion, both the *general* and *local* models have significant potential and offer valid modelling options of biogenic components of carbon exchange in urban and non-urban ecosystems.

1. Introduction

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas (GHG) in the atmosphere (IPCC, 2013). Over the past decade, CO_2 has been responsible for about 83% of the total increase of global radiative forcing (WMO, 2015). The global average atmospheric concentration in 2014 was 43% greater than its pre–industrial levels (Le Quéré et al., 2015). Anthropogenic activities, such as fossil fuel combustion, cement production, deforestation and replacement of natural or agricultural ecosystems by impervious surfaces (dwellings, roads, roofs etc.), are mainly responsible for this trend (Le Quéré et al., 2015). In recent years, more attention has been dedicated to study the role of cities in global climate change to consider mitigation strategies (Rosenzweig et al., 2010). Within their extent, cities emit 30–40%

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of total GHG emissions (Satterthwaite, 2008; Marcotullio et al., 2013; Marcotullio, 2016) and are responsible for 45–70% of total energy-related CO_2 emissions (IEA, 2008; Marcotullio et al., 2013; Marcotullio, 2016). With an estimated 66% of people living in urban areas by 2050 (UN, 2014), an increase in energy demand and carbon emissions is expected. Therefore, it is critical to deepen our understanding of the interaction between natural and anthropogenic processes in response to environmental conditions and urban morphology.

In contrast to natural ecosystems, CO_2 fluxes in cities derive from a complex balance between biogenic (ecosystem respiration, R_{eco}, and gross primary production, GPP) and human activity (i.e. traffic, household activities and heating systems in buildings, and human respiration). Analogous to vegetated ecosystems, the sum of R_{eco} and GPP is the net ecosystem exchange (NEE). As the biogenic component (vegetation and soil) can behave differently in cities to natural ecosystems (Decina et al., 2016; Velasco et al., 2016), understanding the role of vegetation in sequestering the CO_2 emitted by anthropogenic sources has received a lot of attention within the scientific community recently. During the growing season, a negative correlation between CO_2 fluxes and vegetation cover fraction (λ_V) has been identified: as vegetation cover increases, CO_2 emissions decrease because of the greater plant photosynthesis uptake (e.g. Velasco and Roth, 2010; Bergeron and Strachan, 2011; Ramamurthy and Pardyjak, 2011; Nordbo et al., 2012). Although plants help to reduce anthropogenic CO_2 emissions in cities, vegetation is unable to completely offset anthropogenic emissions, and urban annual carbon budgets are almost always positive both on a daily and seasonal scale (Moriwaki and Kanda, 2004; Velasco and Roth, 2010; Crawford et al., 2011). In cities where $\lambda_V \leq 34\%$, the role of lawns and trees in reducing net CO_2 emissions is increasingly less effective (Velasco and Roth, 2010; Bergeron and Strachan, 2011), and when λ_V is less than 5%, the biogenic contribution to the total carbon balance can be considered negligible (Moriwaki and Kanda, 2004; Matese et al., 2009; Velasco et al., 2009; Grimmond and Christen, 2012; Ward et al., 2015). Only parts of cities with $\lambda_V > 80\%$ may potentially be net annual sinks (Nordbo et al., 2012).

The micrometeorological Eddy Covariance (EC) technique has been applied to directly measure the local net energy and mass fluxes (e.g. NEE) in urban areas (Velasco and Roth, 2010; Grimmond and Christen, 2012). Empirical methods or models are needed to partition the measured urban net exchange into biogenic and anthropogenic components, as it is difficult to measure them separately. However, the estimation of carbon uptake by vegetation remains difficult due to the complexity of urban ecosystems and the variety of different species (Jo and McPherson, 1995; Velasco et al., 2013).

Light-response curves are often used to estimate the ecosystem respiration and carbon uptake as a function of photosynthetically active radiation (PAR) or solar radiation, and air temperature (Nemitz et al., 2002; Bergeron and Strachan, 2011; Christen et al., 2011; Crawford and Christen, 2015; Ward et al., 2015). Other methods (Weissert et al., 2014) used to partition EC measurements into its biogenic components are based on soil CO_2 efflux models (Velasco et al., 2013, 2016) and measurements (Christen et al., 2011; Järvi et al., 2012; Park et al., 2013), as well as leaf-level photosynthesis models (Soegaard and Møller-Jensen, 2003) and measurements (Christen et al., 2011; Peters and McFadden, 2012; Park et al., 2013; Björkegren and Grimmond, 2016). Estimates can also be based on similar non-urban vegetation types (Moriwaki and Kanda, 2004; Helfter et al., 2011), biomass allometric equations and growth rate predictive models (Nowak et al., 2008; Björkegren and Grimmond, 2016; Velasco et al., 2013, 2016), and bottom-up approaches to estimate anthropogenic contributions (traffic, household activities, and human respiration) to subtract from the measured fluxes (Velasco et al., 2013, 2016).

The natural (vegetation plus bare soil) cover fraction has been used to estimate annual continental-scale urban NEE for North America, Europe and eastern Asia (Nordbo et al., 2012), but to our knowledge the relation between different urban and non-urban ecosystems, and their dependence on λ_V and environmental variables has not been investigated to reproduce the mean NEE daily trend.

The aim of this work is to develop two sets of model parameters that can be used in two different modelling approaches: a *general* (obtained after the comparison of light-response parameters across different sites) and a *local* (adjusted to site-specific light-response parameters) model. Both models estimate the CO_2 biogenic components of the urban carbon balance. The specific objectives are:

1) to investigate similarities in CO_2 vegetation uptake in urban and non-urban ecosystems;
2) to identify empirical relations among biogenic CO_2 flux, vegetation cover fraction, and environmental variables, in order to develop a *general* model which estimates the NEE biogenic components;
3) to test the *general* model both in suburban (Helsinki, Finland) and natural sites (Mediterranean maquis vegetation of Capo Caccia, Italy) to highlight how generalised light-response parameters adjust to different ecosystems and vegetation cover fractions, capturing the daily trend of biogenic CO_2 fluxes;
4) to compare the performances of the *general* model with those of a site-specific *local* model.

CO_2 fluxes measured with the EC technique at seven different sites are analysed and linked to surface characteristics. The sites cover mid and high latitudes in the northern hemisphere, with different land uses and climates. For this reason, at each site the growing season period is only considered (summer for deciduous ecosystems and the whole year for the evergreen Mediterranean one). For Mediterranean climate the effect of soil water content is explored. After the development of two modelling approaches, the models are compared for the same period in a suburban neighbourhood in Helsinki. CO_2 flux observations of a natural Mediterranean site (Capo Caccia) are then used to verify the biogenic character of the *general* model.

2. Materials and methods

A brief description of the sites analysed to develop the models is given in Section 2.1. The choice of sites was driven by the relatively limited availability of long-term EC datasets in suburban ecosystems and the challenging task to partition EC measurements into its biogenic and anthropogenic components. Therefore, mostly biogenic vertical CO_2 fluxes spanning a wide range of vegetation covers (from natural to urban ecosystems), and accessible to the authors were considered. An initial assessment of light-response parameters focused on understanding their ability to explain the net CO_2 exchange differences across different urban-non-urban ecosystems. The relation between the estimated light-response coefficients and vegetation cover fraction could then be investigated to see how, and if, they were significantly related. Based on these preliminary results, a *general* model is developed (Section 2.2). Another model (hereafter called *local*) is developed that uses light-response parameters estimated for an individual suburban site (Section 2.3). The two models are evaluated with independent data and statistical indices (Section 2.4).

2.1. Sites description and analysis

Seven sites with different vegetation types and cover fractions are used in this study: three Mediterranean vegetated sites (two