



**CO₂ sequestration
by tropical urban
vegetation**

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The role of vegetation in the CO₂ flux from a tropical urban neighbourhood

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Abstract

Urban surfaces are usually net sources of CO₂. Vegetation can potentially have an important role in reducing the CO₂ emitted by anthropogenic activities in cities, particularly when vegetation is extensive and/or evergreen. Negative daytime CO₂ fluxes, for example have been observed during the growing season at suburban sites characterized by abundant vegetation and low population density. A direct and accurate estimation of carbon uptake by urban vegetation is difficult due to the particular characteristics of the urban ecosystem and high variability in tree distribution and species. Here, we investigate the role of urban vegetation in the CO₂ flux from a residential neighbourhood in Singapore using two different approaches. CO₂ fluxes measured directly by eddy covariance are compared with emissions estimated from emissions factors and activity data. The latter includes contributions from vehicular traffic, household combustion, soil respiration and human breathing. The difference between estimated emissions and measured fluxes should approximate the biogenic flux. In addition, a tree survey was conducted to estimate the annual CO₂ sequestration using allometric equations and an alternative model of the metabolic theory of ecology for tropical forests. Palm trees, banana plants and turfgrass were also included in the survey with their annual CO₂ uptake obtained from published growth rates. Both approaches agree within 2% and suggest that vegetation captures 8% of the total emitted CO₂ in the residential neighbourhood studied. A net uptake of 1.4 ton km⁻² day⁻¹ (510 ton km⁻² yr⁻¹) was estimated from the difference between the daily CO₂ uptake by photosynthesis (3.95 ton km⁻²) and release by respiration (2.55 ton km⁻²). The study shows the importance of urban vegetation at the local scale for climate change mitigation in the tropics.

1 Introduction

Effective mitigation of greenhouse gases (GHG) must be based on a good understanding of all emission sources and sinks. Carbon dioxide (CO₂), the most important GHG,

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is emitted by burning of fossil and biomass fuel associated with transport, energy use in households and public buildings, as well as by manufacturing and industry in urban centres. Emissions from electricity generation, incinerators, airports, maritime ports, etc. also contribute to the total CO₂ emissions from cities, but do not always occur within urban boundaries. The net urban CO₂ flux is further influenced by natural sources and sinks. Vegetation (urban parks, scattered trees, private gardens, lawns, etc.) removes CO₂ from the atmosphere through photosynthesis during daytime and releases a fraction of it through respiration at night, with additional release from soils and corresponding belowground activity. Finally, the metabolic release of CO₂ by human respiration is an important and growing component that cannot be neglected in densely populated cities.

Emission inventories at the city scale usually only consider CO₂ emitted from combustion sources. These emissions are typically quantified by a bottom-up aggregation process that accounts for emission factors and fuel consumption data (e.g. C40 and ICLEI, 2012; Kennedy et al., 2010) on long (annual) time scales. Depending on data availability and representativeness of emission factors, this methodology can be fairly accurate. However, it neither considers the known diurnal variations in activity levels and spatial distribution of emission sources nor does it account for fluxes associated with vegetation, soil and human respiration, even though they can be important sources or sinks.

Although urban vegetation can moderate the total urban flux of CO₂, few cities estimate the carbon sequestered by urban trees, the majority in North America, where most of the research in urban forestry has taken place to date (e.g. Aguaron and McPherson, 2012; Nowak and Crane, 2002). Estimates are based on urban tree biomass allometry and tree-growth curves or average annual growth rates. Recently the USDA Forest Service released two computer tools to calculate sequestration rates from urban trees for policy and management purposes: i-Tree Eco (Nowak et al., 2008) and the US Forest Service Center for Urban Forest Research (CUFR) Tree Carbon Calculator (McPherson et al., 2008). Both models use approaches based on biomass

inventories using as reference predominant species in US cities. This is an important limitation for the application of the models elsewhere given the diversity in tree species and climatic conditions. The robustness and validity of the model results are still under scrutiny and independent evaluations are needed.

5 The CO₂ exchange can also be evaluated using meteorological approaches, such as the eddy covariance (EC) method. EC is the only approach to measure the gas exchange directly, capturing all major and minor anthropogenic and natural emission sources and sinks. It has been widely used to investigate the carbon cycle in natural environments, such as forests, crops, grasslands, wetlands, etc. (e.g. Baldocchi, 2008).
10 Because of methodological considerations that need to be observed during its application (Velasco and Roth, 2010), the method works best at the local or neighbourhood scale, characterized by uniform land-use/cover. The EC method has been increasingly used in urban environments during the last 10 yr. Some studies have conducted simultaneous EC flux measurements over surfaces with different urban land cover within the
15 same metropolitan area to qualitatively evaluate the vegetation influence on the CO₂ flux (e.g. Coutts et al., 2007; Bergeron and Strachan, 2011; Ramamurthy and Pardyjak, 2011). Other studies, challenging the EC assumption of homogeneity (in land-use, urban morphology, and distribution of sources and sinks), have examined the impact of vegetation over complex urban surfaces consisting of different characteristics (i.e. residential dwellings, parks, university campuses, etc.) using measurements from a single
20 system in combination with a footprint analysis to delineate the area on the ground which contributes to the observation at the height of the sensor (e.g. Kordowski and Kuttler, 2010; Järvi et al., 2012). Similarly, Peters and McFadden (2012) used EC flux data in combination with sap flow and leaf gas exchange measurements to determine
25 the net CO₂ exchange by vegetation and soil in a suburban neighbourhood. Results show that urban surfaces are net sources of CO₂, in some cases with a reduced intensity during daytime due to vegetation. At a few urban sites negative daytime CO₂ fluxes have been observed during the growing season (e.g. Crawford et al., 2011; Ramamurthy and Pardyjak, 2011; Bergeron and Strachan, 2011). These sites correspond

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to suburban neighborhoods with abundant vegetation and low population density. A recent review has shown that, in general, during summer there is a strong negative correlation between daily net CO₂ exchange and vegetation fraction (Velasco and Roth, 2010). It should be noted, however, that vegetation fraction is not necessarily the most appropriate indicator for the efficiency of biogenic CO₂ uptake; biomass and density of trees stratified by species may be more appropriate parameters.

EC flux systems are also increasingly used to evaluate the accuracy of emission inventories constructed by bottom-up approaches. With proper selection of the footprint an EC system can represent a large upwind area approaching that of a complete urban neighbourhood and on the same scale as the resolution of gridded emission inventories (~ 1 km²). These evaluations are useful to verify and identify CO₂ sources and sinks. For sites with scarce green cover (< 5%) and dominated completely by anthropogenic emissions, the CO₂ flux from vegetation and soil can be neglected (e.g. Matese et al., 2009 in Florence and Velasco et al., 2009 in Mexico City). For sites with a higher proportion of vegetation the biogenic flux has been estimated using different approaches. In the case of a suburban neighbourhood in Tokyo, Japan, Moriwaki and Kanda (2004) applied reference data from a forest with similar tree species to the vegetation fraction of their site to estimate the respective CO₂ flux proportion. Soegaard and Møller-Jensen (2003) modelled the CO₂ sequestered by vegetation in the central area of Copenhagen, Denmark using a leaf-level photosynthesis model in combination with satellite-derived vegetation densities and standard meteorological data. Nemitz et al. (2002) estimated the CO₂ flux associated with plants and soil for the city center of Edinburgh, Scotland using light and temperature response curves from the literature and studies in nearby grasslands. Similarly, Christen et al. (2011) modelled the CO₂ flux from trees using photosynthesis light response curves and measurements of the dark respiration (release of CO₂ during night time) of leaves of a few representative trees in a comprehensive study carried out in a suburban neighbourhood in Vancouver, Canada. These studies report generally good agreement between directly measured fluxes and indirectly estimated emissions at the neighbourhood scale as well as

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a distinct seasonal variation in the CO₂ uptake by plants. Whilst winter uptake is practically zero, summer values demonstrate the potential of vegetation to offset 5–20 % of anthropogenic emissions, depending on the specific neighbourhood characteristics. However, on an annual basis the CO₂ capture is small and may be offset by soil respiration. A notable exception is the densely vegetated (67 %) suburban area monitored by Crawford et al. (2011) in Baltimore which was estimated to offset anthropogenic emissions by 35 % compared to the average annual uptake of six nearby forests.

All studies mentioned above have been conducted in mid-latitude cities. Similar to research into other aspects of urban ecology and metabolism, the potential for carbon sequestration by urban vegetation in tropical cities has yet to be investigated. Tropical forests are usually evergreen and therefore have a larger potential for CO₂ assimilation than boreal and temperate forests (Falge et al., 2002). Tropical cities with substantial amounts of green space and dense vegetation may benefit from strong biogenic offsets in their anthropogenic CO₂ emissions that so far have not been accounted for. To investigate whether tropical vegetation indeed absorbs more CO₂, the present study investigates the influence of urban vegetation on the CO₂ flux from a residential neighbourhood in Singapore. We use two independent approaches to quantify the direct removal of CO₂ from the atmosphere by vegetation. The first approach is based on the comparison of CO₂ fluxes measured directly by EC with emissions estimated by bottom-up approaches. The latter includes contributions from vehicular traffic, household combustion, soil respiration and human breathing. The biogenic flux is assumed to be the difference between estimated emissions and measured fluxes. A tree survey was conducted for the second approach which estimates the annual CO₂ sequestration using allometric equations and an alternative model of the metabolic theory of ecology (MTE) for tropical forests. This model predicts the growth rate of woody trees as a function of their size. Palm trees, banana plants and turfgrass were also included in the survey, but their annual CO₂ uptake was obtained from published average annual growth rates. The methodology proposed here to quantify the CO₂ sequestered by vegetation is expected to provide valuable information on the carbon dynamics at

the neighbourhood scale and contribute to the design and evaluation of climate change mitigation programs.

2 Methods

This section describes the experiment and introduces the two approaches used to estimate the CO₂ capture by vegetation. The site characteristics in terms of land cover, building morphology and climatology are presented first. A discussion of the approach using EC flux measurements and estimations by emission factors and activity data from all emission sources identified in the study area follows. Finally, the approach based on allometry and metabolic ecology is introduced. Additional information and technical details are provided in the Supplement.

2.1 Study area

The low-rise neighbourhood of Telok Kurau located within the Frankel district of Singapore was selected because of its favourable characteristics to conduct EC flux measurements. The generally flat area primarily consists of 2–3 story high residential buildings dissected by a dense network of streets. Vegetation is concentrated in a few parks, as lawns in private backyards and in the form of trees lining most streets. The area is densely populated (7491 inhabitants km⁻²) and is home to 3551 and 1994 woody and palm trees km⁻², respectively. Figure 1 includes a land cover map of the study area centered on the location of the EC flux tower (1°18'51.46" N, 103°54'40.31" E; 5 m above sea level). The area corresponds to “compact low-rise” according to the local climate zone classification proposed by Stewart and Oke (2012). With 39% the predominant land use is buildings, roads and other impervious surfaces account for 12% and 34%, respectively, while vegetation covers the remaining 15% (11% trees and 4% grass). There is little directional variation in the morphological properties and land cover, demonstrating the homogeneity of the studied

neighborhood (Fig. S1). The roughness elements, buildings and trees, have average heights of $z_b = 9.86 \pm 4.00$ and $z_t = 7.26 \pm 3.70$ m, respectively (Fig. S2). Considering their weighted plan area fraction, the mean average of the roughness elements is $z_H = 9.29 \pm 3.93$ m ($z_H = 0.78z_b + 0.22z_t$). The zero-plane displacement height $z_d = 7.34$ m and aerodynamic roughness length $z_0 = 0.80$ m were obtained from curves of z_d/z_H and z_0/z_H vs. plan area fraction of roughness elements developed by Grimmond and Oke (1999).

Because of its geographical location near the equator, Singapore's climate is characterized by perennial high temperatures, relative humidity and rainfall and low average wind speeds typical of a tropical climate. Temperatures range from $\sim 25^\circ\text{C}$ in the early morning to $\sim 35^\circ\text{C}$ in the afternoon with an annual average of $\sim 27.5^\circ\text{C}$. Relative humidity is $\sim 90\%$ in the early morning and remains above 60% during the rest of the day. The local wind climate is dominated by the reversal of wind direction between two monsoon seasons (N-NE and S-SW) and modified by land/sea breezes and a possible urban heat island circulation given Singapore's coastal setting and high proportion of urbanization. The N-NE monsoon occurs between December and March and is characterized by widespread heavy rainfall with monthly means ranging from 170 to 330 mm. Relatively drier conditions with average monthly rainfall between 130 and 160 mm are experienced during the S-SW monsoon that typically falls between May and September. The inter-monsoon seasons are characterized by relatively weak and variable wind. Given high temperatures, humidity and strong solar radiation, strong convection characterizes the daytime mixing dynamics of the atmosphere.

2.2 Approach 1: direct CO₂ flux measurements

The EC instrumentation was mounted at the top of a pneumatic mast at $z_m = 20.7$ m (Fig. S3). This height is 2.1 times z_H , probably close to the lower limit of the constant flux layer but well above the height of the roughness obstacles and sufficiently high to measure spatially representative turbulent fluxes from the underlying suburban area. The effective measurement height was 13.36 m ($z' = z_m - z_d$). The main

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instrumentation consisted of a 3-D sonic anemometer (CSAT3; Campbell Scientific, Logan Utah, USA) measuring the three-dimensional wind velocities and virtual air temperature and an open-path infrared gas analyzer (IRGA LI-7500; LI-COR Biosciences, Lincoln, NE, USA) measuring CO₂ and water vapor concentrations. Both sensors were connected to a data-logger (CR5000; Campbell Scientific, Logan Utah, USA) and signals sampled at 10 Hz. The open-path IRGA was calibrated every six months during the inter-monsoon period when the mast was retracted and the sonic anemometer head turned towards the direction representative of the new monsoonal wind regime. The CO₂ sensor was calibrated with two standard gas mixtures (Scott-Marrin Inc. 337 and 531 ppmv, National Institute of Standards and Technology) and the water vapour sensor was calibrated with the humidity data measured by a sensor (HMP45C; Vaisala) operated near the top of the mast.

Turbulent fluxes of CO₂ were calculated over 30 min periods as the covariance between the instantaneous deviation of the vertical wind component and CO₂ concentration following the guidelines described in Velasco and Roth (2010). The fluxes were corrected for the effects of air density using the Webb correction, a coordinate rotation on the 3-D velocity components was performed to eliminate errors due to sensors tilt relative to the ground, and a low pass filter was applied to eliminate the presence of a possible trend in the 30 min time series. The quality of the flux measurements was evaluated by three criteria: the statistical characteristics of the raw instantaneous measurements, the frequency resolution of the eddy covariance system through the analysis of (co)spectra, and the stationarity of turbulence statistics during the averaging period. The (co)spectra of the measured variables were inspected for selected periods. The logarithmic plot of the spectral and cospectral energy density exhibited the characteristic $-2/3$ ($-4/3$) slope in the inertial subrange, demonstrating that the system is capable of measuring turbulent fluxes of CO₂ by EC (e.g. Roth, 2000) (Fig. S4). Stationarity was determined following the criterion proposed by Aubinet et al. (2000). If the difference between the flux obtained from a 30 min average and the average of fluxes from six continuous subperiods of 5 min from the same 30 min period is less than

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60 %, the data are considered acceptable. Data coverage after data post-processing was 60 %; 23 % of data loss was due to power failures and system maintenance, 5 % due to rain, and 12 % of the data did not meet the stationarity criterion. The fraction of periods missing the stationarity criterion was larger during daytime (33–44 %) when unstable atmospheric conditions prevail, and lower (5–11 %) during stable conditions at night (Figs. S5 and S6).

The fetch of the measured flux was calculated using an analytical model based on Lagrangian dispersion modelling and dimensional analysis (Hsieh et al., 2000) applied to all 30 min periods measured during the study. If the footprint is defined as the upwind area that contributes 80 % of the total measured flux, the calculated footprint extent ranged from 388 to 722 m during day and night, respectively, averaging 567 m. No significant differences were observed as a function of wind direction (Fig. 1).

The EC flux system started operating on March 2006. Unfortunately two incidents, a lightning strike and a truck backing into a supporting guy wire that bent the middle section of the mast, interrupted the measurements. Since October 2010, however, the system has been continuously measuring fluxes of CO₂ and energy. A detailed description of the time series and diurnal patterns from the entire set of flux measurements is provided in Roth et al. (2013). The present study uses data from October 2010 to June 2012, covering 21 months of measurements representing more than one complete year of data.

2.3 Approach 1: estimation of CO₂ emissions by bottom-up approaches

Similar to other authors (e.g. Nemitz et al., 2002; Moriwaki and Kanda, 2004; Crawford et al., 2011; Christen et al., 2011), the CO₂ flux (F_C) between the urban surface and atmosphere is expressed as:

$$F_C = E_T + E_B + R_H + R_S + (R_V - P_V) \quad (1)$$

where E_T represents CO₂ emissions from vehicular traffic and E_B from households activities, R_H is the contribution from human breathing, R_S from soil respiration, R_V from

aboveground biomass respiration and P_V is the net CO_2 assimilated by photosynthesis. By convention, positive fluxes indicate emissions and negative fluxes deposition or sequestration. The first four components of F_C are estimated by bottom-up approaches based on emission factors taken from the literature and activity data collected from local databases or measured in-situ.

The difference between the measured flux by EC and the estimated emissions represents the biogenic flux from vegetation. During daylight hours this difference corresponds to P_V and during night to R_V (i.e. $P_V = 0$ during night and $R_V = 0$ during day). Sunrise (06:00–08:00 h) and sunset (18:00–20:00 h) hours are periods with low or near-zero biogenic fluxes and coincide with the morning and evening rush-hours, when anthropogenic emissions peak. Hence, we assume that the observed fluxes during these two periods almost exclusively represent contributions from E_T , E_B , R_H and R_S . The travelling speed of vehicles and size of the modelled region for the computation of E_T were therefore adjusted to match the observed fluxes during these periods (see below).

The assumption of near-zero or low biogenic flux during the sunrise and sunset transition periods is supported by two facts. Photosynthesis depends primarily on irradiance which is low just after and before sunrise and sunset, respectively. Furthermore, photosynthesis and dark respiration need acclimation periods (i.e. CO_2 capture and release does not begin immediately after sunrise and sunset, respectively). Rather, the photosynthetic rate increases only gradually after irradiance reaches the “light compensation point” to balance for respiratory carbon loss due to photorespiration and dark respiration. Similarly, dark respiration depends on metabolic activity governed by thermal acclimation (Lambers et al., 2008).

The absence of a seasonal climate and the homogeneity of the monitored neighbourhood allow the use of a single diurnal pattern of CO_2 emissions to represent the entire year. Emission differences are expected only between weekdays and weekends, due to different activity levels (mainly from traffic). The diurnal flux from each component was therefore estimated from annual average activity data available at hourly or 30 min

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intervals and compared with the average of the diurnal flux measured by EC. This comparison was limited to weekdays assuming that the CO₂ sequestration on weekdays must be essentially the same as on weekends. The diurnal biogenic flux obtained from this comparison is then extrapolated to an annual scale for a direct evaluation of the annual CO₂ sequestration estimated by the other approach proposed in the present study.

2.3.1 Emissions from vehicular traffic

CO₂ emissions from motor vehicles were estimated using the Mobile Vehicles Emissions Simulator 2010 (MOVES2010). It is the United States Environmental Protection Agency (US-EPA) current official model for estimating air pollution emissions from on-road mobile sources (US-EPA, 2010). Using as reference the diurnal footprint extents calculated previously, the vehicular emissions were estimated for three circular domains of 500, 750 and 1000 m radius centered on the EC flux tower and three average speeds: 45, 50 and 55 km h⁻¹. Further details about the modeling of the traffic emissions are provided in the Supplement.

2.3.2 Emissions from households

The use of fossil fuel in Singapore's households is limited to natural gas mainly for cooking and represents < 10% of the total energy consumption at the residential level (Energy Market Authority, 2011). The natural gas consumption depends on the property type and its average monthly consumption was obtained from Singapore Power Ltd. (2011). The number of dwellings and type within the study domain were obtained from the number of residents living in Frankel district by type of dwelling and the average household size by type of dwelling (Singapore Department of Statistics, 2011a). The CO₂ emissions from households were then calculated by multiplying the natural gas consumption by type of dwelling by the emission factor of 56 100 kg TJ⁻¹ (Eggleston et al., 2006). The total emissions were divided by the area of Frankel district (4.21 km²) to

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obtain emissions per unit area. As there is no available information about the temporal variation of natural gas consumption, we assume that it occurs mainly during daytime with three peaks during breakfast, lunch and dinner, with additional contributions from water heating during early morning and late evening.

2.3.3 Emissions from human breathing

The metabolic CO₂ released by human breathing was estimated as the product of per capita respiration rate, average CO₂ concentration of the air exhaled and population density (West et al., 2009; Prairie and Duarte, 2007). The respiration rate depends mainly on the corporal weight, age and physical activity of every person (Sherwood, 2006). Under normal breathing conditions every breath moves 7 mL kg⁻¹ of air per kg weight of a person. An adult takes an average of 15 breaths per minute whilst children have a faster respiration rate. The exhaled air contains about 4 % of CO₂ by volume. Using local ambient temperature and pressure the CO₂ density is calculated first from which the mass of CO₂ released by respiration per unit of time can be estimated. The per capita respiration rate was estimated as a function of population distribution by weight, gender and age of Frankel district residents. The details and sources of these data are provided in the Supplement.

2.3.4 Emissions from soil respiration

The empirical “ Q_{10} model” based on van’t Hoff’s equation was used to estimate the CO₂ release by soil respiration. This model assumes that soil respiration responds only to temperature changes in the absence of soil moisture limitations:

$$R_S = R_{10} Q_{10}^{\frac{(T_S - 10)}{10}} \quad (2)$$

R_{10} is the specific respiration rate at 10 °C, Q_{10} the increase in respiration rate per 10 °C increase in temperature, and T_S the soil temperature in degrees Celsius. Despite the

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fact that this model has no rational basis and does not consider other important controls, such as soil carbon content and root-growth phenology, it has been extensively used and provides realistic simulations of soil carbon exchange over long time periods (Reichstein and Beer, 2008). This was recently confirmed with the finding of an almost universal Q_{10} value of $1.4 \pm 0.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ across climate zones and ecosystem types (Mahecha et al., 2010). The global database of soil respiration reports an average R_{10} of $2.13 \mu\text{mol m}^{-2} \text{s}^{-1}$ for all types of ecosystems (Bond-Lamberthy and Thomson, 2010) with values for 13 tropical sites ranging from 0.46 to $2.07 \mu\text{mol m}^{-2} \text{s}^{-1}$. We selected the maximum rate knowing that respiration rates in urban soils tends to be higher than in natural ecosystems as a consequence of constant maintenance, watering and fertilization. The diurnal pattern of T_S was calculated from a polynomial correlation with air temperature (T_a) (Fig. S11). This correlation was obtained from continuous measurements of T_S over a 4 months period. The resulting average daily emission rate of $4.08 \mu\text{mol m}^{-2} \text{s}^{-1}$ ($179.4 \mu\text{g m}^{-2} \text{s}^{-1}$) is similar to that reported for other tropical regions (Kosugi et al., 2008).

2.4 Approach 2: estimation of annual CO₂ sequestration by vegetation based on allometry, metabolic ecology and average growth rates

The second approach intends to be an independent validation of the first approach. Here the annual CO₂ sequestration by vegetation is calculated from current biomass (carbon stock) and growth rates using allometric equations. An inventory of the vegetation within the study domain is needed for this approach. A comprehensive survey was therefore conducted within a 500 m radius domain centered on the EC tower. Location, height and girth at breast height (GBH) were measured for 2789, 1566 and 244 woody trees, palm trees and banana plants, respectively following guidelines for urban forest inventories (Climate Action Reserve, 2010). Thirty-one and 14 species of woody and palm trees were identified. Shrubs and herbs were omitted due to their insignificant contribution to total biomass (Nowak, 1993) and lack of allometric formulas. The growth

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rate of woody trees was obtained from an alternative model of the metabolic theory of ecology (MTE) for tropical forests (Muller-Landau et al., 2006). For palm trees and banana plants tree-growth curves or average annual growth rates from the literature were used. For turfgrass we used average annual rates of biomass production. Such estimation of annual CO₂ sequestration at the scale of individual vegetation types allows further insight into the importance different types can potentially have for climate change mitigation.

The following sections describe the equations and methods used to estimate the dry biomass, CO₂ storage and sequestration. Emphasis is on woody trees because of their number and importance in the CO₂ cycle. The main characteristics of the most abundant species of woody and palm trees within the study area are presented in the Supplement together with the allometric equations and growth rates used for palm trees (Tables S2 and S3).

2.4.1 Dry biomass and CO₂ storage estimation for woody trees

CO₂ storage refers to the accumulation of biomass as trees grow over time. The amount of CO₂ stored by an urban tree is proportional to its dry biomass and influenced by management practices (McPherson, 1994). The common method to estimate dry biomass is by allometric equations based on parameters such as GBH, tree height, wood specific density (WSD), tree age and condition, and forest type. The methodology to convert dry biomass into stored CO₂ is well established (e.g. summary in Aguaron and McPherson, 2012).

Because of a lack of species-related biomass information for tropical urban trees, we tested different allometric equations to calculate the aboveground dry biomass (AGB), including boles and branches, for each surveyed tree. The equations used were developed for forest inventories of primary (Yamakura et al., 1986; Brown, 1989; Carvalho et al., 1998; Araujo et al., 1999; Chave et al., 2005) and secondary (Ketterings et al., 2001; Hashimoto et al., 2004; Kenzo et al., 2009; van Breugel et al., 2011) tropical forests, as well as urban trees in California, USA (Aguaron and McPherson, 2012;

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McPherson et al., 2008). These equations have in common the use of GBH as the only input variable, with the exception of Chave et al. (2005) and van Breugel et al. (2011) who also consider WSD. Biomass predictors for tropical forests in decreasing order of importance are GBH, WSD, tree height and forest type (Chave et al., 2005). According to Brown (2002) and other authors, the inclusion of height in allometric equations can increase the precision of biomass values. However, similar to forests, tree height measurements are often difficult to make in urban environments. In our case we used a laser rangefinder (TruPulse 200; Laser Tech Inc.) with an accuracy of ± 30 cm for targets at 75 m of distance, but the urban morphology, obstacles (e.g. houses, parked vehicles, other trees, etc.) and the narrow size of streets often prevented accurate measurements. A total of 11 allometric equations were applied to each tree. As discussed in the results section below, the best predictive allometric equations for Singapore's trees and weather condition were those proposed by Chave et al. (2005) and van Breugel et al. (2011) for primary and secondary tropical moist forests, respectively:

$$AGB = \rho \exp \left(-1.499 + 2.148 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3 \right) \quad (3)$$

$$AGB = \exp \left(-1.130 + 2.267 \ln(D) + 1.186 \ln(\rho) \right) \quad (4)$$

where AGB is in kg, ρ is WSD in g cm^{-3} and D the diameter at the breast height in cm derived from GBH. An average WSD = 0.69 g cm^{-3} was obtained for all trees and species within a 350 m radius domain (Table S2). Leaf biomass (LB) was calculated following the relationship proposed by Chave et al. (2008) for moist tropical rain forests:

$$LB = \exp \left(-5.136 + 2.882 \ln(D) - 0.156 \ln(D)^2 \right) \quad (5)$$

where LB is in kg and D in cm. Root biomass (RB) was obtained from the relationship between AGB and RB proposed by Cairns et al. (1997), where AGB and RB are both in ton ha^{-1} :

$$RB = \exp(-1.085 + 0.9256 \ln(AGB)) \quad (6)$$

To compare the performance of existing allometric equations for urban trees with equations developed for tropical forests, Aguaron and McPherson's (2012) equation derived for trees in Sacramento, California, and the general equation for broadleaf trees used by CUFR Tree Carbon Calculator (McPherson et al., 2008) are also used. Finally, the sum of AGB, LB and RB is converted to carbon by multiplying by 0.50 (i.e. 50% of dry biomass corresponds to carbon) and then to CO₂ by multiplying by 3.67 (ratio of molecular weights of CO₂ and carbon) (e.g. Aguaron and McPherson, 2012).

2.4.2 Application of MTE for allometric scaling of woody tree growth

MTE explains the physiology and performance of individual organisms through basic principles of physics, chemistry and biology (West et al., 1997; Brown et al., 2004). For trees in particular, it predicts specific relationships between tree size, growth and mortality under the basic assumption that biomass growth is proportional to gross photosynthesis. Although there is considerable debate about its validity and consistency, MTE appears to predict reasonably well both tree diameter growth and biomass production (e.g. Enquist and Niklas, 2001; Ernest et al., 2003). For tropical forests there is no universal scaling relationship between biomass growth and tree size. Muller-Landau et al. (2006) proposed a power-function relationship to predict the growth rate of tropical forests based on the basic assumptions of MTE and empirically fitted exponents. We use this alternative model of MTE to evaluate the annual CO₂ assimilation by woody trees in our study area.

MTE proposes that the scaling of metabolic rates with tree size depends only on the potential for resource uptake and redistribution. Muller-Landau et al. (2006) suggested that the availability of resources is also an important factor to consider. For plants, light is the limiting resource, and therefore a forest tree's gross photosynthetic rate is proportional to its crown area times the light reaching its crown (i.e. plants in shaded

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areas are farther from their maximum potential metabolic rate rather than plants in open areas). Instead of deriving relationships for tree size with crown area and light from basic principles, Muller-Landau et al. (2006) used empirically observed relationships obtained from tree inventories of 10 tropical forests with different characteristics. The expected D at time t of a tree with initial diameter D_0 can be expressed as:

$$D_t = \left[D_0^{1-c} + r(1-c)t \right]^{1/(1-c)} \quad (7)$$

where r and c are the growth scaling parameters for a particular forest and three different size ranges: all trees, small trees ($D < 20$ cm) and large trees ($D \geq 20$ cm). The growth scaling parameters used here correspond to the scaling parameters reported by Muller-Landau et al. (2006) for two forests in neighbouring Malaysia: Pasoh Forest Reserve in peninsular Malaysia and Lambir Hills National Park in Sarawak which both represent climatic conditions similar to Singapore. For Pasoh and Lambir, two and one set of parameters are available, respectively which were obtained from forest censuses at 5-yr intervals. D_t at $t = 1$ yr was calculated for each tree in the study area using scaling parameters from each set and for the three different size ranges defined above. The average D_t of each tree from the three sets of scaling parameters was used to estimate the biomass production after one year. The CO_2 storage of each tree was then recalculated using D_t in the 11 allometric equations mentioned above and the annual biomass production estimated as the difference between the CO_2 storage computed with D_t and the initially measured D .

Production of biomass consumes the majority of the carbon assimilated which is not returned to the atmosphere by dark respiration. The rest is used by physiological processes associated with the maintenance, reproduction and defense of the plant. The carbon associated with these mechanisms is difficult to measure. Processes include the carbon invested in understory growth and in reproductive organs (i.e. flowers, seeds and fruits), carbon exuded from roots or transferred to mycorrhizae, and carbon lost by emission of volatile organic compounds (e.g. isoprene and monoterpenes) as

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defense mechanisms against adverse climatological conditions, pests and herbivores (Luyssaert et al., 2007). According to Clark et al. (2001) the carbon associated with these mechanisms can easily amount to 20% of the biomass production in tropical forests which is accounted for by a factor of 1.2 in the present biomass production estimates.

2.4.3 Allometric equations and growth rates for palm trees

The dry biomass of each surveyed palm tree was calculated using allometric equations. As for tropical woody trees, the available equations in the literature are few and only one was found for the species identified in Telok Kurau. For the rest, we used equations of palms with similar appearance and characteristics, such as height, girth and height to girth ratio. Palms whose species could not be identified or their height exceeded the range imposed by the equations were classified as generic palms. The biomass of these palms was calculated using the equation for Manila palm, which thus became the most abundant species. Unlike woody trees, palms do not grow in diameter, only in height; hence allometric equations for palms use only tree height as input variable. The total dry biomass was converted to carbon and CO₂ in the same way as for woody trees, but considering a carbon content of 42% (Gehring et al., 2011). The annual biomass production was estimated from growth rates and curves published in the literature (Table S3). With the exception of coconut palms for which respective urban data is available, the growth rates correspond to palms in plantations or natural forests. Similar to woody trees, a factor of 1.2 was applied to the annual biomass production to account for all other physiological mechanisms associated with CO₂ consumption.

2.4.4 Allometric equations and growth rates for banana plants

Similar to other plants, the CO₂ stored by banana plants is proportional to its dry biomass which depends on its phenology stage. During the growing phase, the biomass is mainly associated with leaves and pseudostem, the corm and bunch

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become important at flowering, while bunch and pseudostem are the main components at harvest. A total of 244 plants was surveyed within a 500 m radius domain, which represent 311 plants km⁻¹. Their total dry biomass was calculated using the allometric equations for banana plants before and after flowering (i.e. vegetative and harvest stages) developed by Nyombi et al. (2009). The stage of each plant was determined according to the volume of its pseudostem as proposed by Yamaguchi and Araki (2004). The carbon and CO₂ storage were calculated in the same way as for woody and palm trees, but using a carbon content of 39.7 % (Gonzalez et al., 2012).

The average cycle of a banana plant is ~ 17 months. In plantations the annual turnover rate of dry biomass ranges from 70 % to 90 % (Yamaguchi and Araki, 2004). The annual biomass production was calculated considering the lowest turnover rate and 7 kg as the total dry biomass of a mature plant. The CO₂ capture was conservatively estimated assuming that all plants reach the harvest stage.

2.4.5 Estimation of biomass and CO₂ uptake by turfgrass

Investigations of carbon sequestration in turfed landscapes are rare. The few available studies only evaluate turfgrass in temperate cities. No studies have been conducted in tropical environments. Biomass, CO₂ storage and annual sequestration were calculated using average estimates from urban lawns in US cities and applied to the entire area covered by vegetation (i.e. trees and grass) within the study domain. Guertal (2012) reports average estimates of carbon content for turfgrass verdure and roots of 100 and 139 g m⁻², respectively which represents a total of 560 g m⁻² of dry biomass and 877 ton CO₂ km⁻² (considering a carbon content of 42.7 %). The biomass production was conservatively estimated using the average annual production of 547 g m⁻² of dry biomass found by Jo and MacPherson (1995) for lawns in Chicago. This rate represents an annual CO₂ uptake of 858.5 ton km⁻² and considers annual turnovers of 50 % and 34 % of verdure and roots biomass, respectively.

3 Results

The CO₂ flux and emissions measured and estimated by the EC and bottom-up methods, as well as their difference (Approach 1) are discussed at the beginning of this section, followed by the CO₂ storage and sequestration results using allometric equations and MTE (Approach 2). The uncertainties from assumptions and scaling parameters chosen to estimate the dry biomass and growth rates are emphasized. The reconciliation of the two approaches is discussed at the end of the section.

3.1 Approach 1: estimation of the CO₂ sequestration by vegetation as the difference between measured EC fluxes and estimated emissions from bottom up approaches

The average diurnal pattern of the measured flux and emission profiles by source type is shown in Fig. 2. As noted above, the CO₂ assimilated by photosynthesis and released by dark respiration lead to different diurnal patterns in the observed CO₂ flux by EC and the sum of emissions estimated by bottom-up approaches. The diurnal pattern of the measured CO₂ flux is similar to that reported for suburban neighbourhoods in mid-latitude cities during the growing season (Velasco and Roth, 2010). Similar to neighbourhoods with extensive vegetation and few emission sources, the fluxes reported here occasionally become negative around midday, more frequently so during the N-NE monsoon season (Fig. S12). The presence of negative fluxes during this period might be due to a small public park located 325 m to the WNW of the EC tower (Fig. 1). Generally little seasonal variation in the diurnal pattern of CO₂ flux can be observed (Fig. S12). Since Singapore's climate is characterized by perennial high temperature and relative humidity, rainfall throughout the year and evergreen vegetation, the observed variability is mainly due to changes in wind direction and associated variations in the distribution of emissions sources and sinks in the flux footprints.

An interesting feature, also observed in tropical rainforests (e.g. Kosugi et al., 2008), is the asymmetry in the diurnal pattern of CO₂ exchange. This is a consequence of

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stronger assimilation rates in the morning than in the afternoon. As a mechanism to prevent excess water loss through evapotranspiration under severe environmental conditions (i.e. high radiation, temperature and vapour pressure deficit), leaves experience patchy stomatal closure which results in a drastic depression of photosynthesis (Kamakura et al., 2011). Given that leaves at the top of the canopy are exposed to harsher conditions, this photosynthetic inhibition is more significant in tall trees.

In general, Telok Kurau is a net CO₂ source of 6502 ton km⁻² yr⁻¹. On weekdays the average daily flux is 17.9 ± 15.1 ton km⁻². An important characteristic of the CO₂ plume from urban areas is its high variability from one day to another which is also the case in the present study as demonstrated by the large hourly standard deviations plotted on Fig. 2. Although nocturnal anthropogenic emissions are relatively low, fluxes at night are higher than during the day as a consequence of the abundant and active biomass which counteracts the daytime fluxes.

This is contrary to the majority of CO₂ flux observations over urban surfaces reported in the literature (Velasco and Roth, 2010). Night(day) time fluxes represent 47 % (29 %) of the total daily flux. The remaining fraction corresponds to fluxes during the sunrise and sunset transition periods. Their contributions are similar with 11 % and 13 %, respectively of the daily flux. The difference between directly measured fluxes and estimated emissions during these two transition periods is very small. As explained before, these periods were used to adjust the emission estimates assuming near-zero biogenic flux.

Because of difficulties to evaluate the accuracy of emission factors and many of the activity data, emission estimates were constrained by traffic emissions. Errors in emissions from natural gas burning, human breathing and soil respiration will therefore accumulate in traffic emission estimates. Traffic emissions were calculated for the 500 m circle domain considering traveling speeds of 45 and 50 km h⁻¹, and selected accordingly to obtain the best agreement with the observed flux. The latter is the speed limit on the roads within the study area and was used to calculate the emissions throughout the day, except during the morning and evening rush hours. Between 06:30 and 08:30

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h the best agreement was obtained using a travelling speed of 45 km h^{-1} and considering one standard deviation for the traffic volume average. Similarly, from 18:00 to 20:30 h the traffic emissions for a traveling speed of 45 km h^{-1} fit better. Slower speed is realistic considering more intense traffic during these two periods. The need to include one standard deviation in traffic volume average during the morning rush hour is explained by a larger fetch reaching a number of heavily transited roads during this period. The CO_2 uptake was very sensitive to small changes in the emission estimates. For example, if a constant traveling speed of 45 km h^{-1} was used throughout the entire day, traffic and total emissions would experience a small increase of 4.2 % and 2.7 %, respectively, but the CO_2 uptake a significant increase of 37.9 %.

On a daily basis, all emissions estimated by bottom-up approaches amount to 19.3 ton km^{-2} . The difference between measured fluxes and estimated emissions is -1.4 ton km^{-2} . The negative value indicates a net CO_2 assimilation by vegetation. During daytime vegetation captures 4.0 ton km^{-2} by photosynthesis, but releases 2.6 ton km^{-2} by dark respiration at night. This means that 65 % of the CO_2 sequestered during daytime is returned to the atmosphere at night. This ratio is exactly the same as reported by Luysaert et al. (2007) for tropical humid evergreen forests in a synthesis study based on data from 29 different forests. This finding is a good indicator of the reliability of the approach proposed here.

Of all CO_2 emission sources vehicular traffic was, as expected, the main contributor in Telok Kurau. Even though only 25 % of Singapore's dwellers commute by passenger cars (Singapore Department of Statistics, 2011b), they are responsible for almost half of the total emissions in Telok Kurau (Fig. 3). Whilst per capita metabolic emissions from respiration represent a tiny fraction of the total flux, the high population density makes human respiration the second largest source of CO_2 . Soil respiration is the main contributor in natural environments. In cities, however, its contribution is reduced because of the prevalence of impervious surfaces. In our case the release of CO_2 from soil represents 12 % of the total flux. Similar to other residential sites with benign weather, household emissions are restricted to natural gas burning for cooking, making

emissions from households the least important emission source. Vegetation closes the partitioning of the total CO₂ exchange. Photosynthesis captures 22 % of the CO₂ released to the atmosphere, but dark respiration returns 14 %, resulting in a net uptake of 8 % of the total emissions (Fig. 3).

3.2 Approach 2: estimation of the annual CO₂ sequestration by vegetation using allometric equations, metabolic ecology and growth rates

As mentioned earlier, this approach produces only annual averages of carbon sequestration and cannot be applied to evaluate the diurnal variability. The magnitude of the annual CO₂ sequestration estimated from this approach depends directly on the allometric equations used to calculate the dry biomass (Fig. 4). The dry biomass of woody trees is clearly larger when equations for primary forests are used (2919 to 3417 ton km⁻²) compared to those developed for secondary (1343 to 1956 ton km⁻²) and urban forests which yield similar results (Fig. 4a). The urban forest equations represent trees common to the USA and not the tropics. These results are included here to demonstrate the potential error associated with their use and are not considered in further calculations.

Using as reference the trees age/size range for each type of forest, the allometric equations for primary (secondary) forests are expected to be the most appropriate ones for biomass estimation of old/large (young/small) trees. Hence trees within the sampling domain were divided into large and small ones based on their *D* (diameter at the breast height) size (following Muller-Landau et al., 2006) and applying allometric equations for primary and secondary forests which were selected as follows. The average dry biomass from all five equations tested for primary forests is 3174 ± 289 ton km⁻² (Fig. 4a). The equation from Chave et al. (2005) shows the smallest deviation from the average (+5 %) and was therefore selected to calculate the dry biomass of the large trees. This equation was obtained from a synthesis study of many sites across the tropics and includes WSD as a variable. This is in contrast to other equations which were developed for specific forests or from a small number of study sites only

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and without considering WSD. Similarly, from among the four equations tested for secondary forests, the equation proposed by van Breugel et al. (2011) provides the estimate closest to the average and also includes WSD as a variable.

5 A total dry biomass of 3288 ton km^{-2} is calculated for all woody trees. Although large trees represent only 36.8% of all trees, they contain 95.3% of the tree biomass and thus carbon. Boles and branches account for 83.4% of the dry biomass, and roots and leaves 15.4% and 1.2%, respectively. This biomass allocation is similar to that reported in the literature for tropical forests (e.g. Poorter et al., 2011). Adding the dry biomass of palm trees, banana plants and turfgrass we obtain a total dry biomass of 3484 ton km^{-2} . This represents a total CO_2 stock of 6337 ton km^{-2} , of which woody trees store 95.2%, palm trees 2.7%, turfgrass 2.1% and banana plants 0.004%. No similar data is available for other tropical cities, only limited results for CO_2 stored in private gardens in Indian and Indonesian cities were found (Kumar, 2011; Roshetko et al., 2002). Considering AGB only, reported CO_2 pools ranged from 5872 to $13212 \text{ ton CO}_2 \text{ km}^{-2}$.
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Growth predicted by MTE depends strongly on scaling parameters. Muller-Landau et al. (2006) found no universal scaling relationship between growth and size for trees in different forest types. We believe the alternative model of MTE for tropical forests works well in the case of Singapore because (i) the scaling parameters from nearby forests of Malaysia are representative of local conditions and (ii) it may provide good scaling approximations for individual trees which grow in the absence of competition as is the case for urban trees. However, we are aware that ontogenetic variations in physiology and allometry, even amongst individuals of the same species, may severely influence growth rates. We consider that the best predictions in our case are obtained using separate scaling parameters for small and large trees. The forest censuses in Pasoh and Lambir reported a slightly slower diameter growth in larger trees in comparison with other tropical forests (Fig. 2 in Muller-Landau et al., 2006). As shown in Fig. 4c, the dry biomass of all woody trees estimated using scaling parameters for all sizes of trees combined is smaller than using individual scaling parameters for small and large trees.
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When allometric equations for primary and secondary forests are used simultaneously to calculate the dry biomass, the difference in the annual CO₂ sequestration by all woody trees is 77 ton km⁻² yr⁻¹ (horizontal bars marked Mix in Fig. 4c).

The annual CO₂ sequestered by woody trees, including the correction factor that accounts for other processes associated with carbon consumption, is 342.5 ton km⁻². Palm trees sequester 26.7 ton km⁻², turfgrass 128.8 ton km⁻² and banana plants 2.2 ton km⁻², for a total of 500.1 ton km⁻². This value may be slightly higher if contributions from small bushes and other herbaceous plants are considered. On average every woody tree captures 96.4 kg CO₂ yr⁻¹. The median value is 17.1 kg CO₂ yr⁻¹ which shows the importance of large trees. Large and small woody trees capture on average 243.7 and 10.6 kg CO₂ yr⁻¹ tree⁻¹, respectively. This means that 23 small trees are needed to replace one large tree to match its sequestration potential. Similarly, 18 palms sequester the same amount of CO₂ as one large woody tree. Figure 5 shows the spatial distribution of CO₂ storage and annual sequestration potential of the surveyed trees. Trees with highest stocks and sequestration rates are generally located along the main roads and in a small park. Trees along secondary roads are usually small and therefore have smaller sequestration rates.

The large difference in CO₂ assimilation rates between small and large trees is explained by differences in stem volume and foliage. Palm trees are limited by the small WSD of their stems. The WSD of an average palm is 0.31 g cm⁻³ (Baker et al., 2004), less than half of that of woody trees. If palm trees were planted, coconut and oil palms would be the recommended species. They grow faster than other species and their large fruit production enhances the carbon uptake. At the present site coconut and oil palms capture on average 51.5 and 176.3 CO₂ yr⁻¹ tree⁻¹, respectively while all other palms species capture only 6.5 kg CO₂ yr⁻¹ tree⁻¹. Roupsard et al. (2007) also found that coconut plantations under optimal growing conditions display gross primary productivities similar to those of tropical humid evergreen forests.

Compared to woody trees, the CO₂ uptake by banana plants could be neglected. However, it provides insight into the contribution small species have in the urban carbon

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cycle. In contrast, the carbon uptake by turfgrass is significant. Its contribution represents 25.6 % of the total CO₂ uptake, though a full assessment of the net CO₂ capture needs to consider emissions associated with its management. Previous studies have evaluated the potential of turfgrasses to capture CO₂ concluding that irrigation and fertilization enhance CO₂ sequestration but can also increase emissions of CO₂ and other greenhouse gases. For example, Townsend-Small and Czimczik (2010) found that the CO₂ emissions from fossil fuels used during maintenance (e.g. mowing) may offset the turfgrass sequestration.

3.3 Comparison of approaches

Figure 6 summarizes the results from both approaches to estimate the biogenic CO₂ exchange. The first is based on the difference between directly measured fluxes using EC and the sum of emissions estimated by bottom up approaches, while the second uses allometric equations and MTE. The annual CO₂ sequestration of 510.1 ton yr⁻¹ extrapolated from the daily uptake obtained from the first approach closely matches the 500.1 ton yr⁻¹ estimated by the second approach. However, the potential uncertainties, mainly present in the second approach, prevent a conclusive cross-validation of the two independent methods.

The main sources of uncertainty of both approaches have been described above. A quantification of the errors is difficult. The errors in the annual EC estimates are significantly smaller than the observed day-to-day variability in urban environments, as demonstrated in previous work (Velasco et al., 2005). Recent evaluations of emission inventories suggest that emissions from combustion sources are properly predicted by existing emission factors if accurate activity data is used (e.g. Velasco et al., 2009; Smit et al., 2010). Small errors are expected in the models used to estimate emissions from human breathing and soil respiration; however, their contribution to the total emissions is small. In addition, the area “seen” by the EC flux system (footprint) and the one used for estimating the bottom-up emissions (within a 500 m circle centered on the EC tower location) do overlap but are not exactly the same. This potential error source

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however is minimized by choosing a study area with homogeneous land cover and CO₂ source/sink distribution (Fig. S1).

The second approach, in contrast, is prone to a number of uncertainties. First, and possibly most relevant, is the use of allometric equations and growth rates developed for trees in natural or non-urban environments. Research suggests that urban environments impact tree growth, carbon allocation and phenology. Allometric equations developed using trees in traditional forest settings may therefore misrepresent urban trees (McHale et al., 2009). Second, the use of biomass production rates for cool-season instead of warm-season turfgrasses may not properly represent warm tropical conditions. Third, the scaling factors used in the MTE model to estimate the growth rates of woody trees, as well as the classification of trees into large and small to determine which allometric equation to use, may have a significant influence on the final estimations. For example, if large trees were considered as those with a $D > 30$ cm for the calculation of dry biomass, the CO₂ sequestered by all woody trees would be 7.9% smaller. Finally, mistakes in the species identification during the tree survey, as well as uncounted trees in private properties are additional sources of uncertainty.

The results from the first approach are more robust and defensible. However, only the second approach provides the opportunity to evaluate the contribution from different types of vegetation to offset anthropogenic emissions as shown in Fig. 6. Currently, there is no method that can directly evaluate the CO₂ uptake from vegetation. All methods mentioned in the introduction rely on indirect estimations at some point. Sensors capable of measuring stable isotopes in CO₂ (¹²C and ¹³C) at high frequency are necessary to be able to directly measure the biogenic contributions to the total CO₂ flux. In this respect recent improvements made in Cavity Ring Down Spectrometry to measure carbon isotopic ratios are promising (Vogel et al., 2012).

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4 Conclusions

This study shows that vegetation in residential areas of tropical cities can offset a significant fraction of the anthropogenic CO₂ flux emitted within a specific neighbourhood depending on the intensity of the local anthropogenic emission sources and biomass characteristics. The CO₂ sequestered by vegetation in the present study, however, cannot be extrapolated to the whole city. Although results are only valid for the particular neighbourhood investigated, they provide valuable information on the importance of urban vegetation for climate change mitigation strategies. For example, the data demonstrate the importance of large trees for GHG management (Figs. S13 and S14). Tree-planting programs should also consider the growth rate and potential carbon uptake when selecting type and species. Priority must be given to woody trees over palms and ornamental plants which sometimes are preferred for aesthetic reasons. Similarly, large trees should not be replaced by young trees and palms, as it is the tendency along secondary roads in Singapore.

The influence of vegetation on the urban CO₂ flux may be even higher if the indirect effects from local cooling through shading and transpiration are included. Local cooling results in lower demand for air conditioning, which can reduce the emission of GHG if the energy used to run the cooling devices is obtained from fossil fuel sources (Akbari, 2002). A complete assessment of the benefits and costs of urban vegetation needs to consider all environmental, economic, social and cultural aspects as suggested by Pataki et al. (2011). Here, we have quantified the reduction in the net CO₂ flux by vegetation considering only emissions due to activities occurring within the boundaries of the study domain. External emissions arising from local activities, such as electricity generation, are not considered.

Singapore has a national per capita emission of 6.8 ton CO₂ yr⁻¹ (Velasco and Roth, 2012). When limiting emissions to the Telok Kurau neighbourhood and considering only emissions from combustion sources (i.e. vehicular traffic and households) as is usually the case for emissions inventories at the city scale, per capita emission is only

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688 kg yr⁻¹. This suggests that the majority of Singapore's GHG emissions have their origin outside residential areas. This is consistent with the local emissions inventory, which shows that 81 % of the CO₂ emissions come from industry and electricity generation (Ministry of the Environment and Water Resources, 2008) which are concentrated in industrial parks. Considering all CO₂ sources and sinks within the study region, the per capita CO₂ emission is 874 kg yr⁻¹ (human breathing and soil respiration add 147 and 107 kg person⁻¹ yr⁻¹, respectively, but vegetation absorbs 68 kg person⁻¹ yr⁻¹). This value can be compared with the per capita emission of 16 ton yr⁻¹ associated with the production of all consumed goods, including those produced overseas, (Schulz, 2010). The present vegetation in Telok Kurau therefore reduces the carbon footprint of the residents living in this low-rise residential neighbourhood of Singapore by only 0.4 %.

Supplementary material related to this article is available online at:
**[http://www.atmos-chem-phys-discuss.net/13/7267/2013/
acpd-13-7267-2013-supplement.pdf](http://www.atmos-chem-phys-discuss.net/13/7267/2013/acpd-13-7267-2013-supplement.pdf)**

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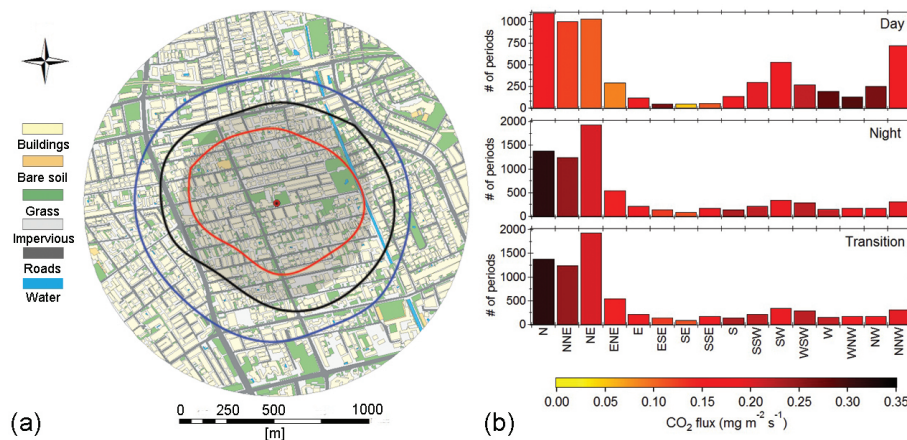


Fig. 1. (a) Average footprints encompassing 80 % of the EC flux source area overlaid on a land cover map centered on the EC tower location (red dot) and (b) number of EC 30 min periods (after data post-processing and quality control) during the study period as a function of wind direction for three periods of the day. Red, blue and black contours in (a) are average footprints for Day (08:00–18:00 h), Night (20:00–06:00 h) and the complete diurnal course, respectively. Transition period in (b) is defined as two hours centered on sunrise and sunset, respectively. Shaded area in (a) represents the 500 m radius domain used for estimating the bottom-up emissions. The colour of bars in (b) indicates the average CO₂ flux observed for each wind direction sector plotted.

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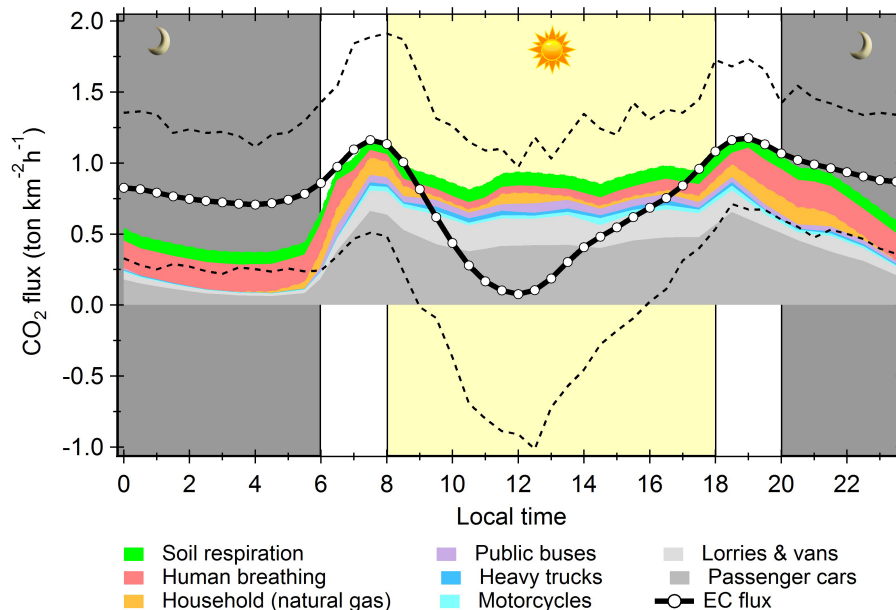


Fig. 2. Total CO₂ flux measured directly by EC and the sum of emissions from 8 source types within a 500 m circle centered on the EC site estimated by bottom-up approaches. The difference between the two methods is related to the influence of vegetation on the CO₂ exchange and is positive during nighttime because of dark respiration and negative during the day because of uptake through photosynthesis. Data are weekday averages. Dashed lines are ± 1 standard deviation from the EC flux average and give an indication of the day-to-day variability at every hour of the day.

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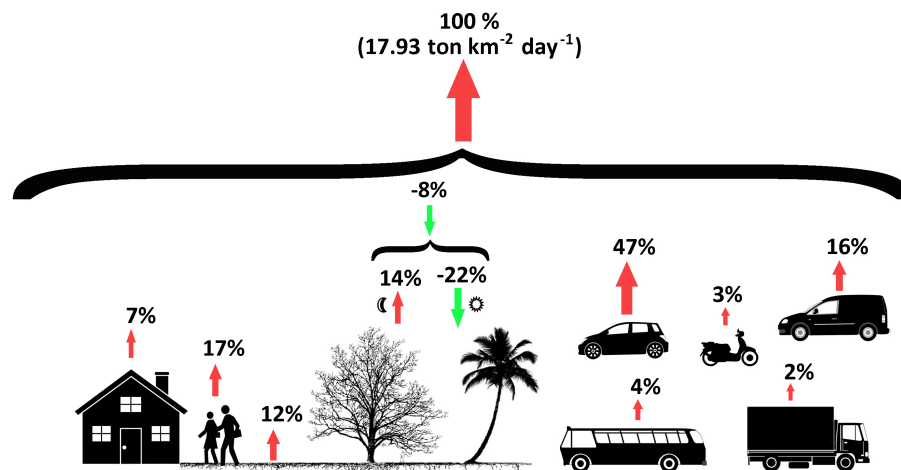


Fig. 3. Partitioning of weekday CO₂ exchange in the low-rise residential neighbourhood of Telok Kurau, Singapore, according to emission sources (red arrows) and sinks (green arrows) calculated from direct EC flux measurements and bottom-up approaches. Vehicular traffic is the main contributor of CO₂ to the atmosphere: Passenger cars (47%), motorcycles (3%), commercial vehicles (16%), transit buses (4%) and trucks (2%) contribute a total of 72%. Other emission sources are in descending order of importance: Human respiration (17%), soil respiration (12%) and household emissions (7%) for a total of 36%. Vegetation captures 22% of the total emissions during daylight hours, but releases 14% at night resulting in a net CO₂ capture of 8%.

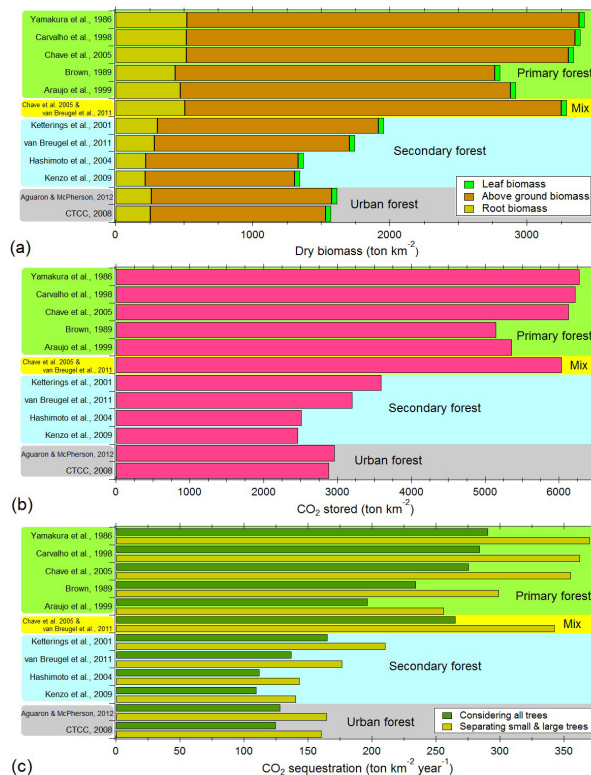


Fig. 4. (a) Dry biomass, (b) CO₂ stored and (c) annual CO₂ sequestration by all woody trees in Telok Kurau calculated from allometric equations and metabolic theory of ecology for different forest habitats. The horizontal bars marked “Mix” correspond to estimations when trees were separated into large and small to calculate their biomass using allometric equations for primary and secondary forests, respectively. Biomass production was calculated from Eq. (7) using scaling parameters depending on tree size (i.e. small and large). Annual CO₂ sequestration was calculated as biomass production multiplied by a factor of 1.2 to incorporate other physiological processes associated with carbon consumption.

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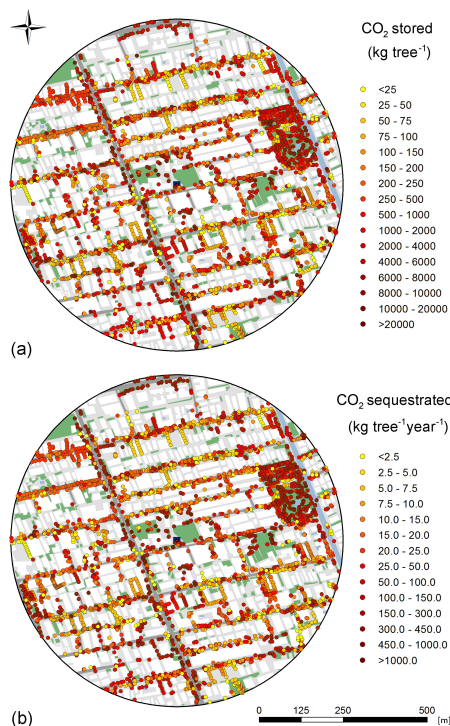


Fig. 5. (a) CO₂ stock and (b) sequestration rates for all inventoried trees (woody, palm trees and banana plants) within the sampling domain. Blue square in center of panel is location of EC tower. The similarity in spatial distribution of both parameters is expected given that they strongly depend on tree size. The important contribution to the carbon cycle by large trees located along main roads and in a small park towards the WNW is evident.

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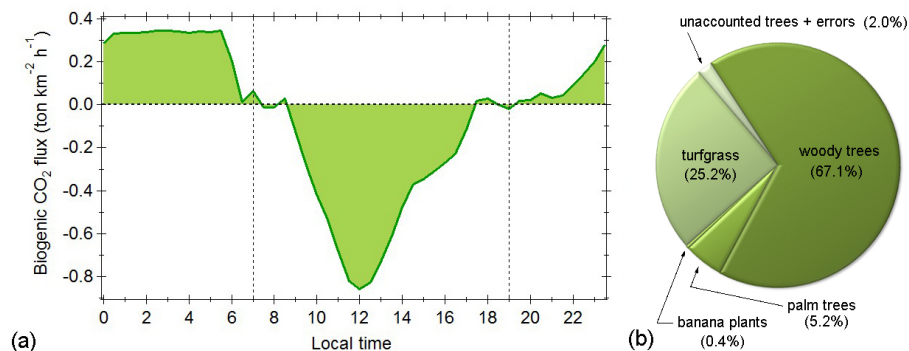


Fig. 6. (a) Diurnal pattern of biogenic CO₂ flux calculated as the difference between total CO₂ fluxes directly measured by EC and estimated emissions from bottom up approach. Positive and negative fluxes represent emissions from dark respiration and sequestration by photosynthesis, respectively. The biogenic flux during the light transition periods (i.e. just before and after sunrise and sunset indicated by vertical dotted lines) is essentially zero. (b) Partitioning of CO₂ assimilated by type of vegetation: woody trees contribute two thirds of the total followed by turfgrass, palm trees and other plants (e.g. banana). Data are for a residential area (Telok Kurau, Singapore).

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