An empirical approach to estimate the biogenic components of urban CO_2 flux

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dated: 07June 2015

1. Introduction

Both vegetated and urban ecosystems can act as carbon *sinks* and *sources*. In natural ecosystems, the carbon balance is given by the sum of ecosystem respiration and photosynthesis, whereas in urban and suburban areas additional anthropogenic contributions, such as emissions from traffic, household activities and human respiration need to be considered too.

Suburban areas, which commonly have higher vegetation cover fraction (λ_V) than city centers, show a similar behaviour to natural ecosystems in terms of patterns and magnitudes of CO_2 fluxes (e.g. Crawford et al., 2011; Ward et al., 2015). As the fraction of vegetation decreases, anthropogenic impacts become more important. In cities, the diurnal uptake of carbon by trees, plants and lawns can help in mitigating CO_2 emitted by human activities. As vegetation cover decreases, CO_2 emissions tend to increase given less photosynthetic uptake (Bergeron and Strachan, 2011; Velasco and Roth, 2010). This effect is particularly evident during the growing season, as observed for example in Montreal (Bergeron and Strachan, 2011) and Baltimore (Crawford et al., 2011). In summer there is a negative correlation between daily CO_2 fluxes and λ_V (Velasco and Roth, 2010). When urban vegetation is low (< 5%), data suggest that soil and vegetation exchanges can be neglected (Matese et al., 2009; Moriwaki and Kanda, 2004; Velasco et al., 2009), whereas when the natural fraction is greater than 80%, cities can be considered *sinks* on an annual scale (Nordbo et al., 2012).

In a recent study, Nordbo et al.(2012) have shown how the natural cover fraction (obtained as the difference between total land cover and urban fraction) can be used as a robust proxy to estimate annual carbon exchange in urban sites. This suggests that natural (vegetation and bare soils) and urban (buildings and impervious) cover fractions can be used to provide an estimation of net carbon exchange. Given this, an important issue is to understand how the net CO_2 exchange varies, in different urban and non-urban ecosystems, according to land cover fractions.

The overall aim of our work in this realm is the development and testing of an empirical model which simulates the biogenic components of the vertical CO_2 flux, based on environmental variables and vegetation cover fraction, which can be applied over different ecosystems (natural, agricultural, urban, and suburban). In urban and suburban ecosystems it can allow us to investigate the role of vegetation in acting as a carbon *sink* or *source*. The advantage of such a model is that the estimation of the CO_2 flux is based on a small number of commonly measured variables, such as global radiation (R_g) and λ_V.

The empirical model simulates soil and vegetation respiration and photosynthesis uptake. It is developed using both experimental and literature-based Eddy Covariance observations of CO_2 fluxes, and is based on the analysis of light response curves for different ecosystems.

A brief description of the modeling approach is reported below along with results from model testing both over a natural ecosystem, mainly composed by Mediterranean maquis vegetation (Sardinia, Italy) and over a suburban site (Helsinki, Finland).

2. Materials and Methods

2.1 Model development

The model was developed for six sites with direct observations of CO_2 fluxes, monitored with Eddy Covariance (EC) instrumentation (Bellucco et al., 2014, Table 1). The sites are characterized by different vegetation types and cover fractions: a natural Mediterranean Maquis site (Capo Caccia, Italy, Marras et al., 2011), two managed vineyards (Serdiana and Montalcino, Italy, Marras et al., 2012, and Marras, 2008, respectively), two suburban areas (Swindon, UK and Baltimore, MD, USA, Ward et al., 2013, and Crawford et al., 2011, respectively) and a forest site (Morgan Monroe State Forest, IN, USA, Schmid et al., 2000). Where available, original datasets (non-gap-filled) were used (i.e. Mediterranean sites), otherwise data were obtained from the literature (i.e. forest and suburban sites).

Table 1. Description of the measurement sites (all with EC observations) used to develop the biogenic empirical model. Each site has different vegetation type and cover fraction (λ_V).

Site	***Area***	***Latitude***	***Period***	***% veg***	***λ_V***
Morgan Monroe State Forest[L] (MMSF), IN, USA (Schmid et al., 2000)	Deciduous forest	39.32° N 86.42° W	May–September (1998)	0 (grass) 100 (tree)	1.00
Baltimore, MD, USA[L] (Crawford et al., 2011)	Suburban	39.41° N 76.52° W	Summer (2002–2006)	13.8 (grass) 53.6 (tree)	0.70
Swindon, UK[L] (Ward et al., 2013)	Suburban	51.58° N 1.80° W	Summer (2011)	36 (grass) 9 (tree)	0.40
Serdiana, Italy[or] (Marras et al., 2012)	Vineyard	39.36° N 9.12° E	Summer (2009–2011)	~50 (grapevine)	~0.50
Montalcino, Italy[or] (Marras, 2008)	Vineyard	43.08° N 11.80° E	Summer (2005–2006)	~50 (grapevine)	~0.50
Capocaccia, Italy[or] (Marras et al., 2011)	Mediterranean Maquis	40.61° N 8.15° E	Year (2005–2010)	~70 (shrubs)	~0.70

[L]literature dataset, [or]original dataset

Light response curves of each site (i.e. CO_2 fluxes as a function of photosynthetically active radiation, PAR) were analyzed selecting daytime data (global radiation, $R_g > 5$ W m^{-2}) and by calculating median values of CO_2 fluxes (in bins of 50 µmol m^{-2} s^{-1} of PAR). The light-response curves were fitted by the non-rectangular hyperbola (NRH) equation (Figure 1), using non-linear least square regression in order to estimate its coefficients α, β, γ, and θ. α represents the mean apparent ecosystem quantum yield, as well as the initial slope of the light-response curve; β is the light saturated gross photosynthesis of the canopy (the plateau parameter); γ is the ecosystem respiration (intercept value), and θ is an a-dimensional bending parameter. The non-rectangular hyperbola was chosen above others given it is the most commonly used empirical equation to simulate biogenic carbon fluxes (e.g. Aubinet et al., 2012; Crawford and Christen, 2014; Gilmanov et al., 2003; Stoy et al., 2006).

For two of the Italian sites (the Serdiana vineyard and the Capo Caccia Mediterranean maquis site), measurements of soil water content (SWC) were also available, therefore investigations of the variability of the NRH coefficients as function of SWC were also carried out. All the estimated coefficients (not shown here) are in accordance with literature reported values (Boote and Loomis, 1991; Gilmanov et al., 2003).

Next, the dependence between λ_V and the site-specific NRH coefficients (for data not split based on SWC) were analyzed through a linear regression analysis (Bellucco et al., 2014). This enabled the empirical relations among sites to be identified. Only the curvature parameter (θ) was fixed to the median value across the sites (0.96) because no clear relation was highlighted during the analysis. These empirical relations were therefore used in the development of the biogenic module of the empirical model proposed hereinafter.

2.2 Biogenic empirical model

Across a range of vegetation cover fractions, the biogenic model estimates the surface-atmosphere carbon net exchange due to soil efflux and canopy respiration, and vegetation uptake. R_g and λ_V are needed as input variables (Figure 1): with the first the model calculates PAR; with the latter it estimates the NRH coefficients as a function of vegetation cover fraction, using the empirical relations as described in the previous section.

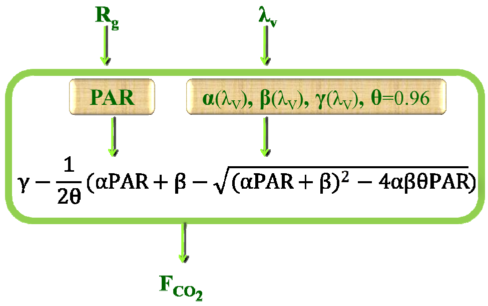

Fig. 1 Scheme of the biogenic empirical model

2.3 Model testing and statistical analysis

Two sites with different morphological characteristics, vegetation cover fractions and climatic conditions were chosen to test this biogenic empirical model: the suburban area of Helsinki, Finland, and the unmanaged evergreen Mediterranean maquis ecosystem of Capo Caccia, Italy.

In Helsinki, the EC station (Kumpula, 60.203° N, 24.961° E, 26 m above sea level) is located in a suburban area approximately 4 km north-east from the Helsinki city centre. Around the EC tower, land cover is variable, but a more vegetated area characterizes the 180° – 320° wind sector (see e.g. Järvi et al., 2014, and Vesala et al., 2008 for more details). Across all wind sectors, the surface cover is 52% vegetation within a radius of 500 m, whereas for the wind sector with more vegetation, this percentage increases up to 59% within a radius of 1000 m. Two months during the summer season (June and July 2010), when vegetation is at its maximum and vehicular traffic rates are reduced (Järvi et al., 2012) were selected for analysis. Given most of the buildings in the area use district heating, which is generated outside the footprint area by power plants, emissions from buildings are negligible with respect to the other CO_2 sources.

The second EC tower is located in the Capo Caccia peninsula (municipality district of Alghero (SS), Italy) within a natural reserve called *Prigionette*, also known as *Arca di Noè*, on the North-West Sardinia coast (40.61° N, 8.15° E). At this site, Mediterranean maquis appears as a shrub land of different species (mainly juniper and lentisk), randomly distributed in the measurement area (Marras et al., 2011). The discontinuous vegetation covers 70% of the surface on average. Drought periods affect ecophysiological processes in Mediterranean ecosystems especially during the summer season. Therefore, in this analysis, data of the winter season and during well-watered conditions (from January to March 2011) were used.

The EC measurements of CO_2 fluxes from both sites were sorted and averaged by time, and then compared with CO_2 fluxes simulated by the biogenic empirical model.

For the suburban area, the biogenic module was first run for λ_V calculated for all wind sectors (λ_V=0.52), and then considering λ_V calculated for the higher vegetation wind sector only (180°–320°, λ_V=0.59). In both cases, data were also stratified into workdays and weekends in order to investigate the differences between modelled and measured fluxes and to exclude the contribution of anthropogenic sources, especially vehicular emissions. For the natural Mediterranean site, the model was run considering λ_V=0.70 and all wind sectors.

As a first assessment, linear regressions between simulated and measured CO_2 fluxes were calculated. Then, four statistical indices were calculated: the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), the Mean Bias Error (MBE), and the Index Of Agreement (IOA).

3. Results and discussion

Results of the comparison between the CO_2 fluxes simulated using the biogenic empirical model and measured using the EC technique, for both Helsinki and Capo Caccia sites, are shown in Table 2.

Model performance is better at the unmanaged natural Mediterranean ecosystem (R^2=0.98) and for the suburban sites when considering the vegetation wind sector only (R^2 up to 0.96).

More detailed analyses show that in Helsinki the net CO_2 flux is less negative (i.e. uptake) during workdays when compared to weekends, due to higher emissions from road traffic. Conversely, during weekends the traffic rates are smaller. This behavior is evident in Figures 2c and 2e, where all wind directions are considered. On the other hand, workdays and weekends exhibit more similar behavior when considering only the vegetated wind sector (Figure 2d, f). For this reason, model performance was better when considering only weekend data (R^2 up to 0.96 in Table 2, Figure 2f) and weaker during workdays when all wind directions are considered (R^2 up to 0.77 in Table 2, Figure 2c). These findings are valid both for simulations for single months, and cumulative periods.

Table 2. Statistics of the biogenic model simulations for the suburban site of Helsinki and the unmanaged Mediterranean maquis site of Capo Caccia. Indices indicate the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), the Mean Bias Error (MBE), the Index Of Agreement (IOA), and the R-squared (R^2). RMSE, MAE and MBE values are expressed as µmol m^{-2} s^{-1}. Significant values with P<0.001.

Helsinki	**Period**	**All wind directions**					**Vegetation wind direction (180°– 320°)**				
		RMSE	MAE	MBE	IOA	R^2	RMSE	MAE	MBE	IOA	R^2
all days	June	2.66	2.44	-2.00	0.87	0.81	1.89	1.69	-0.44	0.96	0.94
	July	3.01	2.85	-2.85	0.82	0.91	2.14	1.88	-1.81	0.95	0.95
	June+July	2.72	2.47	-2.46	0.86	0.89	1.77	1.58	-1.16	0.97	0.95
workdays	June	4.17	3.62	-3.46	0.70	0.57	2.14	1.80	-0.70	0.95	0.87
	July	3.98	3.75	-3.75	0.72	0.85	2.52	2.19	-2.14	0.93	0.93
	June+July	3.97	3.62	-3.62	0.71	0.77	2.11	1.86	-1.49	0.95	0.92
weekend	June	2.87	2.35	0.87	0.90	0.95	2.20	1.98	-0.28	0.95	0.96
	July	1.93	1.57	-1.24	0.93	0.86	2.00	1.69	-1.38	0.95	0.91
	June+July	1.79	1.52	-0.28	0.95	0.93	1.71	1.53	-0.78	0.97	0.96

Capo Caccia		RMSE	MAE	MBE	IOA	R^2
all days	January	0.99	0.72	0.09	0.98	0.93
	February	1.25	0.97	-0.70	0.98	0.96
	March	1.34	0.98	-0.48	0.98	0.94
	Jan+Feb+Mar	0.82	0.63	-0.46	0.99	0.98

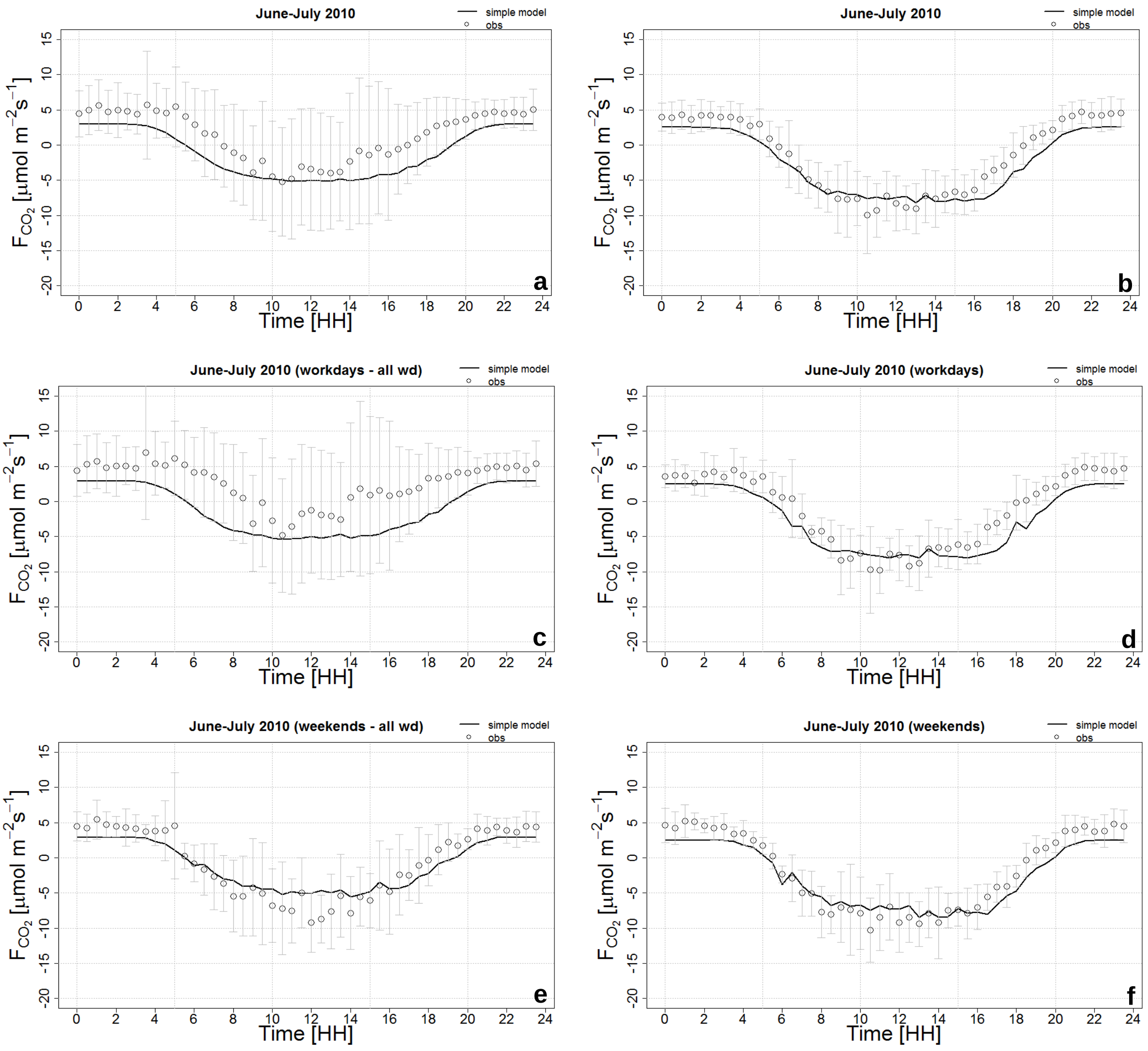

Fig. 2 Simulated (solid line) and observed (dots) CO_2 flux data for the city of Helsinki (June and July 2010 summed periods). Left panels (a, c, e) show all wind directions (λ_V=0.52), whereas right panels (b, d, f) vegetation wind directions only (λ_V=0.59). Rows (from top to bottom) show all data (a, b), workdays data (c, d), and weekends data (e, f). Error bars represent standard deviations of measured hourly means.

These assessments highlight the capability of the model to reproduce the diurnal mean trend of biogenic CO_2 fluxes. The model is therefore able to capture the diurnal vegetation uptake, especially during midday hours where the biogenic processes are more important. Under these conditions simulations almost always fall within the range of variability of observed values (Figure 2). At night, as well as in the early morning and late evening, differences between modeled and observed data are observed, most likely due to the significance of other sources, such as traffic emissions and human respiration. However, in general, both daytime and nightime trends are reproduced, reaching IOA values higher than 0.90 both when simulating the vegetation wind sector, and weekends for all wind sectors (Table 3).

Results for the Mediterranean maquis site of **Capo Caccia** (Table 3, Figure 3), show that the model is able to reproduce the mean daily trend of CO_2 fluxes better than at the suburban site of Helsinki. Simulated values match almost perfectly observations which mainly represent the photosynthetic activity during the day and the respiration processes at night. This is also confirmed by the high values of the IOA which ranges between 0.98 and 0.99. The regression between modelled and observed data explained from 93% to 96% of half hourly variance for single months, and up to 98% when considering the summed months of January, February, and March. In these months, the other statistical indexes are also smaller, indicating better model performances.

In all the periods considered and for both sites, the regression analysis between simulated and measured CO_2 fluxes were statistically significant (at 0.001 probability). In general, the MBE index, indicates a slight tendency of the model to underestimate real measurements (-0.28<MBE<-3.62). The possible explanation is that the model does not take into account sources that are different from biogenic contributions. This is also the reason why the statistical analysis reveals a better performance of the model in the natural Mediterranean ecosystem than in the suburban area of Helsinki.

The good agreement of the biogenic module, both with human-modified and unmanaged ecosystems, confirms the evidence that CO_2 fluxes depend on vegetation cover fraction and opens a new approach in the study of relations among different ecosystems and the role of vegetation in urban areas.

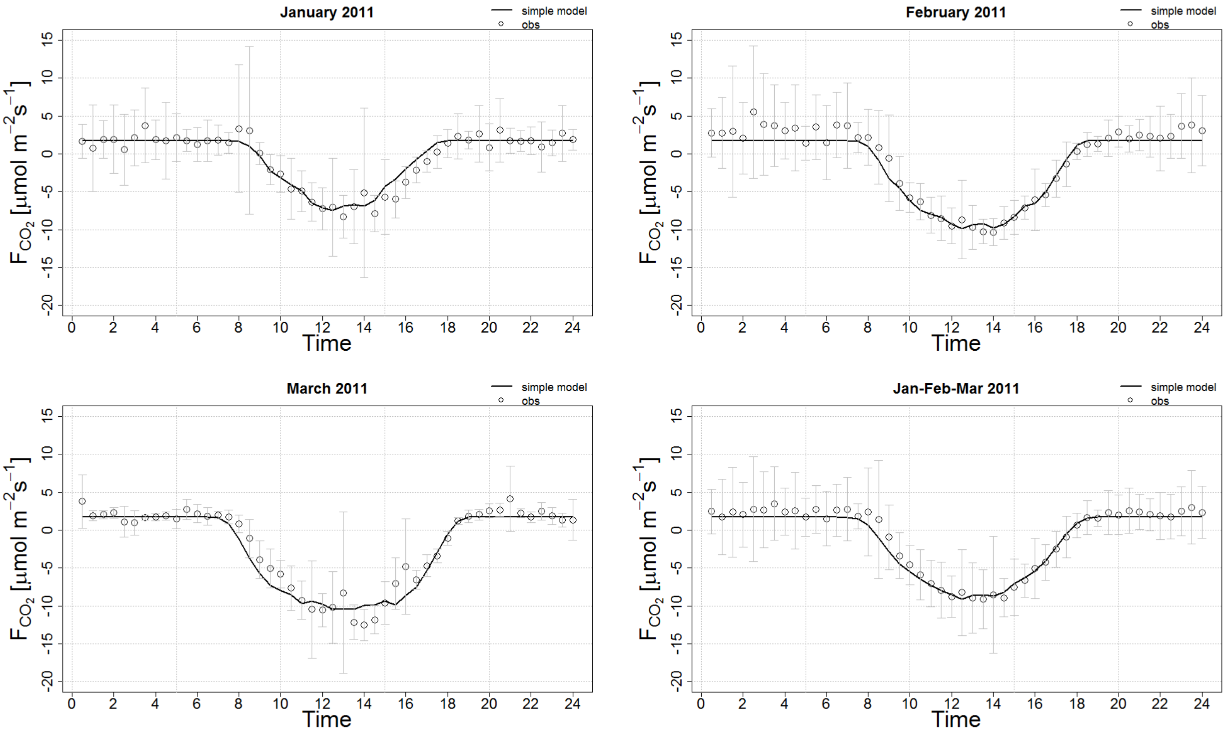

Fig. 3 Simulated (solid line) and observed (dots) Capo Caccia CO_2 flux data. Measurements are from all wind directions (λ_V=0.70) and summed both per single month and the three months period. Error bars represent standard deviations of measured hourly means.

4. Conclusions

The dependence of urban CO_2 fluxes on vegetation cover has been well documented (see, for example, Velasco and Roth (2010) and Nordbo et al. (2012)).This study presents the first step in the development of a simple empirical model based on land cover fraction and environmental variables, able to simulate carbon dioxide fluxes over urban and non-urban ecosystems.

The biogenic module was developed from the preliminary analysis of the light response curves of independent sites. Solar radiation was used to infer PAR values, and combined with the vegetation cover fraction (λ_V) to calculate, through linear regression equations, the coefficients of the Non-Rectangular Hyperbola as function of λ_V, and to estimate the CO_2 flux.

This simple empirical model reproduces ecosystem respiration and vegetation uptake both in urban and natural ecosystem during periods when maximum ecophysiological processes occur. Preliminary results showed good performance between modelled and observed data explaining up to 96% and 98% of total variance over the suburban site of Helsinki (for weekend measurements in the vegetated sector) and over the natural Mediterranean Maquis ecosystem, respectively. The model has general utility in capturing the general behavior of different ecosystems.

Further improvements of the biogenic empirical model are planned based on this simple modeling approach. To increase the robustness of the relations used by this empirical model, and to include a second anthropogenic module, a greater number of sites will be considered.

Acknowledgment

This work was found by the Italian MIUR and MATTM under grant agreement 232/2011(GEMINA Project) and by the Sardinian Regional funding through LeggeRegionale 7 Agosto 2007, N.7: "Promozione della ricerca scientifica e dell'innovazione tecnologica in Sardegna"

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