Modelling biogenic and anthropogenic carbon dioxide exchange in urban area - a data fusion approach

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Abstract: Much effort of carbon dioxide (CO₂) mitigation as the countermeasure to global changes has focused on the urban areas – the hotspots of fossil fuel and concentrated emission and pollutants. Despite their critical role in CO₂ exchange in urban ecosystem, emission sources from vegetation and soil surfaces are largely overlooked in existing urban land surface models. In this study, we parameterized the biogenic CO₂ exchange in cities using an advanced single-layer urban canopy model, by incorporating a plant physiological model in the built environment. In addition, the proposed model also includes the anthropogenic CO₂ fluxes especially that from traffic emissions, based on gridded dataset. We evaluate the proposed model using CO₂ measurements from an eddy covariance flux tower located at west Phoenix, Arizona, USA. The model results are in good agreement with the observed carbon flux over the built terrain, with a RMSE of 0.21 mg m⁻²s⁻¹. Furthermore, our simulations show that the abiotic traffic-emitted CO₂ amounts the largest source in cities, as expected. Nevertheless, the biogenic carbon exchange can be significantly enhanced in the built environment, which makes an equally important contributor to the total carbon emission especially in sub-urban areas.

Keywords: Anthropogenic sources; Plant physiology; Urban canopy model; CO₂ exchange.

1. Introduction

Urban land surface models (LSMs) have undergone continuous development from a simple urban energetic models (Masson, 2000; Kusaka et al., 2001), to incorporate momentum transport (Martilli et al., 2002), urban hydrological processes (Wang et al., 2013), and anthropogenic heat (Sailor and Lu, 2004; Sailor, 2011). In particular, urban LSMS have gradually included parameterization schemes of urban vegetation with increasing complexity, like green roofs (Yang and Wang, 2014), urban trees (Upreti et al., 2017), and urban irrigation (Wang et al., 2019). These new schemes significantly enhanced the model predictive skills over realistic built terrains, furnishing further improvement of urban LSMS for capturing biogenic and anthropogenic carbon emission in urban areas (Song et al., 2017).

In addition to the pronounced urban heat island (UHI) effect, cities are also hotspots of greenhouse gas (GHG) emission, especially CO₂, with concentrated sources and human activities (Hutyra et al., 2014). In particular, anthropogenic CO₂ (AnCO₂), primarily emitted from the fossil fuel combustion, constitutes the largest flux of CO₂ to the atmosphere and represents the dominant source of GHG.
forcing to emergent climate patterns (Gurney, 2014). AnCO₂ emissions are often used as a near-certain boundary conditions when solving for total carbon budget, which is essential to improve our fundamental understanding of the feedback mechanisms between the carbon cycle and climate changes (Vetter et al., 2008). Accurate quantification of the urban CO₂ emission, either biogenic or anthropo-genic in source, requires the integration of observational, mechanistic, and modelling methods at fine resolutions (Gurney, 2014).

By combining the advantages of “bottom-up” inventory data by sectors and the “top-down” spatial distributed dataset from remote sensing imagery (Sailor and Lu, 2004), the CO₂ mapping technology today can represent the efflux estimation over space and time with wide coverage (global or continental scale), high spatial resolution (1~10km) and reliable with cross validations. However, the mapping of biogenic CO₂ release or uptake is usually missing in the built environment, mainly due to the complex flow field and dynamics of transport in the built environment (Fernando, 2010). Up to date, the biogenic sources of CO₂ emission is largely under explored as compared to the AnCO₂ counterpart, especially in residential areas with substantial fraction of vegetation cover. This inadequacy of capturing CO₂ emission by plant physiological functions in urban areas, in turn, surfaces in the net ecosystem exchange (NEE) gridded data, leading to large uncertainties and degraded data quality (Macknick, 2011).

Recently, a pioneering work has been conducted for numerical CO₂ flux modelling at the street scale (Goret et al., 2019). The model was tested over a heavily urbanized city centre (90% impervious surface), and showed urban vegetation played a minimum role in CO₂ exchange (less than 3%) due to the small vegetation fraction in city core. While the model performance is good, the limited representation of biogenic CO₂ emission constrains its applications to highly impervious areas. In contrast, nearly half of the urban land in the U.S. attributes to residential use, where the vegetation fraction is significantly higher than it in urban cores (USDA, 2017), with the presence of urban vegetation in the forms of urban parks, golf courses, and most importantly, maintained urban gardens. It is therefore critical for urban LSMS to capture plant responses to elevated temperature, CO₂ level, irrigation, and active lawn management.

The continuous development of urban LSMS, gridded anthropogenic emission data products, and plant physiological modelling techniques, hitherto in parallel lines, provides the possibility for the modelling of CO₂ exchange in urban areas. With the tools and datasets readily available, the development of holistic urban CO₂ modelling framework becomes increasingly imperative. This study aims to bridge the research gap, in which we first disentangle the relative contribution to urban carbon fluxes from each component (anthropogenic, biogenic, soil), and then integrate various contributors. The proposed model is evaluated against year-long eddy covariance (EC) measurements of urban carbon flux, located in a residential built environment in west Phoenix, Arizona, USA with hourly data sampling.

2. Model description

2.1. Urban canopy modelling

Among existing urban LSMS, the single-layer urban canopy models (UCMs) are probably the most widely used. They are particularly attractive to researchers for maintaining a fine balance between the numerical simplicity (i.e. urban canyon representation) and the comprehensiveness of land surface dynamics. Despite its comparative simplicity to more sophisticated LSMS, single-layer UCMs have tractable parameter sensitivity (Wang et al., 2011) and often give satisfactory performance with the same level of model calibration (Grimmond et al., 2010, 2011). These UCMs have been incorporated into
the popular meso-scale Weather Research and Forecasting (WRF) model (Kusaka et al., 2001; Yang et al., 2015) and extensively applied for local and regional urban hydrometeorological modelling for cities all over the world.

In this study, we adopt a single-layer UCM as the numerical stratum for capturing the dynamic transport in urban energy and hydrological cycles (Wang et al., 2013; Yang et al., 2015). The UCM represents the built terrain as a generic unit of two-dimensional (2D) street canyon, consisting of two arrays of buildings separated by a road, with infinite longitudinal dimension (Wang et al., 2013). The in-canyon transport of energy, water, and scalar fluxes are resolved separately for each sub-facet (walls, impervious and vegetated roads, shade trees, etc.); and aggregated by areal means to compute the total urban fluxes. The in-canyon meteorological variables (radiation, temperature, humidity, and aerodynamic resistance) resolved by UCM are used to drive the plant physiological model for the estimation of biogenic CO2 in street canyon. Depending on the height of the plants, those variables at prescribed elevation in the street canyon are applied to differentiate the types of plant. Anthropogenic heat emission from the buildings is calculated by the heat conduction module of UCM, which is in turn utilized in building CO2 release estimation in combination of the local heating profile (i.e. types of fuels and their relative contributions).

2.2 Biogenic CO2 fluxes from plant physiological functions

The physiological functions of plant, primarily the stomatal control, in CO2 exchange in natural environment have been extensively studied (Collatz et al., 1991, 1992; Jacobs, 1994). Here we adopt a typical physiological plant model (Ronda et al., 2001; Jacobs et al., 2003) and integrate it with the UCM model.

Given micrometeorological conditions, the gross primary productivity (GPP) at leaf level, \( A_g \), is given by,

\[
A_g = f(PAR, T_{\text{leaf}}, C_i),
\]

where \( PAR \) is the photosynthetic active radiation; \( T_{\text{leaf}} \) is the leaf temperature; and \( C_i \) is CO2 concentration inside of leaves. The ratio of \( PAR \) to the total solar irradiance is roughly a constant around 0.46 (Pinker and Laszlo, 1992). In addition, \( C_i \) can be estimated as the plant regulates the ratio via stomatal opening and closure as a function of water vapor pressure deficit (Jacobs, 1994):

\[
\frac{C_i - \Gamma}{C_i - \Gamma} = \left(1 - \frac{D}{D_0}\right)^{-1}\frac{D}{D_0},
\]

where \( \Gamma \) is the CO2 compensation point; \( D_i \) is the vapor pressure deficit at leaf level; \( D_0 \) is the \( D_i \) at stomatal closure; and \( \chi_{\text{max}} \) and \( \chi_{\text{min}} \) are the maximum and minimum value of the ratio \( (C_i - \Gamma) \) to \( (C_i - \Gamma) \). The values of \( D_0, \chi_{\text{max}}, \chi_{\text{min}} \) and \( \Gamma \) are parameterized for given types of plants analytically or empirically (Ronda et al., 2001). It is noteworthy that \( \Gamma \) is temperature-dependent and can be estimated using \( Q_{10} \) method as

\[
V(T_{\text{leaf}}) = V_{25} Q_{10}^{(T_{\text{leaf}} - 25)/10},
\]

where \( V \) is a generic temperature-dependent variable (in this case, \( \Gamma \)); \( V_{25} \) is the value at 25°C; and \( Q_{10} \) is the rate of increase per 10°C change in temperature.

Specifically, we adopt the formulas of Jacobs (1994), Ronda et al. (2001), and Jacobs et al. (2004) to determine the plant function in Eq. (1) as
where $R_d$ is the plant dark respiration and usually calculated as a fraction of $A_m$; $A_m$ is the primary productivity, given by

$$A_m = A_{m,\text{max}} \left[ 1 - \exp \left( - \frac{g_m}{A_{m,\text{max}}} \right) \right].$$

with $A_{m,\text{max}}$ the maximum primary productivity under high CO2 concentration and sufficient light condition, and $g_m$ the stomatal conductance. Here $A_{m,\text{max}}$ and $g_m$ are temperature-dependent, and can be estimated using the $Q_{10}$ or $Q_{10}$-type method (Ronda et al., 2001).

To find the gross primary production at canopy level, CO2 uptake at leaf level needs to be integrated over entire leaf surface area, as

$$A_{c,g} = \int_0^{L_d} A_z \, dL = A_m \left( \text{LAI} - \frac{E_{\text{int}}}{K_x} \right),$$

where $A_{c,g}$ is the assimilation rate at canopy level; $A_m' = A_m + R_d$; LAI is the leaf area index; $K_x$ is the extinction coefficient; and $E_{\text{int}}$ represents the overall leaf density from top to bottom of the canopy, calculated as

$$E_{\text{int}} = E_i \left[ \frac{\alpha K_x PAR}{A_m'} \exp \left( - K_x \text{LAI} \right) \right] - E_i \left[ \frac{\alpha K_x PAR}{A_m} \right],$$

with $E_i$ [•] the exponential integral.

### 2.3 Soil and plant respiration

Carbon release from bare soil in urban area is often neglected due to the usual perception that soil is a minor source of CO2 comparing to anthropogenic release. In fact, soil respiration is a major contribution to atmospheric CO2 in manmade landscapes with irrigation and fertilization. Designated urban garden soil with enriched organic matter and nitrogen is often used in cities for a better plant growth. Decina et al. (2016) reported that the soil respiration in residential areas with active landscaping management is 2.2 times higher than that of urban forests. The total CO2 flux from soil is comparable with fossil fuel emission in summer months.

Bare soil respiration is primarily regulated by soil temperature ($T_s$) and soil water content ($\theta$). Though other factors such as the presence of organic matters, nitrogen, the change of air pressure, etc. will also influence the respiration rate, their contribution is considered minor or embedded into the change of $T_s$ and $\theta$ (Luo and Zhou, 2006). Like plant physiology, $Q_{10}$-type methods are often used for temperature-dependent relation in soil respiration. Kirschbaum (1995) proposed temperature dependency model to estimate soil respiration due to biotic and abiotic processes. The method permits an optimum temperature as an input and a variable $Q_{10}$, as

$$Q_{10}(T) = \exp \left[ 10 \beta \left( 1 - \frac{T}{T_{\text{opt}}} \right) \right],$$

where $\beta$ and $T_{\text{opt}}$ are empirically fitted parameters. Combined with Eq. (3) and the dependency on soil moisture, the soil respiration rate can be obtained as

$$R_s(T, \theta) = f(\theta) R_{12} Q_{10}(T)^{T-15}/10,$$
where $R_s$ and $R_{25}$ are the soil respiration rate under $T_s$ and 25°C; and $f(\theta)$ is the respiration reduction function due to water stress. The typical forms of $f(\theta)$ can be found in literature for urban evapotranspiration (Wang et al., 2013; Li and Wang, 2019) and photosynthesis (Ronda et al., 2001).

Plant respiration is usually evaluated empirically using statistical regressions for field experiments. Here we adopt the formula derived over a grassland to represent the ecosystem respiration $R_e$, for low vegetation surfaces (Norman et al., 1992)

$$R_e = \left( a + b LAI \right) \theta_0 e^{(T_s - T_{s,\text{ref}})},$$

where $a = 0.159$, $b = 0.064$, $c = 0.054$, and $T_{s,\text{ref}} = 27.7 \degree C$ are empirical coefficients fitted from 900 on-site observations over grassland (Norman et al., 1992) and $\theta_{10}$ is the soil moisture at 10 cm below the surface.

3. Result and discussion

3.1. Model test and evaluation

The proposed model was first tested against field measurements by an EC located in west Phoenix, Arizona, USA (33.483847 °N, 112.142609 °W). The EC tower recorded four-component net radiation, 3D wind field, air temperature, humidity, CO2 concentration, and pressure at 10 Hz continuously. The original 10 Hz atmospheric measurements were processed, quality-controlled, and integrated at 30 min intervals with no gap filling. In this study, we used the measurements recorded from January 1, 2012 to May 28, 2013 (513 days) for subsequent analysis.

3.2. Model evaluation

Figure 1. The comparison of model simulation to EC observation of (a) net radiation $Rn$, (b) sensible heat $H$, and (c) latent heat $LE$, from January 01, 2012 to May 28, 2013.

The source area of the flux tower covered a typical residential area of single-family houses (Song et al., 2017a). Most lots have small front and backyard spaces with automated irrigation system. The overall land cover within 1 km² of the EC tower were 48.4% impervious surfaces (26.4% building and 22.0% road), 36.8% bare soil, 14.6% vegetation, and 0.1% water pool (Chow et al., 2014). We first calibrated the UCM by comparing the model predictions and meteorological measurements of net radiation $Rn$, sensible heat $H$, and latent heat $LE$, during the period of May 13, 2012 00:00 to May 27, 2012 23:30 (15 days). Then the calibrated parameter space is fixed and applied to the consequent study period. We then compared the model results against field measurements for the entire study period (513 days). Figure 1 shows the results of comparison for all available 30-min data points in scattered plots. The mean bias error (MBE) for $Rn$, $H$, and $LE$ are 0.3 Wm⁻², 5.1 Wm⁻², and 5.2 Wm⁻², respectively, and RMSE values of 24.7 Wm⁻², 20.8 Wm⁻², and 24.6 Wm⁻², respectively.
3.2. Biogenic CO2 exchange of urban plants

Plants in Phoenix area have distinct photosynthesis patterns, mainly consisting of C3 trees and C4 bushes or grasses. The fraction of C4 plants in Phoenix area is generally estimated to be 0.4 to 0.5 of total vegetation area (Still et al., 2003), making C4 plants a non-negligible contributor of carbon uptake. Specifically, many residential lots in the study area use a C4 plant, Bermuda grass (*Cynodon dactylon*) as the yard lawn (Chow et al., 2014). The function of C3 trees are simulated under the meteorological conditions at the roof level, while the ground level condition is used for C4 grass. In particular, the solar irradiance is the primary source of PAR, and the ratio of 0.46 (PAR to total irradiance) is used in this study. Temperatures and humidity in street canyons are obtained from the UCM predictions and used to drive the plant physiological model and estimate the soil respiration.

To aggregate the leaf level CO2 uptake to the canopy level, we obtain the vegetation fraction and its seasonal dynamics from remote sensing datasets. At the study site, the urban vegetation fraction (14.6%) was estimated from a single frame of QuickBird satellite image based on local land cover classification at 2.4 m resolution (Chow et al., 2014). Despite of its high spatial resolution, the temporal dynamics is underrepresented. In this case, we use the Copernicus Global Land Services (CGLS, https://land.copernicus.eu) 10-day 1 km2 resolution data to find the seasonal variation of vegetation coverage and LAI. The fractions of C3 and C4 plants used in plant physiological model are first set based on the derived total fraction and characteristics in phenology, and then fine-tuned for the best model performance in the prediction of total CO2 exchange. Other model parameters used in plants physiological model are listed in Table 1. The extinction coefficient, \( K_x \) in Eq. (6) is set to 0.5 for both C3 and C4 plants, according to Zhang et al. (2014).

![Figure 2. Diurnal variation of observed (black) and simulated (blue) CO2 flux at the study site. The shaded area shows one standard deviation (±1.0) from the observed or modelled monthly means.](image)

The CO2 uptake only occurs during daytime when photosynthesis is active to assimilate carbon. During hot months, the peak of canyon temperature lags several hours behind the peak of the irradiance, depending on the ET rate (Wang, 2014b). While the out-phased irradiance-temperature evolution tends to reduce the optimum rate of CO2 uptake, the active synthesis, driven by both PAR and heat, will be prolonged due to the hysteresis so to achieve overall greater daily carbon assimilation. Within the total CO2 uptake, 74% comes from C3 plant primarily due to its consistent photosynthesis rate throughout a year and the higher carbon assimilation rate at its optimum condition for growth. In contrast, C4 plants account for 26% of annual uptake with the maximum contribution at July and August for its adaptation to high temperature. The CO2 release from vegetated area is quantified by Eq. (6). The annual net CO2 exchange from plants is -668.8 gCO2 m\(^{-2}\), negative sign indicating the net uptake. Along with the CO2 releases and uptake from soil and anthropogenic sources, the diurnal variation of CO2 fluxes is shown in Figure 2, while the seasonal change is shown in Figure 3.
3.3. Soil respiration

Using variable $Q_{10}$ method in Eqs. (8) & (9), soil respiration is calculated using soil temperature and water content. The annual total soil respiration is 1147.0 gCO$_2$ m$^{-2}$. This value is very close to the observational value 1112.5 gCO$_2$ m$^{-2}$ reported in Koerner and Klopatek (2002) as the annual mean soil respiration in Phoenix residential area. However, the value is significantly lower than soil respiration obtained from low density residential area near Boston (7395.8 gCO$_2$ m$^{-2}$, Decina et al., (2016)). The difference can be possibly contributed from the dry environment in Phoenix. Most homes in arid environment used xeric landscape design to save water from irrigation. Gravels, sometimes bare soil take a large portion of xeriscaping, leading to the reduction of root activities in subsurface. Less irrigation and fast evaporation also caused water deficit in soil, lowering the biotic activeness. From the modelling perspective, $R_{25}$ needs to be adjusted for the change in land cover and climateregion.

The seasonal variation in soil respiration is primarily determined by temperature. Though the soil respiration is suppressed by reduced $Q_{10}$ during the hottest month, the greatest rate of soil respiration happens during June to August. Soil respiration accounts for over 30% of total CO$_2$ release during May to October, which is comparable with the traffic emissions in the residential area. During winter months, only ~12% of CO$_2$ release is from soil, making it the smallest source of CO$_2$. Despite of the dramatic seasonal variation, soil respiration comprises 27% of total annual release at the study site, which is greater than the total CO$_2$ released from the vegetated surface (20%). Evaporative cooling and shading provided by plants reduce the temperature in the soil, leading to an unfavoured condition for respiration. On the other hand, vegetated surface has additional CO$_2$ uptake capabilities, thus...
converting bare soil to vegetated land in housing lots might be considered as an effective way to reduce the CO₂ release in the residential area.

### 3.4. Anthropogenic CO₂ release

The anthropogenic CO₂ release is primarily determined by human activities and their working schedules. The variation is more related to the time of a day (diurnal cycle) rather than to the day of the year (seasonal variation). The diurnal variation of traffic release at the study site during workdays displayed a bimodal shape, corresponding to the two rush hours in the morning and evening. The bimodal trend becomes less apparent in weekends and holidays. Throughout a year, only a small seasonal change is observed at study site. The monthly mean release from traffic is 142.5 ± 11.0 gCO₂ m⁻² with the maximum in August at 160.9 gCO₂ m⁻² and the minimum in July at 119.2 gCO₂ m⁻². The traffic emissions constitute the largest contributor to the annual total release in the study area.

According to GPWv4 statistics, the population density is 1578 person per km² in 2010 and 1758 person per km² in 2015 in the study area. We used linear interpolation to estimate the population density in 2012 and 2013. The average annual release from human respiration is 552.7 gCO₂ m⁻² without seasonal variation, accounting only 12.3% of total CO₂ release.

### 4. Concluding Remarks

In this study, we developed a modelling approach for holistic evaluation of CO₂ exchange in cities and evaluated its performance in a typical residential area in Phoenix, Arizona. The proposed model integrates the available urban land surface schemes, plant physiological model, and the spatial gridded emission datasets. The model shows a good agreement in comparison with the in-situ measurements of CO₂ flux by an EC tower. In particular, we quantified the enhanced CO₂ absorption and release in the study area, owing to the modified in-canyon temperature, elevated CO₂ level, and irrigation schedules in the built environment. Due to the lawn management, respiration from soil releases a significant amount of CO₂ into the surface layer. The modelling framework demonstrated here will contribute to the knowledge gap from two major perspectives. First, the coupling of UCM and plant physiological model unravels the mutual influence between UHI-induced environmental stress and the presence of urban vegetation in terms of heat, moisture, and CO₂ exchanges simultaneously. Second, the comprehensiveness of the framework make it a proper tool with a high potential in carbon reduction estimation, urban planning and decision making. For example, using the model to explore the environmental co-benefits from urban greening.

Given the paucity of the available observational dataset for urban vegetation, much of the parameter space of the plant physiological functions in the current model was determined empirically from field experiment in agricultural lands. Nevertheless, the proposed model is scalable and versatile in simulating urban carbon exchange at wide spatio-temporal scales, ranging from the sub-urban scale emission driven by local meteorology, to city and regional scale CO₂ simulations when combined with mesoscale models. In the offline simulations, the gridded dataset is able to match the footprint of the EC system mounted on high towers with the high spatial and temporal resolution. When coupling with global climate models, the wide coverage of the spatial gridded dataset on urban geometry, vegetation-related metrics, and anthropogenic CO₂ emission provides a high versatility in data acquisition. It is caveated; however, modelling of urban carbon exchange is hitherto generally subjected to large uncertainties, with their sources inherited from measurement datasets or numerical parameterization schemes, or both. Therefore, further development of urban CO₂ modelling and the improvement of
their predictive skills for, e.g. projections of urban climate changes, calls for fine-resolution and high-quality urban CO₂ observations by large-scale networks of ground-based measurements and remotely sensed data products. The endeavour on observational measurements, albeit at their infancy, is progressing rapidly and shedding more and more lights to guide the model development and applications in quantifying the urban carbon exchange in the built environment.

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