

Communication

Measuring Multi-Scale Urban Forest Carbon Flux Dynamics Using an Integrated Eddy Covariance Technique

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Abstract: The multi-scale carbon-carbon dioxide (C-CO₂) dynamics of subtropical urban forests and other green and grey infrastructure types were explored in an urbanized campus near Shanghai, China. We integrated eddy covariance (EC) C-CO₂ flux measurements and the Agroscope Reckenholz-Tänikon footprint tool to analyze C-CO₂ dynamics at the landscape-scale as well as in local-scale urban forest patches during one year. The approach measured the C-CO₂ flux from different contributing areas depending on wind directions and atmospheric stability. Although the study landscape was a net carbon source (2.98 Mg C ha⁻¹ yr⁻¹), we found the mean CO₂ flux in urban forest patches was $-1.32 \mu\text{mol m}^{-2}\text{s}^{-1}$, indicating that these patches function as a carbon sink with an annual carbon balance of $-5.00 \text{ Mg C ha}^{-1}$. These results indicate that urban forest patches and vegetation (i.e., green infrastructure) composition can be designed to maximize the sequestration of CO₂. This novel integrated modeling approach can be used to facilitate the study of the multi-scale effects of urban forests and green infrastructure on CO₂ and to establish low-carbon emitting planning and planting designs in the subtropics.

Keywords: carbon dioxide offsets; ART footprint tool; urban ecosystems; nature-based solutions; green infrastructure

1. Introduction

Urban areas are a complex matrix of different land covers, primarily including green infrastructure (GI; e.g., urban forests and other vegetation patches) and grey infrastructure (e.g., buildings, roads, and impervious). This matrix affects greenhouse gas (GHG) dynamics due to the combination of fossil fuel emissions from transportation and industrial activities and carbon-carbon dioxide (C-CO₂) sequestration by urban forests and other areas of natural and semi-natural vegetation, wetlands and rivers [1]. As such, there is increasing research on urban C-CO₂ dynamics and the use of urban forests as a nature-based solution across many cities of the world [2–4].

However, multi-scale modeling of urban C-CO₂ dynamics for different urban land covers, including urban and peri-urban forests in developing countries, is complex due to: Landscape heterogeneity, socioeconomic factors, emission sources, seasonality, wind direction-speed, and atmospheric stability [4,5]. Thus, many studies on the role of vegetation on C have used indirect methods such as allometric biomass

equations and tree inventory data to assess C stocks and CO₂ sequestration in urban areas [6,7]. Other empirical approaches, such as urban metabolism [8] and direct measurements using eddy covariance (EC) flux observation systems [9], are also being used to assess these urban C-CO₂ dynamics. However, of these methods, EC allows for integrated measurements of C-CO₂ fluxes between the surface and the atmosphere within a contribution area to measured C fluxes, known as the footprint, which consists of sources and sinks [9–11]. These contribution areas are generally landscape-scale segments or portions within the study footprint [12]. As such, the C-CO₂ dynamics of smaller localized patches and areas within the footprint are much more difficult to model [4,10].

But, the available ART Footprint Tool (Agroscope Reckenholz-Tänikon; ART hereafter), based on the Kormann and Meixner model, is a relatively accessible approach for modeling source-sink heterogeneity and the partial flux contribution of specific local-scale areas inside a footprint [13]. Although little used in cities, it can potentially quantify how local-scale urban forest or other GI patches offset CO₂; a topic that is increasingly important to researchers and decision-makers globally. Such research using direct measurements of C-CO₂ flux source-sink characteristics and their use as a nature-based solution in subtropical urban forests in low-middle income countries is scarce [2,3,9].

Therefore, the aim of this short communication is to explore a novel approach for estimating the landscape and local-scale C-CO₂ flux dynamics of subtropical urban forests in an urbanizing area near subtropical Shanghai, China. Our specific objectives were two-fold. First, we quantified the overall CO₂ flux variation in an urbanized landscape and its different land covers. Second, we then explored the local-scale C-CO₂ flux dynamics of the specific urban forest, mixed, and grey infrastructure patches. We did so by combining Geographical Information Systems, direct annual EC measurements of C-CO₂ fluxes with the ART contribution area model. We then compared the C dynamics of urban forests with other areas of green-grey infrastructure [13].

As we will point out in the methods, the below approach requires advanced expertise, state of the art equipment, and data to implement. In particular, the long-term datasets required include canopy height and fine-scale meteorological and environment measurements, as well as spatial land use cover boundaries. Similarly, these local-scale flux source area assessments need CO₂ flux partitioning in different time series for the different land-use types. As such all these requirements are needed to make the below flux calculations and spatial assessments. That said, the novel, integrated, multi-scale techniques explored here could provide an improved approach to better understand, plan, manage, and design urban forests as essential components of urban nature-based solutions.

2. Materials and Methods

The 456-hectare study area, or landscape, is located at the Fengxian University Campus, approximately 40 km south of central Shanghai, China, in a coastal plain with a subtropical monsoon climate. Southeast winds dominate during the summer and northwest winds in the winter. The annual average temperature is 16 °C, the mean minimum and maximum temperatures are 4 °C in January and 33 °C in July–August, respectively [14,15]. The mean annual precipitation is 1200 mm and occurs mostly in the summer. Seasonality, as used in this study, is defined as follows, where Spring is the 1st of March–31st May, Summer is the 1st of June–31st August, Autumn is the 1st of September–30th November, while Winter is the 1st of December–28th February.

The grey infrastructure land use/covers (LULCs; e.g., building, roads, impervious) accounted for 39.25% of the study landscape. The buildings alone accounted for 24.31% of the total area and had an average height of 10 m. The GI or vegetation-dominated LULCs accounted for 53.2% of the study area, and the remaining was mixed and water bodies. Vegetation is characterized by a subtropical evergreen broad-leaved forest tree types dominated by *Cinnamomum camphora* with a canopy height of 8 m and other common herbaceous species such as *Acorus calamus* L., *Phragmites australis*, and *Ophiopogon japonicus*.

The EC system used for this short communication consisted of a three-dimensional ultrasonic anemometer (Windmaster, Gill, UK), and infrared gas analyzer (Li-7500, Licor, Lincoln, NE, USA),

mounted on 20 m tall antenna tower in the center of the study area. High-frequency data was collected at 10 Hz on a CR3000 datalogger (Campbell Scientific Instruments, Logan, UT, USA) from April 2015 to March 2016. Carbon dioxide fluxes were calculated in 30 min intervals using EddyPro 5.1.1 software (Li-COR, Lincoln, NE, USA), which applied a coordinate rotation to adjust for local wind streamline and corrects for: The frequency response losses, spectral attenuation, and density fluctuations due to changes in air temperature and air moisture content.

The estimated fluxes were filtered following quality control indicators generated by the processing software (0-1-2; where “0” indicates best to “2”, the poorest quality data) and the steady-state and developed turbulent conditions tests [16]. The fluxes were also eliminated under raining conditions or when less than 90% of the high-frequency data was collected in the 30 min intervals. Sixty-six percent of data remained after this filtering protocol was applied [17]. Atmospheric stability was defined according to Obukhov’s stability lengths (L), where $L < 0$ represent unstable and $L > 0$ represent stable atmospheric stability, respectively [13,18]. Temporal gaps in the fluxes, usually less than 2 consecutive hours, were filled using the diurnal variation method (MDV) by interpolating the average value of the data generated at the same time in a cycle of 7 days for daytime and 14 days for night van ’t Hoff model time [18–20]. For longer periods, the Landsberg model was used for daytime and CO_2 fluxes were related to photosynthetically active radiation, while the van ’t Hoff model, which relates fluxes to soil temperature, was used for nighttime gap-filling [19,20]. The MDV method was used for all data gap filling procedures when estimating CO_2 fluxes of both the footprint and different GI areas within the study area. Negative CO_2 flux values indicate CO_2 uptake.

To attribute the CO_2 fluxes to their sources within the study landscape, we first estimated the characteristics and range of flux sources in the entire contributing area, or footprint, located on the urbanized campus [21,22]. The footprint had a radius of 500 m relative to the EC tower. We used the Hsieh model, based on the Lagrangian stochastic model and dimensional analysis, as it is suitable for long-term time series and requires few parameters, including: The observing height (m), zero-plane displacement value (m) and aerodynamic roughness length (m) [22]. Although the Flux—Source Area Model (FSAM) is also used for these types of analyses, it is much more complex and is not suitable for long-term flux footprint calculations [23,24].

Second, we estimated the flux contribution of 3 specific local-scale urban forest (i.e., tree dominated GI), mixed, and grey infrastructure patches to the total measured fluxes in the footprint using ART. We identified and selected the 3 specific patches using the following approach. A 15×15 m grid was initially established inside the footprint to spatially segregate the different LULCs. Then, 200 of these cells were grouped into either green or grey infrastructure types based on their LULCs. Afterward, the selected grey and green infrastructure cells were grouped into 26 different polygons that best represented the green and grey infrastructure patches across the 4 footprint quadrants (Figure 1). All polygons were summed producing the contribution of grey and GI to total measured fluxes and total fluxes from each quadrant [12]. The footprint function was then combined with the LULC data and the footprint contribution was calculated for 3 selected polygons that best represented the 3 different patch types (i.e., urban forest, mixed, and grey infrastructure) [12,13].

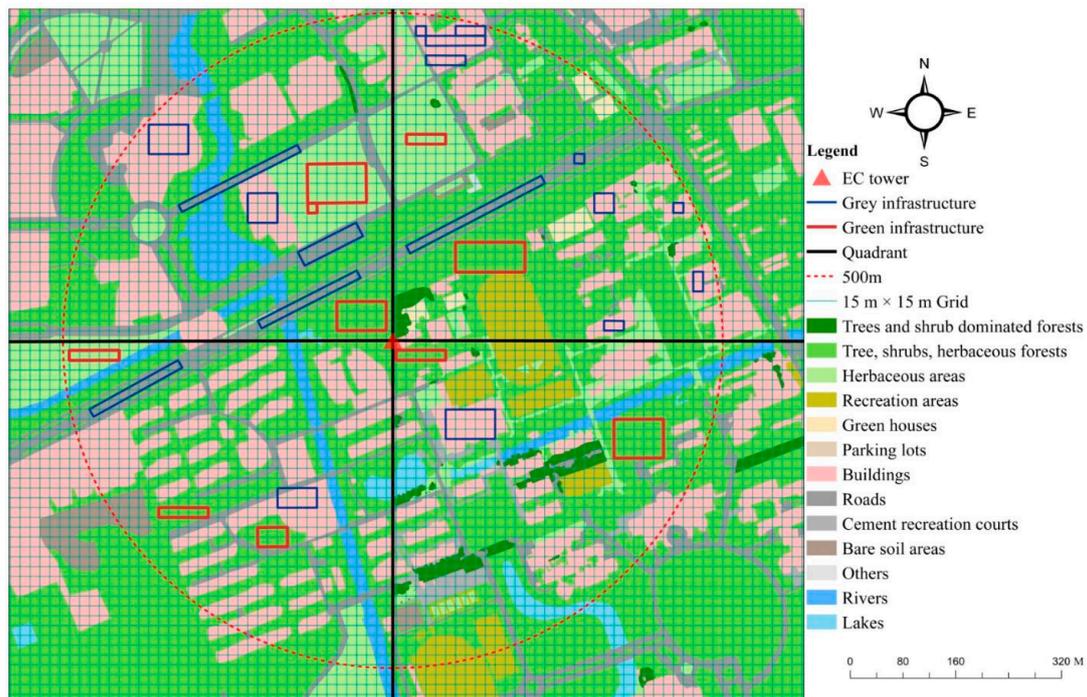


Figure 1. The eddy covariance footprint's grid, quadrants, and 26 polygons representing green (vegetation dominated cells) and grey infrastructure (building and impervious dominated cells) patches in the university campus study landscape near Shanghai, China.

3. Results

Ranges of prevailing seasonal wind direction and the percent of total frequency were estimated (Appendix A) and then the Hsieh footprint model was used to calculate the range of 90% of flux contribution area to the measured C-CO₂ flux according to the prevailing wind direction. The flux contribution area length for non-prevailing winds under stable atmospheric conditions was 260–810 m during the spring. When the atmosphere was unstable, the length of the flux contribution area was 121–220 m. The flux contribution areas for seasonal prevailing winds under stable and unstable atmospheric conditions are shown in Appendix A. As expected, all seasons exhibited a pattern of increased flux contribution areas as the atmospheric stability improved. The total daily C-CO₂ for the study is shown in Figure 2.

The total C-CO₂ balance in the study landscape was 2.98, with the northeast quadrant contributing 1.22, followed by the southwest with 0.78 and southeast and northwest quadrants contributing 0.47 and 0.51 Mg C ha⁻¹ yr⁻¹, respectively. The sum of carbon emissions per quadrant accounts for 88% of the observed values in the total footprint.

The grey and GI areas were then selected throughout the footprint and we combined this EC data to characterize seasonal C-CO₂ fluxes (Figure 2) [12]. Overall, the annual carbon budget for GI areas was −5.00 Mg C ha⁻¹ and the seasonal carbon budget in the spring, summer, autumn, and winter were: −1.52, −2.76, −1.02, and 0.30 Mg C ha⁻¹ yr⁻¹, respectively. The annual average CO₂ flux for GI was −1.32 μmol m⁻²s⁻¹. The annual carbon budget for the grey infrastructure areas was 8.17 Mg C/ha, and there were no obvious seasonal changes. The peak CO₂ flux values were within the range of 5–8 μmol m⁻²s⁻¹. The CO₂ flux peak value decreased due to the lower traffic flow and reduced human activities at night. The annual average CO₂ flux for the grey infrastructure types was 2.16 μmol m⁻²s⁻¹.

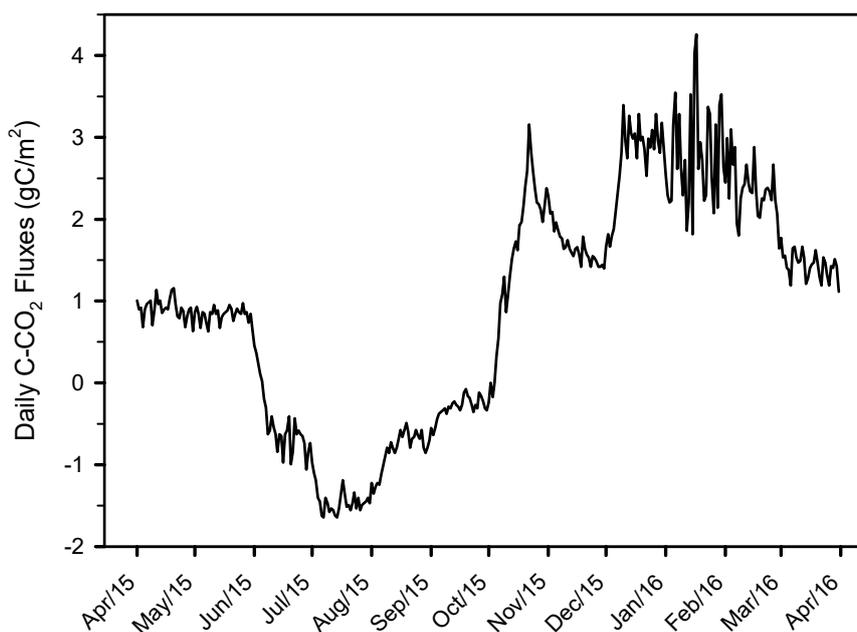


Figure 2. Daily C-CO₂ fluxes (gC m⁻² day⁻¹) for the university campus study footprint near Shanghai, China from 1st April 2015 to 31st March 2016.

Parsing out the C-CO₂ flux of exclusively treed patches versus other areas of mixed vegetation is not possible as conventional EC studies the sum of all vegetation, soils, water, and other attributes in a given area [12]. Thus, hereafter we refer to patches of grey infrastructure and urban forests, or tree-dominated GI. Accordingly, we used three specific patches in the footprint of approximately 400 m² to represent: Urban forests, a mix of buildings and GI, and building-dominated grey infrastructure (Figure 3). An ideal annual average value was estimated according to the CO₂ flux in the three patches (Equation (1)) [18,23,25]. The F_c^i is the ideal value (Annual average, $\mu\text{mol m}^{-2} \text{s}^{-1}$), A_{Green} is the tree-dominated GI/urban forest area (ha), A_{Grey} is the area of the grey infrastructure (ha), and A_{test} is the study area (ha). The calculated annual average value is the calculated ART Footprint Tool CO₂ flux of the study area. The ideal and calculated values for urban forests, grey infrastructure, and mixed were -1.32 and -1.11 , 2.16 , and 2.48 and mixed were 0.42 and $0.95 \mu\text{mol m}^{-2}\text{s}^{-1}$, respectively. By comparing the differences between the ideal and the calculated values, we determined the accuracy of the CO₂ fluxes for the different patches.

$$F_c^i = -1.32 \frac{A_{Green}}{A_{test}} + 2.16 \frac{A_{Grey}}{A_{test}} \quad (1)$$

The difference between the ideal and calculated value for the buildings plus GI patch was $0.53 \mu\text{mol m}^{-2}\text{s}^{-1}$ and differed greatly, relative to the difference between the ideal and calculated value for the vegetation and buildings. The difference of $0.53 \mu\text{mol m}^{-2}\text{s}^{-1}$ was within the acceptable error range, relative to the predicted CO₂ flux values [13].

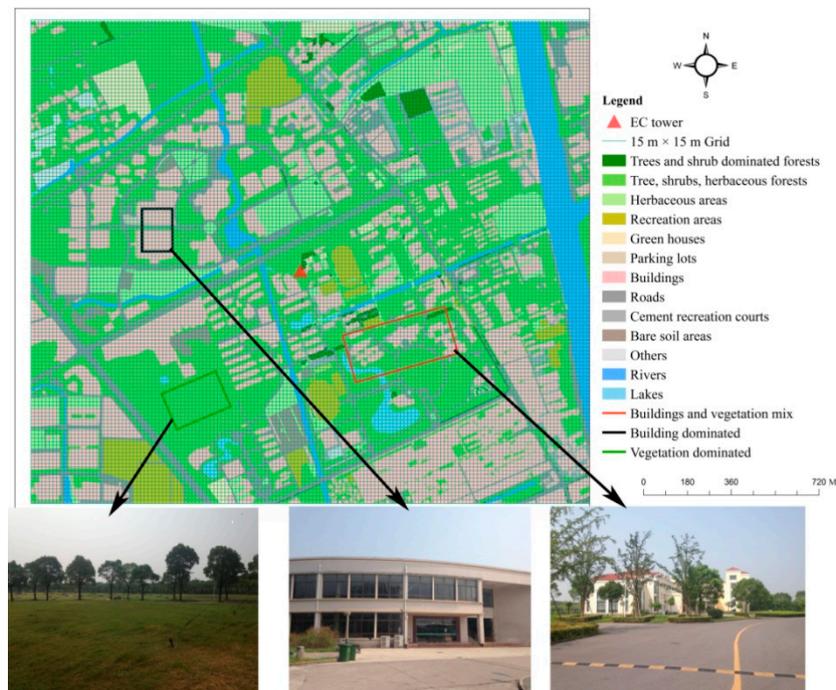


Figure 3. Selected local-scale patches in the study landscape. From left to right are: Urban forests (100% trees and grass), grey infrastructure (100% building impervious), and a mixed patch (50% grey infrastructure, 50% green infrastructure).

4. Discussion and Conclusions

Our measured C-CO₂ fluxes were similar to other studies, despite the climatic and GI compositional differences [11]. Vesala et al. [12] found that vegetation in an area in Helsinki, Finland, had a C-CO₂ flux of less than 5 $\mu\text{mol m}^{-2}\text{s}^{-1}$. A CO₂ flux study in the nearby Chongming Island wetlands found that the distribution range under stable atmospheric conditions can reach 378 m [20,26]. The maximum winter CO₂ flux in Shenyang China can be 84 $\mu\text{mol m}^{-2}\text{s}^{-1}$ [25], which, noticeably, is different from our grey infrastructure peak value and likely due to greater industrial and heating activities in cooler, northern, inland temperate China. Outside China, EC CO₂ fluxes for other cities are reported in Ward et al. [11].

In terms of the CO₂ flux contribution for different urban forest-GI types at the landscape scale, we found that the most notable difference was between herbaceous-woody and building-road LULCs; a finding similar to Yao et al., who identified forest cover in the Shanghai, China area as being a driver of C stocks [6]. The contribution of other LULC types in terms of CO₂ flux contribution was, however, lower as observed in other studies [5]. Thus, our results show the cumulative influence of these urban forests and other green infrastructure can have on CO₂ flux, as opposed to grey infrastructure, on the overall CO₂ flux contribution area [2,4,10].

We do note that the main limitation of this short communication is that we used one year of data and we did not analyze water and bare soil LULC types. These areas of “blue and brown” infrastructures are common in urban areas and will likely influence the C-CO₂ balance in the study area. But, our short communication presents an approach for future research, such as understanding how water bodies, wetlands, and urban development and construction activities affect the C flux of urban ecosystems and in improving the ART footprint tool functionality to better analyze urban ecosystems. Future studies can use the approach presented here and multiple years of data to better characterize the CO₂ budget for other GI types, such as areas planted with native versus non-native vegetation and other high versus low maintenance urban vegetation types. In particular, characterizing their seasonal and annual budgets across time and space could lead to better estimates of their true CO₂ offsetting potential.

Multi-scale studies combining geospatial, EC CO₂ flux data, and footprint/contribution area models are not common for subtropical, coastal, cities in low-middle income countries. Thus, this short communication demonstrates how long-term, local-scale data, and the ART tool can provide a more accessible and novel approach for modeling urban forest C-CO₂ dynamics and heterogeneity in cities. Such information can help us better urban plan, design, and justify the use of urban forests as integral components of nature-based solutions, which are becoming popular in many cities. The research approach presented in the paper can be used to quantify the role of low-carbon cities and local-scale effects of regulating greenhouse gas emissions. This study in subtropical China can also provide a baseline and approach for carbon flux research of the urban environment in other cities in the tropics and subtropics.

Author Contributions: Conceptualization, K.Z., Y.G. and M.Z.; methodology, K.Z. and Y.G.; software, K.Z. and Y.G.; validation, K.Z., Y.G. and M.Z.; formal analysis, Y.G.; investigation, K.Z. and Y.G.; resources, F.E.; data curation, K.Z., Y.G. and X.Z.; writing—original draft preparation, K.Z. and Y.G.; writing—review and editing, F.E., R.B. and M.Z.; visualization, Y.G.; supervision, M.Z.; project administration, M.Z.; funding acquisition, M.Z.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

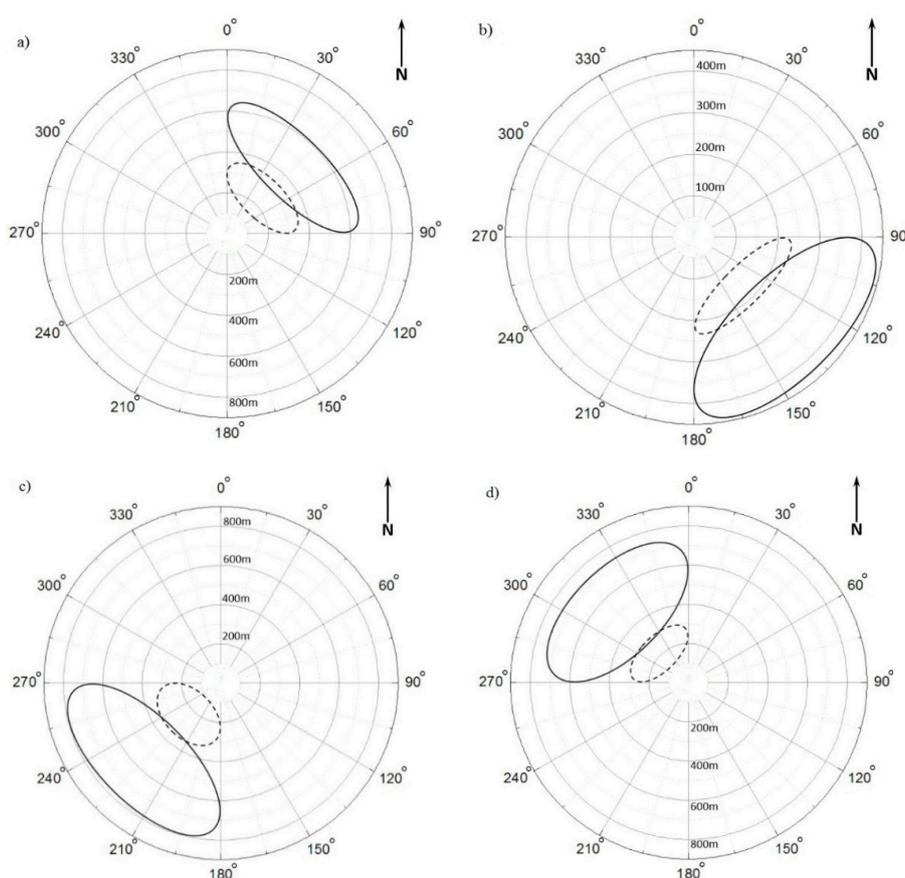


Figure A1. The farthest point distribution of 90% contribution area for dominate wind directions for different seasons in the Shanghai Fengxian University Campus. (a) Spring; (b) summer; (c) autumn; (d) winter. Solid lines represent stable, dotted line represents unstable atmospheric conditions.

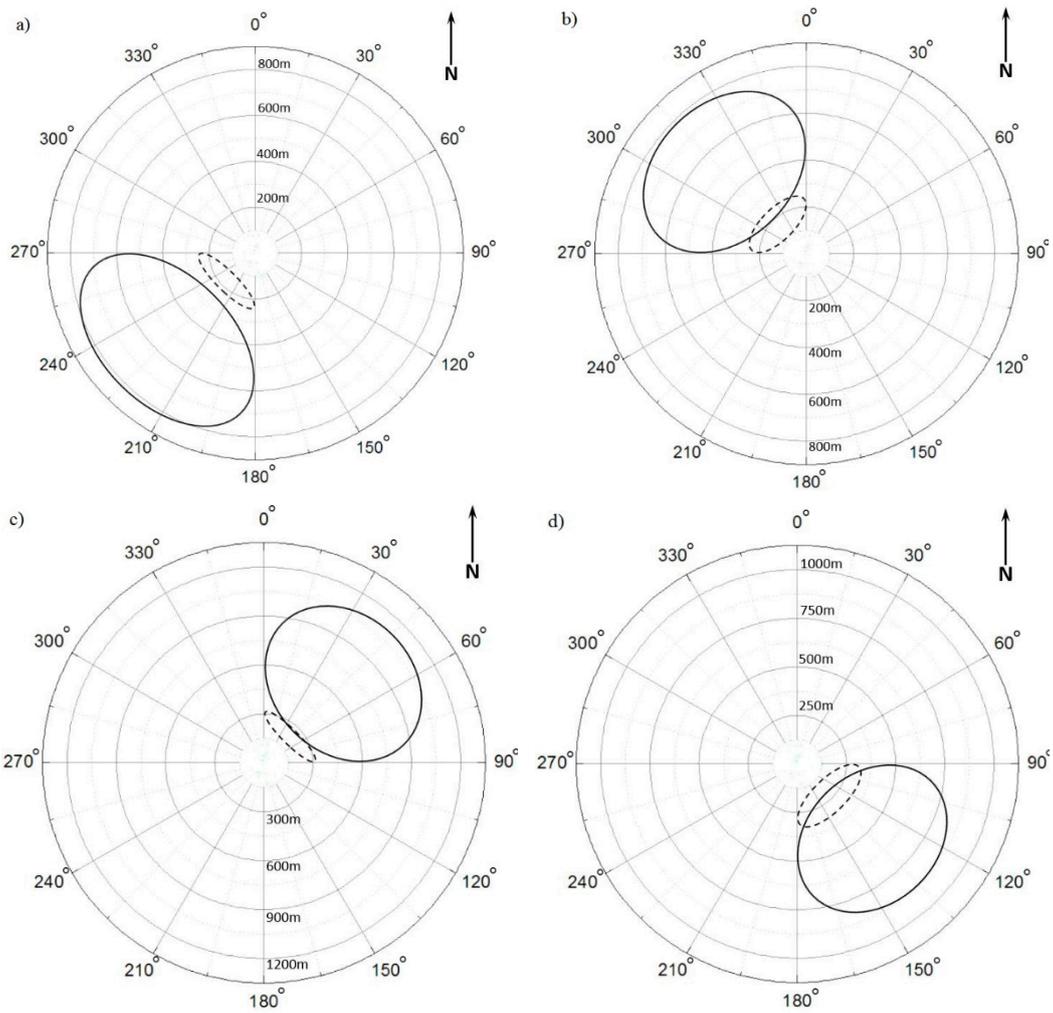


Figure A2. The Farthest point distribution of 90% contribution area for non-dominant wind directions during four different seasons in the Shanghai Fengxian University Campus. (a) Spring; (b) summer; (c) autumn; (d) winter. Circular shapes with solid lines represent stable, while dotted line represents unstable, atmospheric conditions.

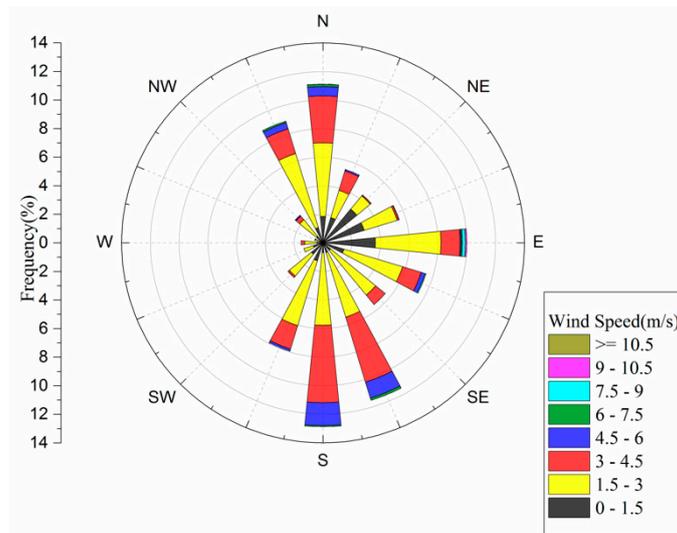


Figure A3. Wind rose for the Shanghai Fengxian University Campus study landscape from April 2015 to March 2016.

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