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EDDY COVARIANCE IN URBAN ENVIRONMENT: A SYNTHESIS WORK TO ANALYZE CO₂ FLUX DRIVERS WITHIN CITIES

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Abstract

The fraction of the global citizens who reside in urban areas has increased over the past several decades, causing cities to play an important role in the overall carbon cycle as an atmospheric carbon dioxide source. Quantifying human-related emissions in an urban environment and understanding the role of vegetation is crucial to assessing global policies aimed to reduce climate warming. The Eddy Covariance (EC) approach has been implemented in many cities globally and greatly contributed to the knowledge of the gas exchange between the urban surface and the atmosphere. The core principle of the method estimates the fluxes as the covariance between vertical wind speed and the target scalar of interest, both measured at high frequency (10-20 Hz) by a sonic anemometer and a gas analyzer.

In this research project a synthesis work is made to compare urban EC flux data coming from twenty-four stations worldwide and investigate the main drivers of carbon dioxide fluxes within cities. Land use land cover analysis has been used to classify the emission source area of each site and possibly define wind sectors of homogeneous land use. In particular, vegetation and roads have been quantified and classified in each city to evaluate their impact on local carbon dioxide emissions. In addition, the impact of heating systems has been estimated by considering the dynamics of air temperatures, with a special focus on residential sectors.

Results highlight the relevant role of roads on fluxes and the importance of vegetation in mitigating the emissions. The observed high sensitivity of fluxes to the air temperatures allowed us to suppose a data-driven method for source flux attribution.

Keywords: Eddy-Covariance; Urban Fluxes; Land Use Land Cover; Greenery Effect; Urban Environment

1 Introduction

1.1 State of the art

Urban areas occupy less than three percent (%) of the planetary landmass but can be considered the core of human and economic activity (Mills., 2007). Cities play a key role in the overall carbon cycle as greenhouse gas emitters since they are responsible for more than 70% of the total atmospheric carbon dioxide (CO₂) from anthropogenic origin (Canadell et al., 2009). Considering that in 2008 more than half the world's population lived in urban areas, and this is expected to reach five billion people in 2030 (UNFPA, 2010), urban centers are the main responsible of world emissions and are becoming more and more important to apply CO₂ emission reduction strategies. Moreover, there is a growing need for establishing robust emission inventories and optimizing methodologies for CO₂ monitoring, and better knowledge of the multiple sources and sinks located within such a complex environment (Stagakis et al., 2019).

In this research, the focus is on CO₂ emissions, considered the primary driver of global climate change. Various are the method to estimate urban emissions indeed at the scale of large urban areas ($\approx 100 \text{ km}^2$), CO₂ flux budgets can be constrained indirectly by in situ and/or remote sensing measurements of CO₂ concentrations using atmospheric transport models (e.g., for Paris (Stauffer et al., 2016) and Indianapolis (Turnbull et al., 2019)). At similar or smaller scales, urban CO₂ fluxes can be estimated by combining bottom-up emissions inventory models based on activity data and emission factors, and biogeochemical models for urban vegetation CO₂ fluxes (Gurney et al., 2019). At the district scale ($\approx 1 \text{ km}^2$), the net turbulent fluxes of CO₂ can be measured directly by the Eddy-Covariance method (EC). Within the last decades, different studies moved toward improving the understanding of the linkage between CO₂ emissions in urban environments and their drivers employing the EC method (Lietzke et al., 2015; Velasco et al., 2014). The application of the EC method within the urban environment has indeed grown over the past 15 years (Helfter et al., 2011). Urban EC records have proven their value for detecting short and long-term flux changes and understanding drivers of local CO₂ emissions and ‘urban metabolism’ to better understand the carbon cycle in cities (Velasco et al., 2010).

The core principle of EC measurements is that the net exchange of a specific gas, i.e., the sum of all sources (emissions to the atmosphere) and sinks (removal from the atmosphere mainly by vegetation), can be determined from simultaneous, co-located, high-frequency measurements of vertical wind speed (WS) and gas concentration. This method is commonly

used by the scientific community to monitor the exchange of CO₂, methane (CH₄), and nitrous oxide (N₂O) mainly between vegetated ecosystems (forests, crops, grasslands, mires) and the atmosphere, and it is globally used at more than 1000 sites.

In cities and urban neighborhoods, the net emissions measured using EC are comprised of the cumulative contributions from multiple anthropogenic sources, such as fossil fuel combustion by vehicular traffic, heating, and cooking as well as biogenic emissions (plant, animal and human respiration, sewage) and sinks (i.e., uptake of CO₂ by urban green spaces). The measured fluxes are in general expressed in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and by convention have a positive sign when the flux is from the surface to the atmosphere (i.e., an emission, as is typical in urban areas) and negative when CO₂ is drawn down through by the process of photosynthesis. In this research, EC data from multiple urban measurement stations were used to investigate the drivers of CO₂ emissions in cities. The dataset involves 24 sites placed in 21 cities worldwide.

The general scope of the study was to assess the potential of a network of urban EC stations, to aid in understanding the emissions drivers controlling the release of CO₂ in a variety of urban environments. This is the first synthesis work in the field of EC in an urban ecosystem able to collect and analyze such as large dataset.

The percentage of vegetated areas estimated with the normalized difference vegetation index (NDVI), the linear meter per hectare of primary roads taken from the open street map data (OSM), the land use land cover (LULC) analyzed with Urban Atlas (GMES/Copernicus land monitoring services, 2018), and the relation between temperature and fluxes, have been used to focus on the main emissions drivers within cities.

1.2 Eddy Covariance method

The EC method was born around 1950 (Montgomery, 1948; Swinbank, 1950), while the first measurement of gas flux, CO₂, has been tested in 1970 (Desjardins, 1974) and the first applications over natural ecosystems such as forests were carried out in the eighties (Wesely et al., 1983; Fan et al., 1990; Valentini et al., 1991). The method was born and it become a standard to monitor the terrestrial carbon cycle, trace gas emissions, and the water exchange between a natural ecosystem and the atmosphere.

Using the EC technique, the fluxes are calculated as the covariance between the fluctuations around the mean of the vertical WS and the concentration of the target scalar of interest (e.g.

CO₂, CH₄, NO₂, O₃, and H₂O), both measured at high frequency (10-20 Hz) by a 3D sonic anemometer and a gas analyzer.

Worldwide there are more than eight hundred active and historic flux measurement sites (Fig. 1), dispersed across most of the climate space and representative biomes that are part of a global network called “Fluxnet” (Baldocchi et al., 2001).

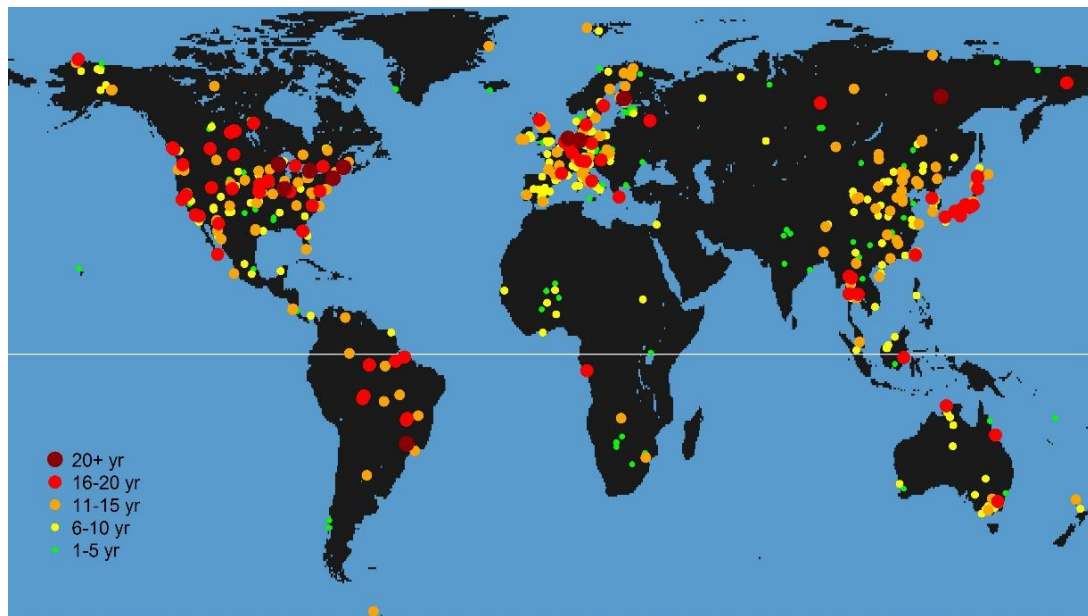


Figure 1. Sites involved within the FLUXNET 2015 dataset. The image is taken from the fluxnet website <https://fluxnet.org/>

The EC method beyond being used in natural ecosystems is employed to measure CO₂ fluxes emissions within the urban environment and has many benefits over other methods (Velasco and Roth 2010): it is a direct measure that can include all-natural and anthropogenic sources and sinks, is non-intrusive, and almost continuous. In addition, by properly setting the measurement system (height and orientation), and according to the local characteristics (surface roughness, turbulence intensity, WS and direction (WD), atmospheric stability), it can sample over a large area with an extent of the order of neighborhood (footprint).

The EC theory and relative equations rely on the application of Reynolds’s decomposition (Foken, 2008) and are founded on several simplifications:

- mean vertical velocity can be neglected;
- within a turbulent flow the molecular diffusion can be neglected;
- the concentration of the constituent does not vary significantly with time;

- in horizontal directions, the mean variation of the scalar quantity of interest can be neglected and the turbulence is homogenous.

With the applications of the previously mentioned steps and neglecting the storage term the turbulent flow is described from the following equation (1):

$$F = \bar{\rho}_a \overline{w^t s^t} \quad (1)$$

Where the flux (F) is calculated from the covariance of instantaneous vertical WS (w') and dry mole fraction (s' , e.g., mixing ratio) fluctuations, averaged over time (usually 30 minutes), and corrected by the average dry air density over the period.

Other quantities that are usually estimated are

Latent heat flux:

$$LE = \lambda \rho_a \overline{w^t q^t} \quad (2)$$

Momentum flux:

$$\tau = \rho_a \overline{w^t u^t} \quad (3)$$

Sensible heat flux

$$H = \rho_a C_p \overline{w^t T^t} \quad (4)$$

In the equations above ρ_a is the air density, C is the specific heat capacity of air and λ is the vaporization latent heat of the water. T' represents air temperature while q' water vapors turbulent concentration in the atmosphere.

For specific and more in-depth treatment of the EC method, refer to the reference bibliography (Baldocchi et al. 1988, Aubinet et al. 2012, Burba 2013) while for advanced discussion on the conservation equation and related to micrometeorological measurements, refer to the suggested references (Kanemasu et al. 1979, Businger 1986).

The EC method would ideally be applied on uniform areas where the CO_2 sources and sinks are equally distributed (Crawford and Christen 2015). The roughness element such as high building and trees, monument and urban canyons together with the spatial and temporal variability of heat and water determine a complex environment which make the EC application challenging. (**Fig. 2; Fig. 3**).



Figure 2. EC site accessorized with gas analyzer on the left side and sonic anemometer on the right-side at Sakai city office, Sakai, Japan



Figure 3. EC system at Ximeniano Observatory, Florence, Italy

The surface area influencing the fluxes called footprint, which depends on the measurement height above ground level, atmospheric stability, and the intensity of crosswind turbulence, is frequently changing as a function of WD and lateral dispersion qualities of the flow (Schmid 1994).

By analysing the WD, it is possible to attribute the fluxes to a particular sector and investigate different type of LULC with the relative source (traffic, building, human and plant respiration, etc) or sinks (vegetation photosynthesis) of CO₂.

In the last two decades, there was a remarkable increase of EC stations within cities all over the world, as also proven by the “Urban Flux Network” which is a database managed by the “International Association for Urban Climate (IAUC)” with the scope of collecting and sharing information about micrometeorological tower sites in the urban environment.

Despite the EC method in urban areas had a great impact on the scientific research, given the total sites that have been applied the method that overtaken 80 cities (Antoniella et al., 2019), the international published literature consider that more direct observations are required to explore the high amount of different urban environments, from a megacity to semi-urban areas (Piringer et al., 2002; Weissert et al., 2014).

However, most studies over cities are made at a local scale, while very few of them considered the contribution of multiple urban areas or even more multiple cities.

This research, therefore, presents a novel contribution to the field of EC in the urban environment to expand the analysis to a network of urban sites at a global scale.

1.3 Research objectives

A synthesis work is made to compare urban EC flux data coming from twenty-four stations worldwide. The objective is to integrate the information from a single site, creating a new level of information that is no more dependent on local characteristics.

The goal of this research is to use the composition of the source areas of the sites, defined through LULC investigation, such as a fundamental driver for the CO₂ fluxes dynamics. Specifically, the aim is to:

- investigate the possible sink effect associated with the presence of vegetation within the sectors of the different EC sites;
- characterize the relation between CO₂ fluxes and air temperature in different LULC conditions (residential, commercial, and vegetated areas) through the change point detection analysis;

- analyze the effect of the traffic, considering the primary roads such as the main potential traffic emissions driver.

During the development of the research activities there was a global emergence due to the Covid-19.

The pandemic and the lockdown has affected our lifestyles and work, forcing us to stay at home. This has strongly reduced road traffic and economic activities, particularly in cities, and, consequently, cut down emissions of CO₂ to the atmosphere. This event opened up a possibility for a specific analysis in collaboration with European research partners focused on the investigation of the effect of the lockdown on CO₂ emissions and to analyze whether reductions in emissions were related to the stringency of the restriction measures in different european cities. This investigation can be considered as specific research within the broader context of the research activities able to highlights the possibility to use the EC technique to provide tracking on emissions in near real-time. The latter study led to a scientific publicationis presented in the section 5. The relative supplementary material is linked in the paper and consultable online.

2 Materials and Method

2.1 Study sites

The analysis involves twenty-four EC urban towers installed worldwide that are still active or that were working in the past years. Twenty EC urban stations are located within eighteen European cities (**Fig. 4**) while another site is situated in Mexico City (**Fig. 5**) and the last three are respectively installed one in Singapore and two of them in the city of Sakai, Japan (**Fig. 6**). The stations are spread in a different climate, passing from Mediterranean type within south Europe to continental climate conditions within the nord areas.

The next images represent a zoom on the three main geographic areas involved in the research with a hotspot focalized to the cities where the urban EC stations are and were mounted.

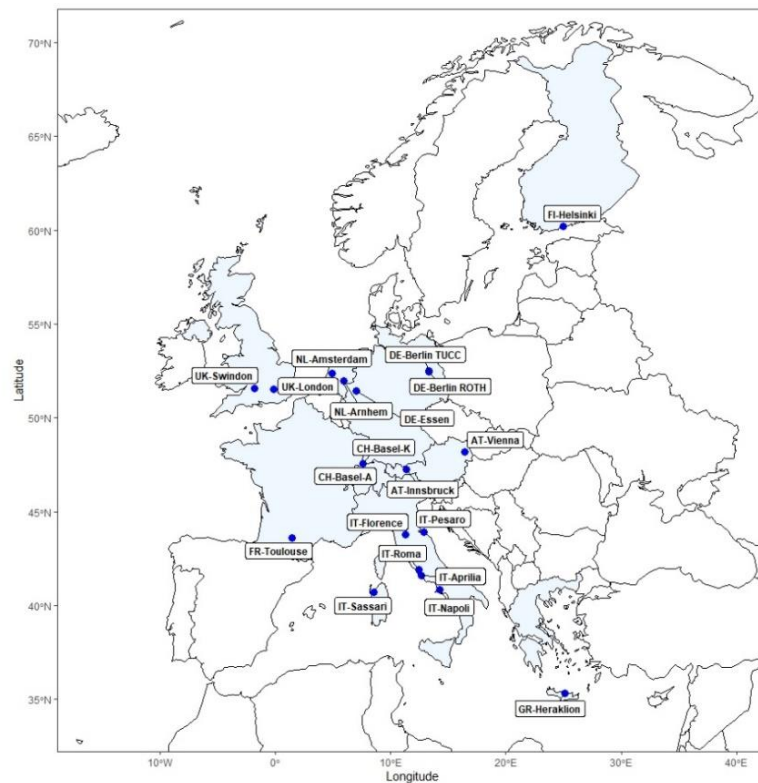


Figure 4. EC urban sites located in Europe

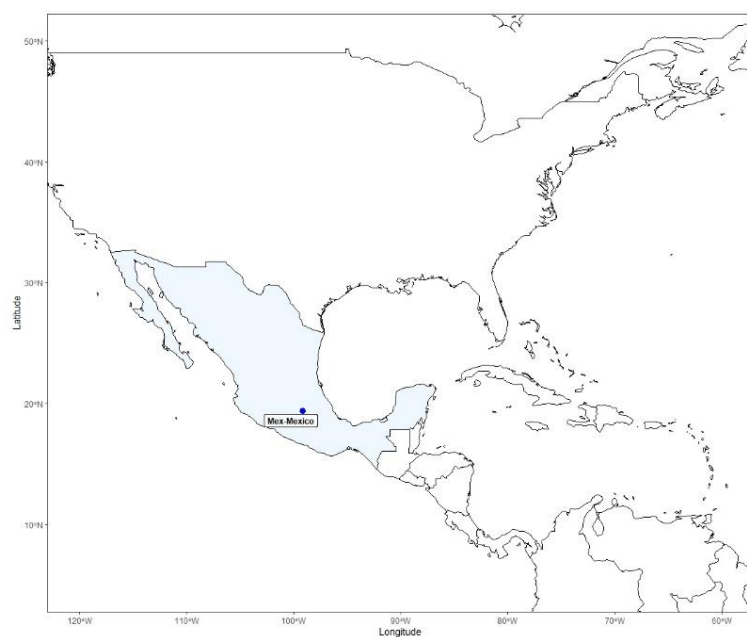


Figure 5. EC urban site of Mexico-City, Mexico

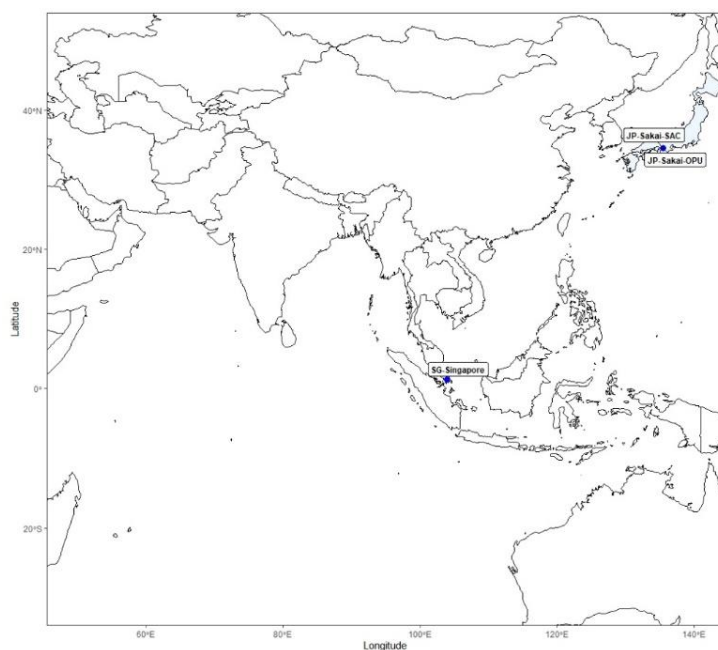


Figure 6. ExtraEurope EC urban sites located in Singapore and Sakai (Japan).

The following scheme (**tab. 1**) gives an overview of the cities involved in the present study with the relative EC sites, the years of EC measurement available for each site, and the instruments setup of the urban towers.

City	Station ID	Latitude	Longitude	Data range	z	z/z h	EC system	Main references
Innsbruck	AT-Innsbruck	47.264 0	11.3857	2017 2020 -08- -10- 01 31	42. 8	2.5	CSAT3; EC155	Karl et al., 2020
Vienna	AT-Vienna	48.181 8	16.3909	2018 2020 -01- -10- 01 01	144	7	WM Pro; LI- 7500	Matthews et al., 2020
Basel	CH-Basel- A	47.551 2	7.5956	2016 2020 -01- -10- 01 19	41	2.5	CSAT3; LI- 7500	Lietzke et al., 2015
Basel	CH-Basel- K	47.561 7	7.5805	2016 2020 -01- -10- 01 19	39	2.3	HS-100; LI- 7500	Lietzke et al., 2013
Berlin	DE-Berlin ROTH	52.457 2	13.3158	2018 2020 -06- -09- 01 30	40	2.4	Irgason	Vulova et al., 2020
Berlin	DE-Berlin TUCC	52.512 3	13.3279	2014 2020 -07- -09- 03 30	56	2.8	Irgason	Jin et al ., 2020
Berlin	DE-Essen	51.430 7	6.9929	2006 2007 -09- -10- 08 25	26	1.7	USA-1; LI- 7500	Kordowsk i & Kuttler, 2010
Toulouse	FR-Toulouse	43.603 5	1.4455	2004 2005 -02- -03- 20 10	47. 5	2.3	81000V; LI- 7500	Masson et al., 2008
Helsinki	FI-Helsinki	60.202 7	24.9623	2014 2020 -01- -09- 01 30	31	1.6	USA-1; LI- 7200	Järvi et al., 2009 Järvi et al., 2012
Heraklion	GR-Heraklion	35.336 2	25.1328	2016 2020 -10- -09- 27 30	27	2.4	Irgason	Stagakis et al., 2019
Aprilia	IT-Aprilia	41.588 8	12.6513	2015 2016 -07- -10- 03 06	31	2	--;LI-7000	n.a.
Florence	IT-Florence	43.774 4	11.2551	2005 2020 -09- -10- 14 22	33	1.3	81000V; LI- 7500	Gioli et al., 2012 Matese et al., 2009
Naples	IT-Napoli	40.847 3	14.2578	2015 2016 -01- -10- 01 12	45	1.5	Gill WindMaster ; IR spectrometer	Famulari et al., 2015

Pesaro	IT-Pesaro	43.912 0	12.9040	2014 -08- 09	2020 -10- 20	23	1.5	WM Pro; LI- 7500	n.a.
Rome	IT-Roma	41.899 0	12.4798	2004 -02- 05	2006 -01- 18	--	--	--	n.a.
Sassari	IT-Sassari	40.717 0	8.5759	2016 -01- 01	2020 -10- 26	22	2	HS-50; LI- 7200	n.a.
Arnhem	NL- Arnhem	51.984 7	5.9183	2012 -01- 01	2017 -09- 05	23	2	R3-50; LI- 7500	Kleingeld et al., 2017
Amsterdam	NL- Amsterdam	52.366 5	4.8929	2018 -05- 01	2020 -10- 13	40	2.8	CSAT3; LI- 7500	Steenefeld et al., 2020
Sakai	JP-Sakai- OPU	34.547 0	135.502 8	2014 -01- 01	2016 -01- 31	16	1.6	DA600;LI- 6262	Ueyama et al., 2016
Sakai	JP-Sakai- SAC	34.573 7	135.483 1	2014 -01- 01	2016 -01- 31	127	11	SAT- 550;LI-7500	Ando et al., 2016
Mexico- City	Mex- Mexico	19.404 2	-99.1761	2011 -06- 01	2012 -09- 13	37	3.8	CSAT3;LI- 7500	Velasco et al., 2014
Singapore	SG- Singapore	1.3143	103.911 0	2010 -08- 30	2017 -08- 28	20	2.2	CSAT3;LI- 7501	Roth et al., 2017
London	UK- London	51.521 4	-0.1388	2011 -09- 15	2020 -09- 30	190	22	R3-50; 1301-f / LI- 7500	Helfter et al., 2011
Swindon	UK- Swindon	51.584 6	-1.7979	2011 -05- 09	2013 -04- 25	12.	5	R3-50; LI- 7500	Ward et al., 2013

Table 1. Overview of the cities and respective EC sites involved in the research. The station ID is the naming used in this analysis, z is the measuring height, z/z_h is the ratio between z and mean building height (z_h). The -- indicate that there is no reference for the instrumentations and n.a indicate that there is no available bibliography

2.2 Data processing

The raw EC urban data were processed by the Principal Investigators (PI) of each site and their relative research group following commonly accepted principles available in the bibliography (Aubinet et al., 2012; Kaimal and Finnigan 1994; Roth 2000). The data processing was needed to obtain the half-hourly CO₂ fluxes used in this study.

Successively, a threshold value was used to eliminate improbable CO₂ fluxes. The range established goes from -50 to 200 $\mu\text{mol m}^{-2}\text{s}^{-1}$. During the processing phase also the data coming from instruments abortion or turbulence problems were eliminated. Furthermore, data coming from wind sectors disturbed by physical obstacles (e.g. tall building, measurement tower structure, etc) were discarded. The data were organized to have the same unit of measurements and same names of the different variables involved in the dataset to be able to process all the data with the same programming code. The name and unit of the variables were standardized following the European Eddy Fluxes Database Cluster rules for variables names and units of measurement (<http://www.europe-fluxdata.eu/home>).

The summary statistics of the distribution of the missing values it is used in the CO₂ flux time-series to understand the length of the gaps and the quality of the series. The missing values are the result of the missing raw data and data filtering explained above, furthermore they are calculated considering all the years of measurement present for each site and giving the percentage of missing value for each series.

2.3 Spatial data analysis

Spatial data has been used to analyze the land use and land cover (LULC) of each site. For each city around the tower, a circular frame was derived with the tower collocated in the middle. The radius of the circular frame was derived from the 70% footprint cumulative distribution distance. This length has been calculated for sites that provided footprint estimations, while for the other it is inter-/extrapolated according to an average fetch-to-height ratio or taken from the bibliography available for each site. This circular area is expected to contain the best part of the surface contributions to the measured fluxes.

Three were the main spatial source data used to analyze the footprint of the sites, and each layer of informations can be considered specific for one land use. Urban Atlas (UA) spatial data has been used to analyze the LULC compositions and was available for European cities with more than one hundred thousand inhabitants. OSM spatial data has been used whether to study the LULC composition of extra-European sites, one city located in the UK and one in Italy and for analyzing the quantity of primary roads for each source areas emission (section 2.4).

The PI recommendations and the Google Earth imagery, has been used, in addition to the spatial layers defined above, to define city-specific sectors by clustering areas with a characteristic composition. The sectors were classified as vegetated only when the presence of an urban park

was detected, otherwise the types of commercial or residential buildings, considered to have a stronger impact on CO₂ fluxes, were used as a guideline for the sectors clustering.

2.3.1 Urban Atlas

UA provides high-resolution LULC data for 788 Functional Urban Area for the 2018 reference year in EEA38 countries (EU, EFTA, Western Balkans countries, as well as Turkey and the United Kingdom). The UA is mainly based on the combination of image classification and visual interpretation of Very High-Resolution satellite imagery. Multispectral SPOT 5 & 6 and Formosat-2 pan-sharpened imagery with a 2 to 2.5 m spatial resolution is used as input data. The built-up classes are combined with density information on the level of sealed soil derived from the high-resolution layer imperviousness to provide more detail in the density of the urban fabric. Finally, the UA product is complemented and enriched with functional information (road network, services, utilities, etc) using ancillary data sources such as local city maps or online map services.

The spatial resolution of UA has a minimum mapping unit of 0.25 ha and a minimum mapping width of 10 m. The LULC categories have been resized to facilitate the result interpretation following the scheme below (**Tab. 2**). The sectors established were: building commercial (BC), building residential (BR), and vegetated (V) areas.

Urban Atlas classification	Analysis ID (Reclassification of the	
class_2018	Prevalent Land use)	Urban Atlas description
Continuous Urban Fabric (S.L. > 80%)	Residential (RES)	Build up areas and their associated land (if not reaching the minimum mapping unit size).
Discontinuous Dense Urban Fabric (S.L. : 50% - 80%)		Residential structures and patterns are predominant, but also downtown areas and city centers, including central building districts and areas with partial residential use subclasses are distinguished by the degree of sealing
Discontinuous Medium Density Urban Fabric (S.L. : 30% - 50%)		
Discontinuous Low Density Urban Fabric (S.L. : 10% - 30%)		
Discontinuous Very Low-Density Urban Fabric (S.L. < 10%)		
Isolated Structures		
Industrial, commercial, public, military, and private units	Commercial (COM)	At least 30% of the ground is covered by artificial surface,

		more than 50% of which are occupied by buildings with non-residential use (industrial areas, commercial activities, schools, universities, hospitals, military areas)
Fast transit roads and associated land	Roads (R)	Fast transit roads are defined as motorways (including motorway rests, parking, etc), other roads, crossing, roundabouts. Railway facilities include stations, cargo, and service areas.
Other roads and associated land		
Railways and associated land		
Port areas	Port areas (PA)	Areas of inland harbours and sea ports, including infrastructures. Areas of airports including runways, associated buildings and military airports
Airports		
Mineral extraction and dump sites	Mineral, dump, construction MD	Open-pit extraction site, the surface under construction or development, waste land, removed former industrial areas, gaps between constructions.
Construction sites		
Land without current use		
Green urban areas	Green urban areas (GA)	Vegetation planted, regularly worked by humans, strongly human-influenced (public green areas, gardens, playgrounds, zoos, cemeteries). Sports facilities and associated land (e.g., public arenas, golf courses, sports fields, racecourses)
Sports and leisure facilities		
Arable land (annual crops)	Agriculture (AG)	Arable land, irrigated or not, permanent crops, pastures, mixed cultivation patterns
Permanent crops (vineyards, fruit trees, olive groves)		
Pastures		
Complex and mixed cultivation patterns		
Orchards at the fringe of urban classes		
Forests	Natural (NAT)	Forests, woodlands, shrubs (tree canopy coverage > 30%), plantations, herbaceous vegetation
Herbaceous vegetation associations (natural grassland, moors...)		

Open spaces with little or no vegetations (beaches, dunes, bare rocks, glaciers)		association, grasslands, inland wetlands
Wetlands		(e.g., water fringe vegetation, peat bogs, alluvial plains, sedges)
Open spaces with little or no vegetation	Bare soil (BS)	Beaches, dunes, bare rocks, sparsely vegetated areas
Water bodies	Water (WA)	Sea, lakes, rivers, canals

Table 2. European UA classification and corresponding aggregated LULC classes used in this analysis.

2.4 OpenStreetMap classification

The OpenStreetMap (OSM) project (www.openstreetmap.org) allows using free spatial data available thanks to Geofabrik GmbH. The spatial data refer to a general use of the essential cover property such as roads, type of building, waterways, different land-use types, and points of interest.

2.4.1 Roads analysis

The OSM roads layer has been used to extrapolate the primary roads within the sector previously established (residential, commercial, and natural areas). Since the roads are expressed as linear features, it was possible to calculate the sum of linear meters per hectare of major roads within each sector representative of the site's footprint. The calculation was done with the use of the software ArcGIS (ArcMap version 10.6.1). Then, the meters per hectare of primary roads have been reported on the surface of each sector or of the entire footprint to calculate the linear meter per hectare of primary roads.

Magnitudes of CO₂ fluxes were related to the quantity of primary roads, expecting higher emissions where there is a higher presence of roads.

In the following table (**Tab. 3**) the classifications used for the primary roads investigation are shown.

code	fclass	Description	Analysis ID
Major roads			
5111	Motorway	Motorway/freeway	Primary roads
5112	Trunk	Important roads, divided	typically Primary roads

5113	Primary	Primary roads, typically national	Primary roads
5114	Secondary	Secondary roads, typically regional.	Primary roads
5115	Tertiary	Tertiary roads, typically local	Primary roads
Minor roads			
5121	Unclassified	Smaller local roads	NOT USED
5122	Residential	Roads in residential areas	NOT USED
5123	Living_street	Streets where pedestrians have priority over cars	NOT USED
5124	Pedestrian	Pedestrian only streets	NOT USED
Highway links (sliproads/ramps)			
5131	Motorway_link		Primary roads
5132	Trunk_link	Roads that connect from one road to another of the same of lower category	Primary roads
5133	Primary_link		Primary roads
5134	Secondary_link		NOT USED
5135	Tertiary_link		NOT USED

Table 3. OpenStreetMap roads classification and corresponding aggregated roads classes.

Only primary roads were used in this analysis, indeed they were considered as those that could have a greater impact on CO₂ emissions.

The analysis of the possible effect of primary roads on CO₂ fluxes focuses on those sites that present the possibility to compare the residential against commercial sectors in terms of meter per hectare of primary roads and magnitude of CO₂ fluxes. Sites with vegetated sectors were discarded from the present analysis since there are no primary roads within those sectors. The difference of linear meter per hectare of primary roads has been calculated between the two sectors and has been related to the difference of CO₂ fluxes between the two sectors in a different part of the day (e.g. night VS day) and in a different part of the week (e.g. Weekday VS Weekend).

2.4.2 Building analysis

OSM land-use layer classification is based on the typology highlighted in the **Tab. 4**. The categories are comparable with UA, indeed the building are divided in commercial and residential type.

code fclass	Description	Analysis ID
7201 forest	forest or woodland	GUA
7202 park	A park	GUA
7203 residential	A residential area	BR
7204 Industrial	An industrial area	BC
7205 cemetery	An industrial area	--
7206 allotments	An area with small private gardens	GUA
7207 meadow	A meadow, possibly used for grazing cattle	GUA
7208 commercial	A commercial area	BC
7209 nature reserve recreation	A nature reserve	GUA
7210 ground	An open green space for general recreation	GUA
7211 retail	An area mainly used by shops	BC
7212 military	Military landuse, usually no access for civilians	BC
7213 quarry	A quarry	MDC
7214 orchard	An area used for growing fruit-bearing trees	AGR
7215 vineyard	An area used for growing grapes	AGR
7216 scrub	An area where scrub grows	GUA
7217 grass	An area where grass grows	GUA
7218 heath	Heath areas	BC
7219 national park	A national park	GUA
7220 basin	A basin	WAT
7221 village green	A green area in the centre of a village	GUA
7222 plant nursery	Areas where plant nurseries exist	BC
7223 brownfield	The land where old buildings have been demolished and cleared	BS
7224 greenfield	Land scheduled for new development where there have been no buildings before	BS
7225 construction	A construction site	MDC

7226 railway	Area used for railway operations. Not all land used for the railway is covered by this type	RR
7227 farmland	Agricultural land (areas where crops are grown)	AGR
7228 farmyard	Area of land with farm buildings and the shrubbery/trees around them	AGR

Tabel 4. OSM LULC classification and corresponding aggregated LULC classes used in this analysis.

The ArcGis program was used to derive the percentage of LULC within each footprint and realtive sectors. In case, the spatial information contained missing values such that it was not possible to have a description of the land use of the site, the bibliography available for each site together with the principal investigator suggestions was used to classify the areas of interest.

2.5 Urban vegetation analysis

2.5.1 Normalized difference vegetation index

The NDVI is one of the most used vegetation indexes for vegetation analysis (Jiang et al., 2006) and its usefulness in monitoring natural ecosystems was shown over the past years (Leprieur et al., 2000). The NDVI index, which normalizes green leaf scattering in the near infra-red with chlorophyll absorption of red wavelengths, was derived from Sentinel-2 satellite images (10 m resolution) available within the Copernicus open access hub of sentinel product (<https://scihub.copernicus.eu>). The index is commonly used as a proxy for live green vegetation activity and its range goes from -1.0 to +1.0. Rocks, sand, or snow show low NDVI values (e.g. 0.1 or negative), shrubs, grasslands, or crops show moderate NDVI values (e.g. 0.2 to 0.5), dense vegetation shows high NDVI values (above 0.6). NDVI time series were obtained from bands 4 and 8 of the Sentinel-2 multispectral imagery ($NDVI = (B8 - B4) / (B8 + B4)$).

The NDVI has been used to characterize and quantify the percentage of vegetated areas within each sector established with the spatial data classification scheme. The NDVI index was needed to focus on vegetated areas within EC urban sites since the UA shape file did not distinguish precisely the vegetation patches: the vegetation is not uniformly distributed and scattered vegetation spots are smaller than the spatial resolution unit of UA.

The NDVI values were filtered for values with a range from 0.4 to 0.8 to focus the investigation on the urban areas with more dense vegetation and possibly with adult trees instead of shrubs and grass.

The mean NDVI value and the percentage of vegetation have been calculated for any site involved in the analysis, using the following operations:

percentage of vegetation:

$$\frac{\text{The total area of vegetated pixel (m2)}}{\text{Area of the sector of interest (m2)}} * 100$$

Mean NDVI value of the vegetation:

$$\frac{\text{Sum of total NDVI values for each pixel}}{\text{Total number of pixel}}$$

NDVI index was needed to calculate the percentage of vegetation within each site or in the relative sectors to investigate the greenery effect within urban areas.

The Sentinel-2 images used for the NDVI calculation were manually downloaded avoiding cloudy periods thanks to a visual inspection that is allowed on the Copernicus website. The NDVI data were downloaded for summer sunny day when the photosynthesis would be considered highly active to determine the quantity of vegetation for each site and/or relative sectors.

Since the Copernicus program has been started in 2015, the NDVI data were downloaded in order to overlay the CO₂ fluxes series present for each site. In the other cases when the EC series were recorded before 2015 the NDVI data were downloaded in the first year available on Copernicus (2015) considered such as the nearest year to the E series. In the latter case, as well as comparing the results of the analysis with those present in the bibliography, a visual inspection was made thanks to the historic function of google earth that allows seeing the same areas in different years to check for any changes in the quantity and eventual position of the vegetation.

The percentage of the green areas within each site's sector has been related to the mean CO₂ fluxes during the summer periods: the aim is to study the sink effect of the vegetation testing whether the major presence of vegetation within the site's sectors is associated with the smaller

magnitude of CO₂ fluxes. The analysis is restricted to those sites that present two sectors so is possible to compare the presence of vegetation and CO₂ fluxes within the same urban EC stations source emissions areas.

To capture the greenery effect, the data were filtered by selecting the most opportune conditions for photosynthesis development:

- the CO₂ fluxes were investigated within June and July considering them such as the moment of the year where the sink effect would be more active. Furthermore, the analysis does not consider the fluxes within August, indeed protracted drought and warm temperature may bring the vegetation to act as a source of CO₂.
- The part of the day where the photosynthesis activity is considered stronger was studied: the analysis is focused on the middle day time between 9 am and 3 pm.

The data treatment regarding the CO₂ fluxes within the periods above specified consisted of:

- calculating the mean CO₂ fluxes within each 30 min window of interest (9 am – 3 pm)
 - calculating a unique average flux considering the previous 30 min averaged period.
- Those operations aims to have a final and unique mean value available for each sector in each period of interest.

The percentage of vegetation within each sector was related to the corresponding mean CO₂ fluxes within the period of interest for each site's sectors.

Furthermore, the type of vegetation, characterized by the averaged NDVI values was considered as a correction factor and it was multiplied for the percentage of vegetation. Indeed higher NDVI values correspond to greater photosynthetic capacity and the other way around.

Finally, wind sector representativeness has been checked following the rules presented in the next chapter.

2.6 Wind sector representativeness

The footprint of the sites can be defined as the area “seen” by the instrumentation mounted on the EC tower (e.g. gas analyzer and sonic anemometer). In other words, it is an area upwind from the tower, such that fluxes generated in this area are registered by the tower instruments (George Burba 2013). In this picture, by analyzing the wind directions it is possible to attribute the fluxes to a particular sector with specific land use. Every time that the CO₂ fluxes are

investigated in a restricted area of the footprint (e.g. sectors) and a confined temporal series (e.g. seasons, specific part of the day) frequency analysis of the wind direction data was done to verify the comparability of different sectors within the same emission area.

2.7 Fluxes and temperature

2.7.1 Change point detection analysis

The change point detection (CPD) analysis is widely used in climate change research to measure temporal detection discontinuities (Solow, 1987; Barr et al., 2012) and it tries to investigate moments when the probability distribution of a time series changes.

The next image (**Fig. 7**) gives an example of urban EC time series that contains one prevalent change point: CPD aims to identify the two stated borders divided from the change point (Aminikhanghahi et al., 2017).

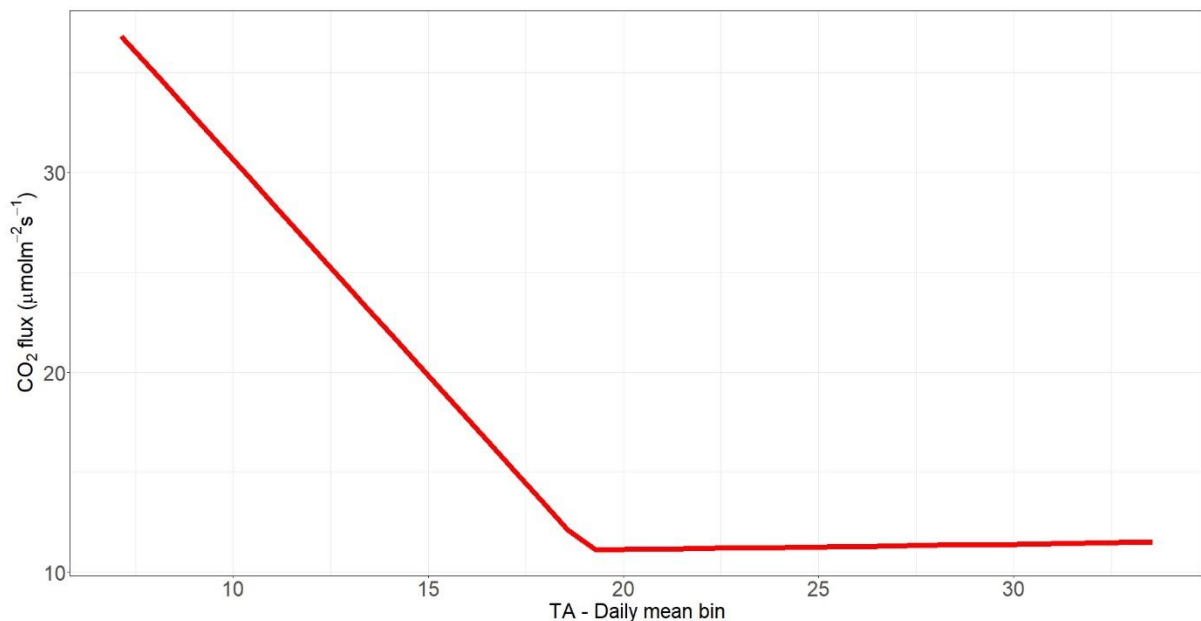


Figure 7. Sample of EC time series from the Ximeniano site of Florence and relate air temperature on the x-axis and CO₂ fluxes on the y-axis.

The overall CPD analysis is based on the segmented function available in the software R statistics according to the package called “segmented” (Muggeo, 2008). The function applies a linear model to a segmented relationship between two variables or two points.

The proficiency of the CDP analysis to discover abrupt variations within time series analysis have been applied in this study to investigate the relation between air temperature and CO₂

fluxes. The main objective was to understand when the magnitude of FC changes according to a possible change in air temperature.

Quantiles of temperature have been calculated for each site according to the corresponding air temperature series using a probability range that varies from 0.1 to 1 with a step of 0.03. Within the latter interval, the mean CO₂ fluxes have been calculated. The time resolution of those calculations was at 30 min intervals.

The CDP has been applied to fluxes and temperatures recorded in different LULC conditions within the same source areas. The aim of this analysis was to asses:

- the influence of the heating systems on emissions;
- classify the typical emissions coming from a residential and Commercial areas;
- explore a data-driven method for flux partitioning.

3 Results and Discussions

3.1 Sector-based classification

3.1.1 Commercial and Residential areas

Sectors have been classified in commercial (BC), residential (BR), and vegetated (V) areas according to the LULC features shown in **Fig. 8**. In case the site showed a uniform LULC in terms of residential or commercial land use, the site has a single reclassified land use.

The Tabel 5 shows the percentage for each type of LULC per each sector and the font used for the description of the source areas. Table 6 shows the LULC composition of the sites for which the spatial information was not enough to characterize the source emission areas

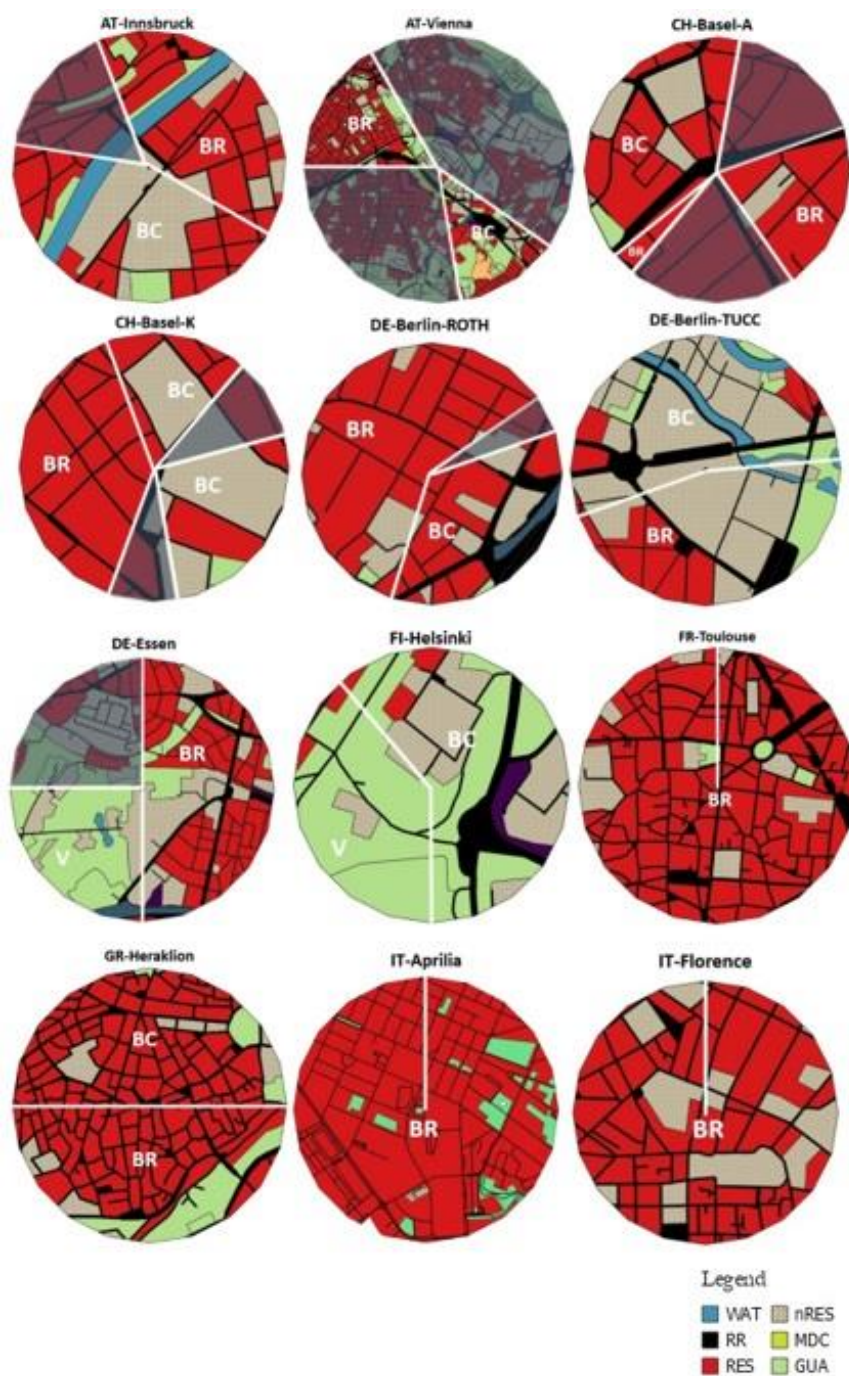
Site_ID	Sector	RES	COM	GA	MD	PA	R	WA	BS	Font
AT-Innsbruck	BC	38.3	39.36	7.72	--	--	6.35	8.27	--	UA
AT-Innsbruck	BR	60.55	14.63	5.82	--	--	10.2	8.8	--	UA
AT-Vienna	BC	30.95	14.45	25.77	1.19	--	20.08	--	--	UA
AT-Vienna	BR	56.29	11.07	11.64	1.23	--	19.78	--	--	UA
CH-Basel-A	BC	58.05	20.57	2.63	--	--	18.76	--	--	UA
CH-Basel-A	BR	77.98	11.2	--	--	--	10.83	--	--	UA
CH-Basel-K	BC	31.84	58.84	2.64	--	--	6.67	--	--	UA
CH-Basel-K	BR	90.15	0.01	--	--	--	9.84	--	--	UA
DE-Berlin-ROTH	BC	49.78	19.55	0.79	--	--	29.88	--	--	UA

DE-Berlin-ROTH	BR	79.65	12.58	0.75	--	--	7.03	--	--	UA
DE-Berlin-TUCC	BC	9.31	58.38	6.86	--	--	18.24	7.22	--	UA
DE-Berlin-TUCC	BR	23.2	48.35	12.58	--	--	12.35	3.52	--	UA
DE-Essen	BR	49.54	25.13	8.48	1.24	--	15.61	--	--	UA
DE-Essen	V	0.44	23.89	67.3	--	--	6.73	1.64	--	UA
FI-Helsinki	BC	5.33	33.67	40.45	3.95	--	16.6	--	--	UA
FI-Helsinki	V	1	5.63	90.13	--	--	3.24	--	--	UA
FR-Toulouse	BR	68.43	10.3	1.62	--	--	19.64	--	--	UA
GR-Heraklion	BC	64.05	8.16	4.85	--	--	22.94	--	--	UA
GR-Heraklion	BR	57.2	6.7	14.58	--	--	21.52	--	--	UA
IT-Aprilia	BR	83.53	0.34	10.37	5.75	--	--	--	--	OSM
IT-Florence	BR	56.71	24.57	2.1	--	--	16.62	--	--	UA
IT-Napoli	BR	47.46	17.21	--	--	8.44	20.37	6.51	--	UA
IT-Pesaro	BC	8.62	63.89	1.74	--	--	25.76	--	--	UA
IT-Pesaro	BR	36.3	3.46	53.22	--	--	7.02	--	--	UA
IT-Roma	BR	51.59	30.51	0.01	--	--	17.89	--	--	UA
IT-Sassari	BC	38.35	47.26	0.69	--	--	13.71	--	--	UA
IT-Sassari	BR	19.84	68.35	--	--	--	11.82	--	--	UA
NL-Amsterdam	BC	55.47	1.59	1.84	--	--	25.81	15.29	--	UA
NL-Amsterdam	BR	64.82	--	--	--	--	21.5	13.69	--	UA
NL-Arnhem	BR	57.87	15.76	9.77	0.19	--	16.41	--	--	UA
UK-London	BC	55.55	19.36	5.49	0.33	--	18.61	0.66	--	UA
UK-London	BR	53.6	7.01	23.57	0.23	--	14.17	1.42	--	UA

Table 5. LULC composition is shown such as percentage of the sector or in the entire footprint area. The column font exprime the type of spatial data used for the analysis. The Land use land cover classification of the sites and relative sectors definition was done according to join evaluation of UA-maps, Google Earth imagery, and specific knowledge of the sites from the principal investigators. For the columns such as indicated in tab.2: RES for building residential, COM for building commercial, GA for green areas, MD for mineral extraction sites, PA for port areas, R for roads, WA for water, BS for bare soil.

Site_ID	Sector	RES	COM	GA	MD	PA	R	WA	BS	Font
JP-Sakai-OPU	BR	9	69	44	--	--	10	--	--	Ueyama & Ando., 2016
MEX-Mexico	BR	57	--	6	--	--	37	--	--	Velasco et al., 2014
SG-Singapore	BR	39.18	--	14.43	--	--	46.39	--	--	Roth et al.,2017
UK-Swindon	BR	16	--	44	--	--	33	--	6	Ward H.C et al.,2013
JP-Sakai-SAC	BC	27	34	14	--	--	27	--	--	Ueyama & Ando., 2016
JP-Sakai-SAC	BR	9	38	14	--	--	29	--	--	Ueyama & Ando., 2016

Table 6. LULC composition is shown such as percentage of the sector or in the entire footprint area. For these sites, the classification was done according to join evaluation of the reference bibliography, Google Earth imagery, and specific knowledge of the sites from the principal investigators. The references allowed a classification that follows the main definition of residential VS commercial land use.



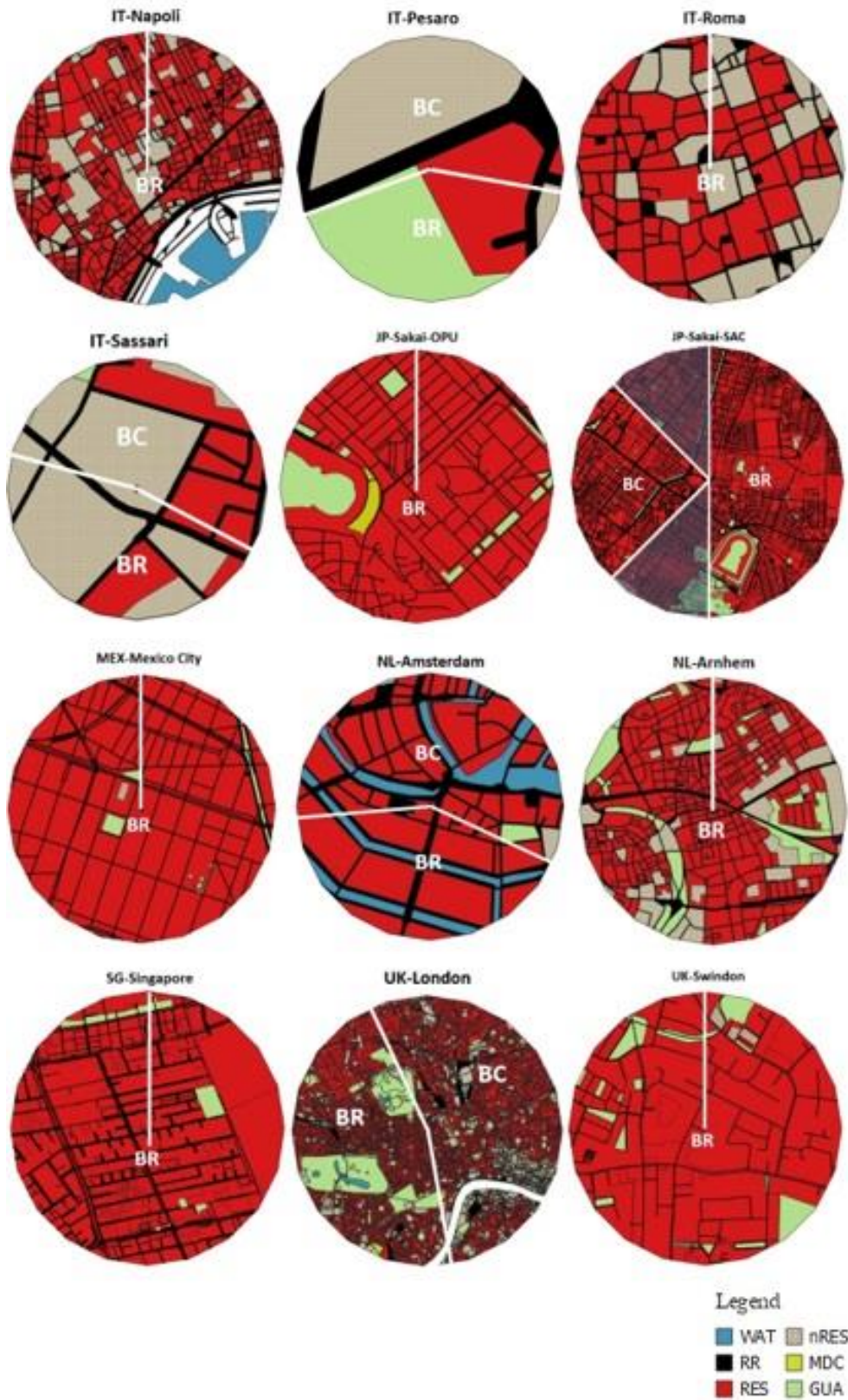
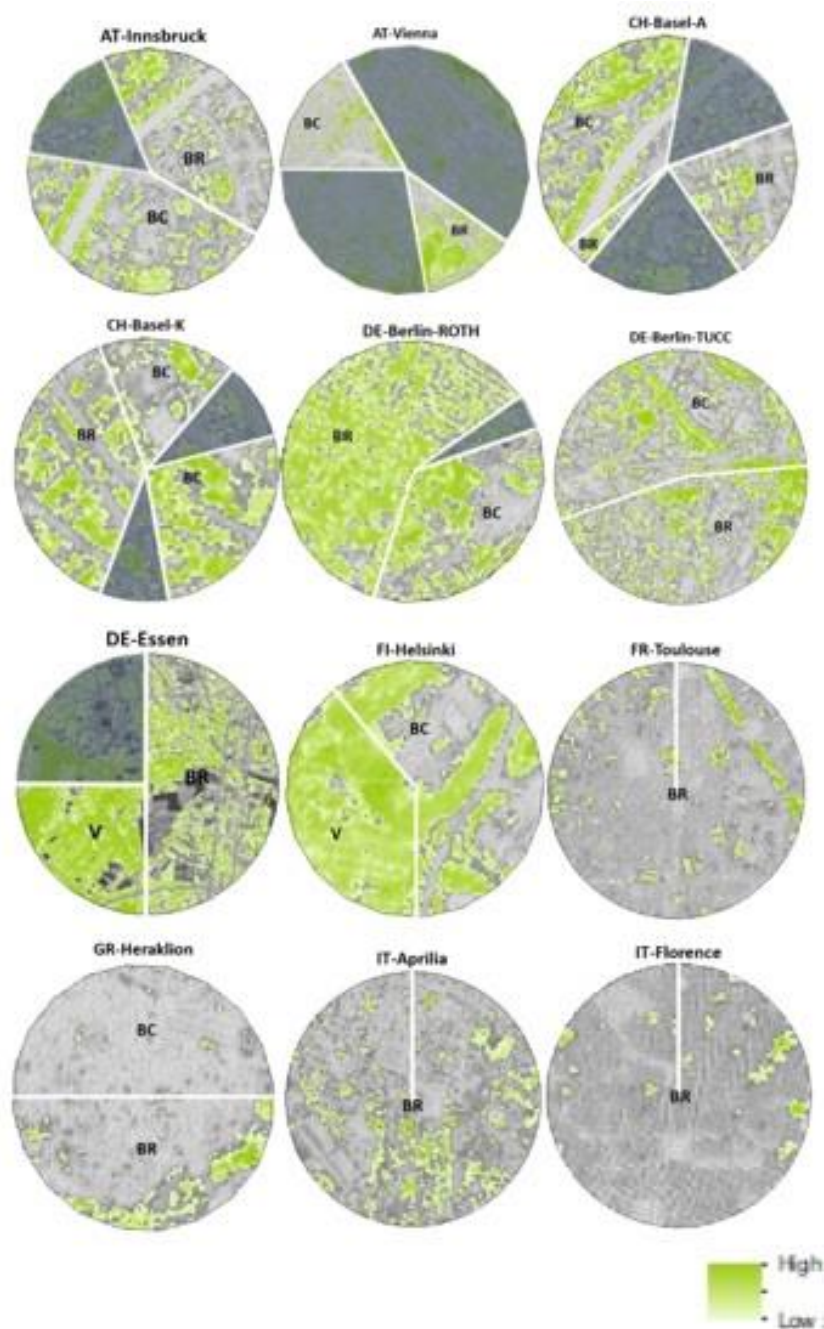


Figure 8. LULC sites maps according to a reclassification of the original layer of UA and OSM. The produced wind sectors are highlighted with white color while the white writing describes the type of sector or the entire footprint definition (BC for building commercial; BR for building residential; V for building residential).

Vegetated). The shaded areas define the sectors discarded from the analysis (e.g. tower obstruction, data filtering, or wind absence) and the circular frame radius length is the average 70% cumulative footprint distance.

3.1.2 Vegetated areas

The green fraction has been calculated for each existing sector within each site (**Fig. 9**). As expected, there is high variability between sites and sectors passing from districts with almost no vegetation like IT-Florence, FR-Toulouse, IT-Napoli, GR-Heraklion, and areas with plentiful vegetation such as DE-Essen, DE-Berlin-ROTH, and FI-Helsinki.



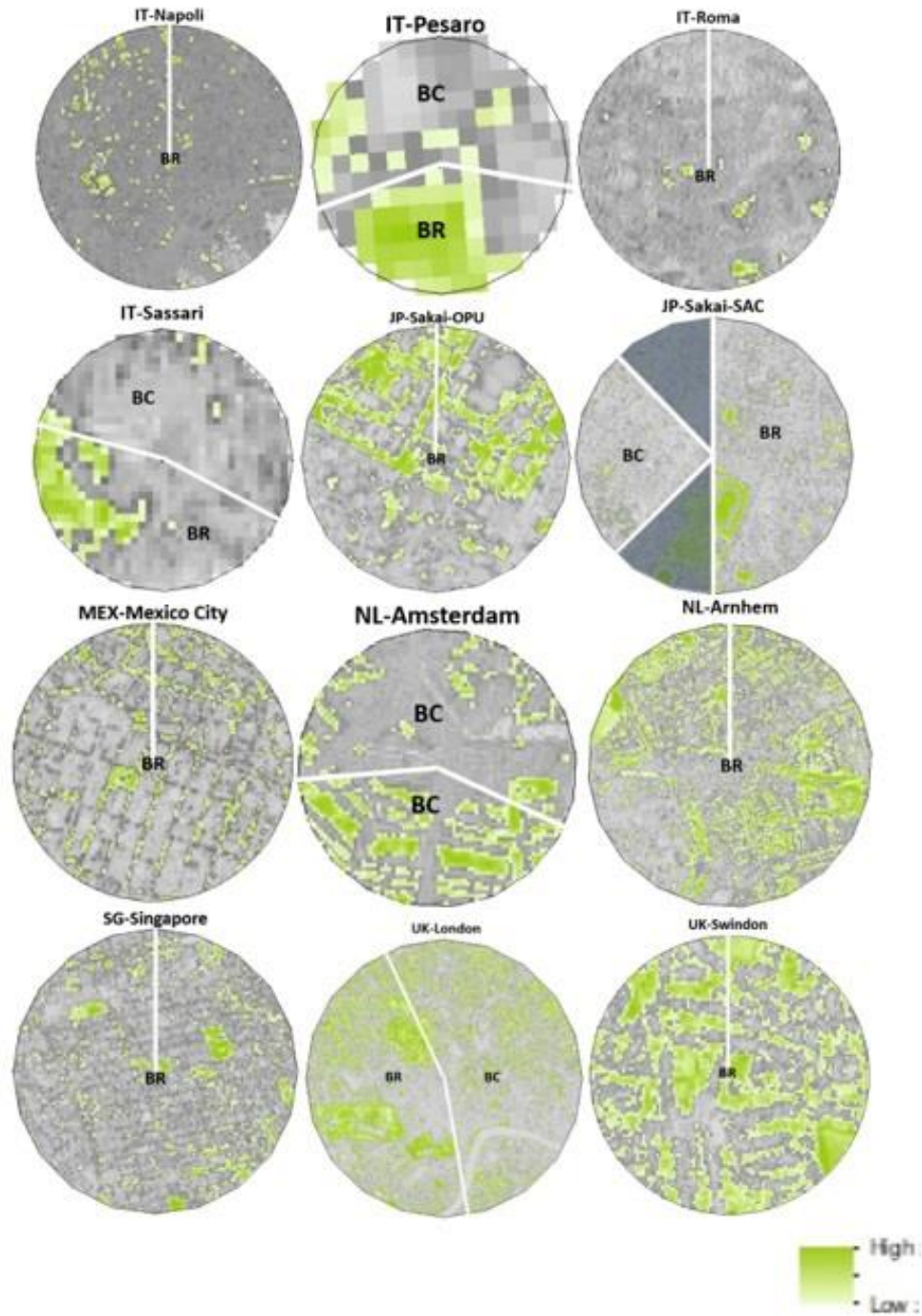


Figure 9. The green areas for each sector are showed. The green color localizes the green areas, high values with a bright green define NDVI values close to 0.8 while low values with a soft green describe NDVI values close to 0.4. The grey color is used as background color and has not any value while the abbreviations of sectors are BC for building commercial, BR for building residential, and V for vegetated areas.

3.1.3 Primary roads

The linear meters per hectare of primary roads for each sector or within the entire footprint are shown in the next plot.

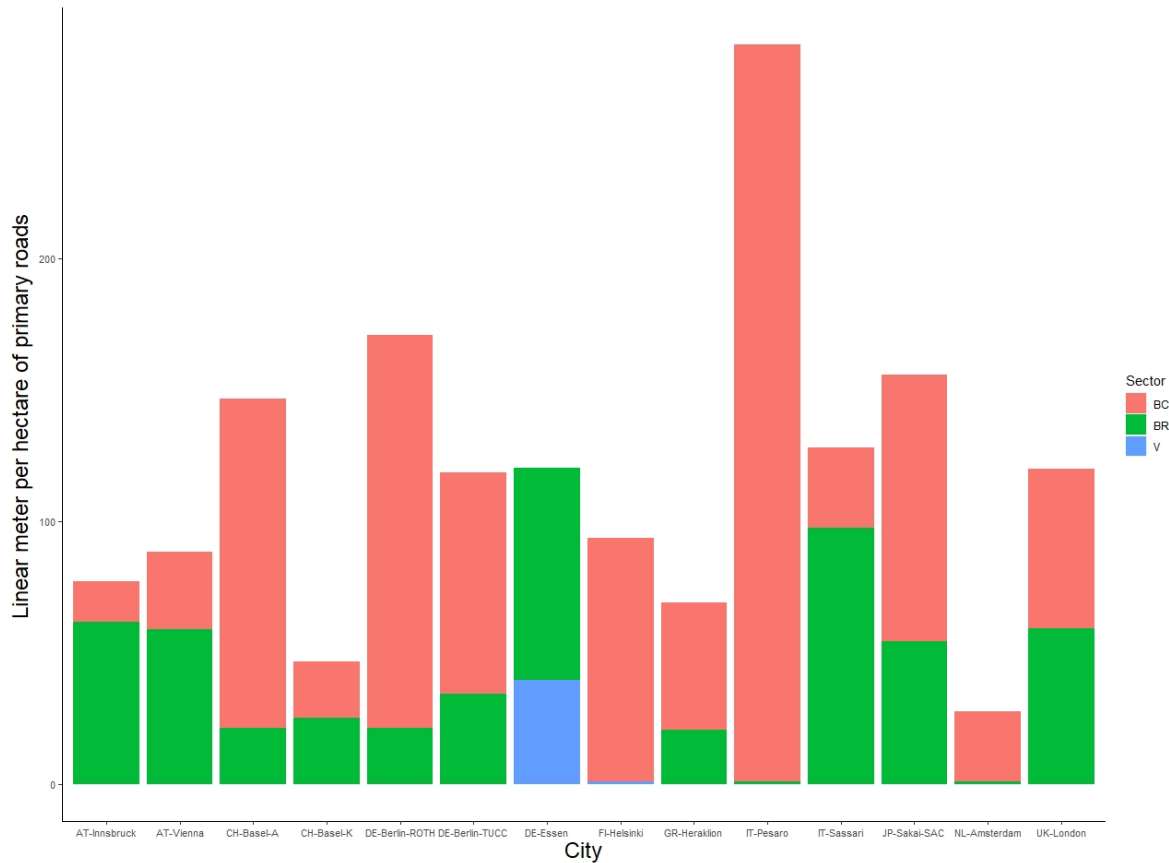


Figure 10. The presence of primary roads is shown using the OSM traffic layer. The first column determines the site name, the second the type of sector previous established while the third column gives the linear meter per hectare of primary roads

3.2 Vegetation analysis

3.2.1 Wind sector representativeness

The representativity of CO₂ fluxes during the period of interest within the sectors involved in the vegetation analysis is presented in the next plots. The first attempt to study the wind sector representativity is to examine the sum of observation for every 30 minutes within each sector in the period of interest and consider all the years of measurement available for each site (**Fig. 11**). This analysis aims to understand whether there is an unbalance between the wind observation coming from each sector within the respective site's footprint.



Fig 11. Wind sector representativeness is shown in the period of interest (9 am - 3 pm) during June and July within the commercial (BC), residential (BR), and vegetated (V) areas. The x-axis represents the half hours involved in the investigation while the y-axis shows the sum of observations for each sector. The colours distinguish the three sectors: red for commercial, green for residential, and blue for vegetated areas. The two numbers in the upper part of each plot give the percentage of the observation calculated in all the half hours between 9 am to 3 pm.

The sector representativity can be considered comparable for all the sites except for the site of GR-Heraklion. In the latter site, there is a small contribution to the measured fluxes within the residential sector with a percentage of observation calculated in all the periods under investigation equal to 1.4 %. The next analysis takes into consideration the number of observations that compose each 30-minute bin to discard or not a site or a precise half-hour from the vegetation study (**Fig. 12**). In this analysis, the boxplot of CO₂ fluxes is used showing at the same time the number of observations that compose each 30 minutes bin. The analysis is threefold: i) to investigate the variability of the data, ii) to analyze the representativity of each 30 min bin, iii) to check if there are CO₂ fluxes at 30 min scale that can be considered as

spike.



Figure 12. The x-axis defines each half-hour, the y-axis shows the CO_2 fluxes in $\mu\text{mol m}^{-2}\text{s}^{-1}$, the upper limit shows the 75th percentile, the lower limit shows the 25th percentile while the black bar in the middle shows the median. The black numbers in the upper part of each boxplot show the number of observations that compose each 30 minutes bin.

The percentage of data within the residential sector of GR-Heraklion in the middle day is equal to 1.4 % against the 99.6 % of the building commercial sector, besides the mean number of observations within each 30 minutes bin shows an average equal to 2.7 for the residential sector while the BC sector shows an average of observation equal to 195. The latter results confirm that there is no balanced representativity between the BR and BC sector for the site of GR-Heraklion and for this reason this site will be discarded from the vegetation analysis.

The emissions that occurred in JP-Sakai-SAC at 10 am within the building commercial sector are eliminated: the upper limit of the interquartile range arrives at $120 \mu\text{mol m}^{-2}\text{s}^{-1}$ so three times bigger than the average emissions of the site, furthermore this result is composed just of two observations.

3.2.2 Greenery effect in the urban context

Figure 13 shows the percentage of vegetation for each district: high variation amongst sites is observable, passing from sites with almost no vegetation such as IT-Roma, IT-Florence, and FR-Toulouse to sites with profuse vegetation such as DE-Essen and DE-Berlin-ROTH and FI-Helsinki.



Figure 13. The percentage of vegetation and relative averaged NDVI is presented for each site's sector. The x-axis shows the sector of interest while the y-axis shows the percentage of vegetation. The two red numbers in the upper part of each site sector's barplot indicate the averaged NDVI value relative to the vegetation that insists in each sector. The name of the sectors refers to building commercial (BC), building residential (BR), and vegetated areas (V).

Figure 14 summarize the analysis on the impact of vegetation sink on CO₂ fluxes: the x-axis shows the percentage of vegetation multiplied for the mean NDVI value within each city sector, while the mean fluxes within the summer middle day time (9 am - 3 pm) are shown in the y axis. The arrows connect the sectoral emissions within the same footprint and they are moving from the sector with less to the sector with more vegetation: smaller fluxes are expected in the sector with greater amount of vegetation.

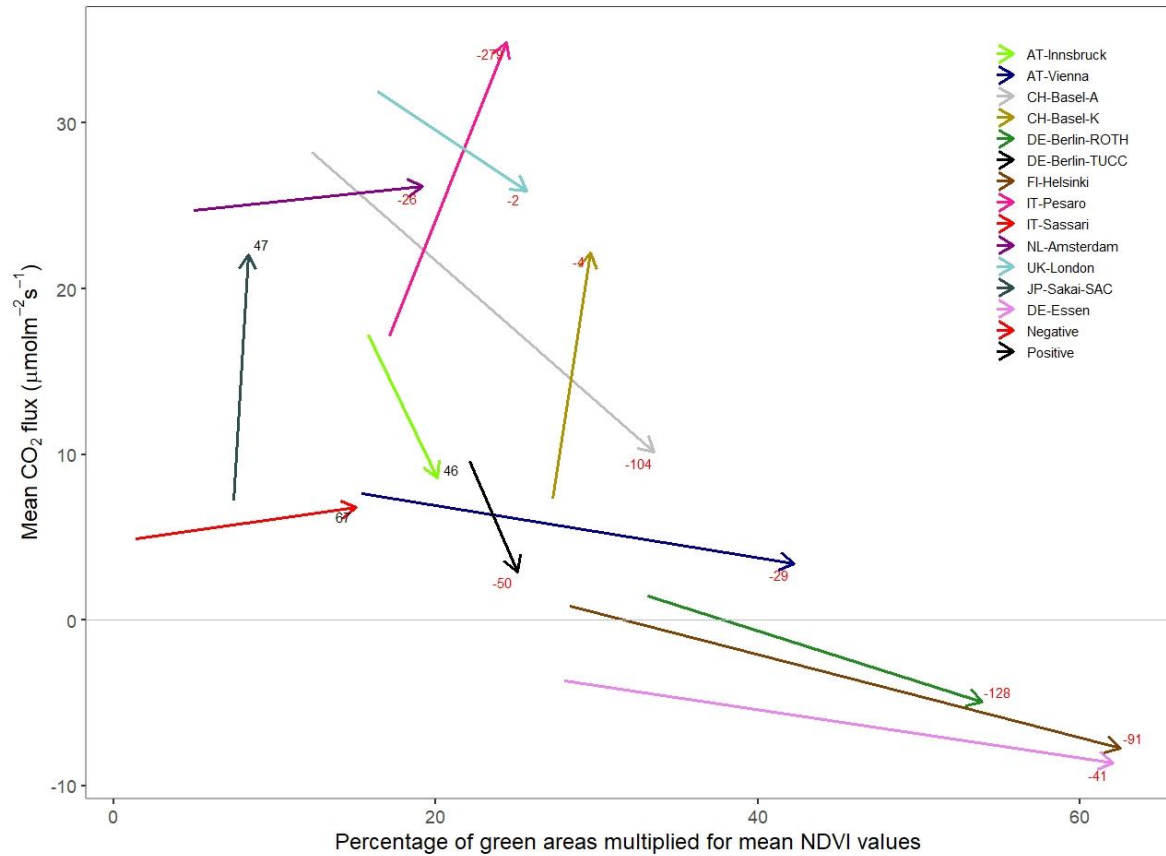


Figure 14. The x-axis shows the percentage cover of vegetation within each sector (residential, commercial, and vegetated) multiplied per the mean NDVI value (used such as correction factor) while the y-axis shows the averaged 30 min fluxes within the period of interest (middle day in June and July) for the two-sector within the same footprint. The arrows move from the sector with less to the one with more vegetation and the ends of the arrows show the average 30 min fluxes within each of the two sectors. The numbers at the end of the arrows show the difference of linear meter per hectare of primary roads between the two sectors and they are red if the sector has fewer primary roads and black in the opposite case.

For the sites of AT-Innsbruck, IT-Pesaro, JP-Sakai-SAC, DE-Berlin-TUCC, CH-Basel-K the difference in vegetation between the two sectors, represented from the distance between the ends of the two arrows in the x-axis, is very small: vegetation could not be considered one of the responsible of the difference in CO₂ emissions observed within the sectors.

The site of IT-Sassari and NL-Amsterdam shows a similar emissions pattern indeed the sector with more vegetation shows major emissions attesting that the vegetation signal is not giving any evidence. The level of emissions between the two sectors for each site are comparable, attesting that the urban metabolism is acting similarly within the different sectors of IT-Sassari and NL-Amsterdam.

For the sites of AT-Vienna, CH-Basel-A, DE-Berlin-ROTH, DE-Essen, and FI-Helsinki the arrows are moving from the upper left side to the right down part and the major presence of vegetation can be associated with smaller CO₂ fluxes. In these cases, the percentage of vegetation difference between the two sectors is higher than 30% and a possible sink effect is observed: the sector with more vegetation shows smaller averaged fluxes within the period investigated.

The assumption that the reduction in fluxes is due to the sink effect is confirmed in the cases of DE-Essen, DE-Berlin-ROTH, and FI-Helsinki where the mean fluxes in the sectors with more vegetation reach negative values attesting that the vegetation is acting such as sink. For the first site, the CO₂ fluxes arrive at -8.61 umol/m²s⁻¹ for the second arrive at -4.9 umol/m²s⁻¹ and the last site shows values close to -7.75 umol/m²s⁻¹. The major presence of green fraction is associated also with less presence of primary roads attested from the red numbers in the ends of the arrow that describe the negative difference in linear meter per hectare of primary roads between the two sectors. The latter consideration finds evidence in past studies that were using the EC method in an urban ecosystem: a greater green fraction correlates with lesser road and population densities (Nordbo et al., 2012).

3.3 Primary road's effect on carbon dioxide fluxes

Figure 15 displays in the y-axis the difference of the mean CO₂ fluxes between BC-BR sectors (Building commercial – Building residential) in umol/m²s⁻¹ while the x-axis shows the difference in linear meter per hectare of primary roads between the same sectors.

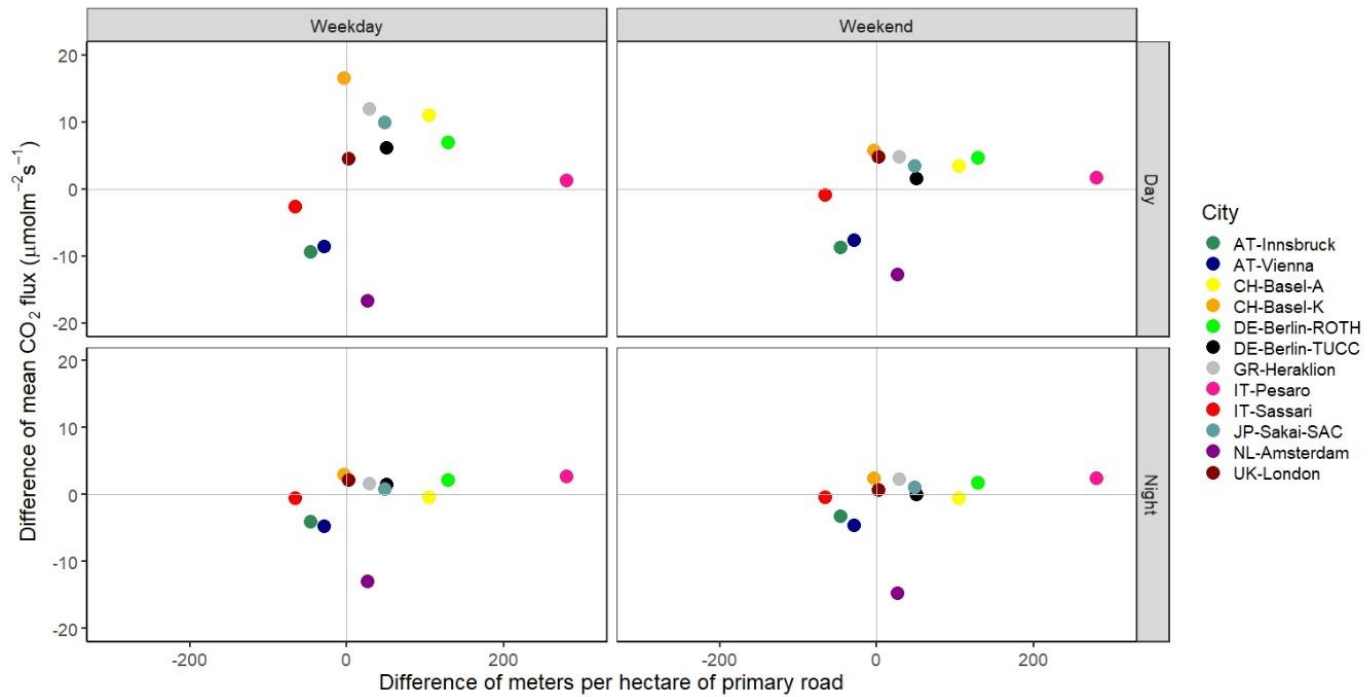


Fig 15. The x-axis shows the difference of linear meter per hectare of primary roads between the two sectors available for twelve cities and has been related to the difference of mean CO₂ fluxes between the two sectors in a different part of the day (e.g. night VS day) and in a different part of the week (e.g. Weekday VS Weekend).

Throughout the daytime, on weekdays, the sites are grouped in the first and in the third quadrant of each subplot attesting that major length of primary roads within the commercial or residential sector could be associated with major fluxes within the same areas. Indeed, the first quadrant of each subplot characterizes a site where major emissions from the building commercial sector are associated with the major length of primary roads while the third quadrant concern a site where high emissions from the building residential sector are associated with a greater quantity of primary roads within the same areas. The correlation test used to prove the strength of the relationship between the two variables (fluxes VS primary roads) during the day on weekdays, shows small values ($R^2 = 0.29$). The site of NL-Amsterdam represent an exception: in fact at major roads in the commercial sector correspond to major emissions in the residential sector pointing out that the quantity of roads is not driving the emissions.

Overnight (Fig. 14 bottom panels), the differences in fluxes between the two sectors are small and all the sites tend to be close to the cross of the four-quadrant, pointing out that the length

of primary roads, cannot be considered responsible for differences in fluxes between sectors during the night. During the nighttime, the differences in fluxes between the two sectors are similar for weekday and weekend (3rd - 4th subplot) attested also from an identical R^2 derived from the correlation test that is equal to 0.23.

Eleven sites on a total of twelve of the cities involved in this analysis showed higher emissions within the districts with the most extension of primary roads suggesting the high impact of traffic on CO₂ emissions.

3.4 Changepoint detection analysis

The changepoint detection investigation will be presented by grouping the results for the sectors that have shown a similar trend in the relationship between air temperature and CO₂ emissions.

The first group of sites is presented in the following paragraph (**Fig. 16**). The broken line of the residential sector has a strong negative correlation between CO₂ fluxes and temperature in the first part, while in the second segment, the CO₂ fluxes remain stable after exceeding a characteristic threshold temperature that identifies the changepoint.

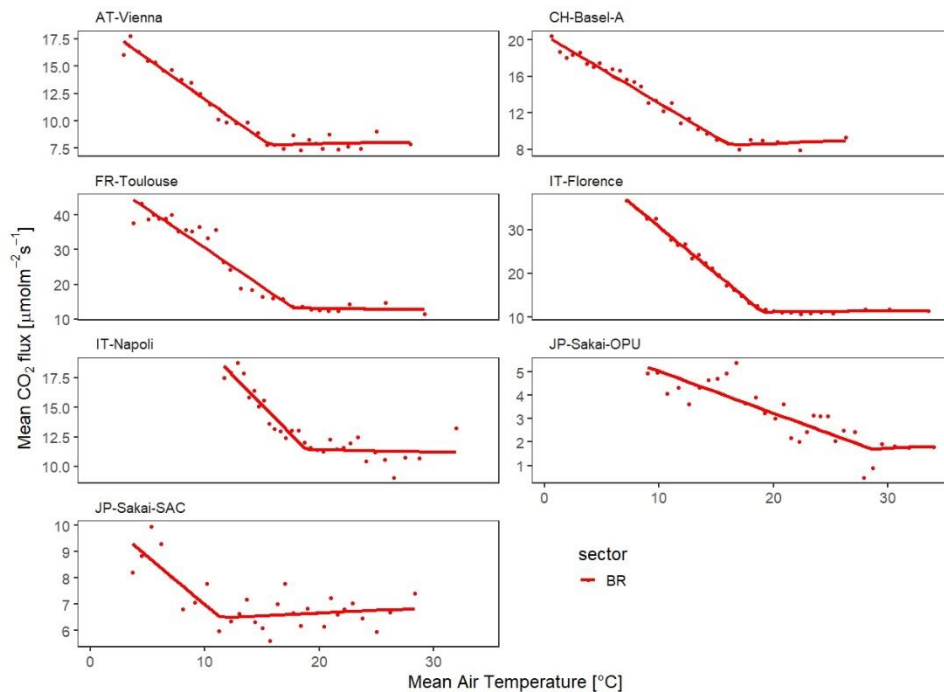


Figure 16. Changepoint detection analysis within the first grouped sites

The emissions at colder temperature are linearly related to the air temperature and can be assumed to be made by a constant part (traffic) and a temperature-dependent part (heating systems). Differently, emissions at warmer temperatures are stable for all the sites and can be assumed to be traffic. The turning temperature is between 15°C and 18°C for the best part of the sites. The CO₂ emissions coming from the residential sectors become relevant when the daily mean air temperature is below 15 °C. This threshold is considered as the temperature at which heating in Europe is expected to be turned on (Matzarakis and Balafoutis, 2004; Pigeon et al., 2007). The site of JP-Sakai-OPU shows a turning point around 28°C, and the site of JP-Sakai-SAC has a turning point close to 10 °C which suggests that there is another emissions source that drives the fluxes.

The commercial sectors located in the footprint areas of the sites of AT-Vienna, CH-Basel-A, and JP-Sakai-SAC have been removed from this analysis, indeed the coefficient of determination relating to the broken line has very low values in a range between 0.12 and 0.42 (**Tab. 7**).

Site ID	Sector	R ²
AT-Vienna	BC	0.12
AT-Vienna	BR	0.97
CH-Basel-A	BC	0.42
CH-Basel-A	BR	0.98
FR-Toulouse	BR	0.94
IT-Florence	BR	0.99
IT-Napoli	BR	0.87
JP-Sakai-OPU	BR	0.76
JP-Sakai-SAC	BC	0.28
JP-Sakai-SAC	BR	0.63

Table 7. Multiple R² calculated for the broken lines of the first group for the commercial and residential sectors. The commercial sectors eliminated from the changepoint analysis are highlighted in bold character.

The second group of sites is presented in figure number 17. The general trend of these sites shows the first part of the broken line having a strong and negative correlation between CO₂ fluxes and temperature, while in the second segment, at higher air temperature the CO₂ fluxes tend to increase.

The trend is similar for the residential and commercial sectors. The increase or decrease in CO₂ emissions at high temperatures, such as shown in a unique case for the sectors of the site of IT-Sassari, could result from a change in the activity of traffic or human presence within the footprint which is closely related to CO₂ emissions due to human respiration.

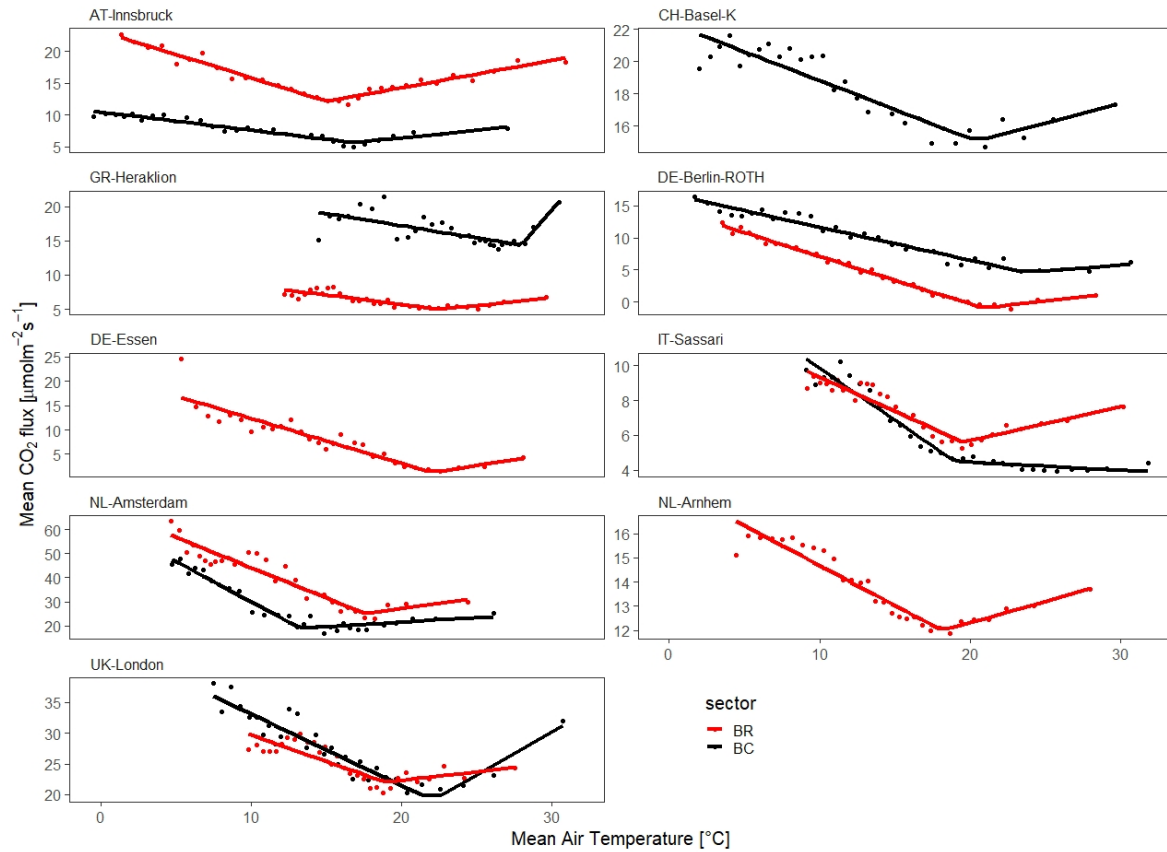


Figure 17. Changepoint detection analysis within the first grouped sites

The analysis of the determination index shown in the table 8 suggests that the analysis is statistically valid for all the sites and relative sectors belonging to the second group.

Site ID	Sector	Multiple R ²
AT-Innsbruck	BC	0.92
AT-Innsbruck	BR	0.95
CH-Basel-K	BC	0.86
GR-Heraklion	BC	0.59
GR-Heraklion	BR	0.71
DE-Berlin-ROTH	BC	0.95
DE-Berlin-ROTH	BR	0.99

DE-Essen	BR	0.85
IT-Sassari	BC	0.95
IT-Sassari	BR	0.89
NL-Amsterdam	BC	0.95
NL-Amsterdam	BR	0.90
NL-Arnhem	BR	0.91
UK-London	BC	0.88
UK-London	BR	0.72

Table 8. Multiple R^2 was calculated for the broken lines of the second group for the commercial and residential and vegetated sectors.

The last group of sites and relative sectors is presented in figure 17. In this case, the broken lines could be driven by vegetation, hence by the effect of photosynthesis. The latter hypothesis is confirmed in the vegetated sectors of DE-Essen and FI-Helsinki. Indeed, there are constant CO₂ emissions at low temperatures that can be interpreted as ecosystem respiration, while for higher temperatures when the vegetation starts photosynthesis, the CO₂ fluxes begin to decrease and go below zero attesting to the sink effect. The commercial sector of the FI-Helsinki site also appears to be affected by the vegetation effect.

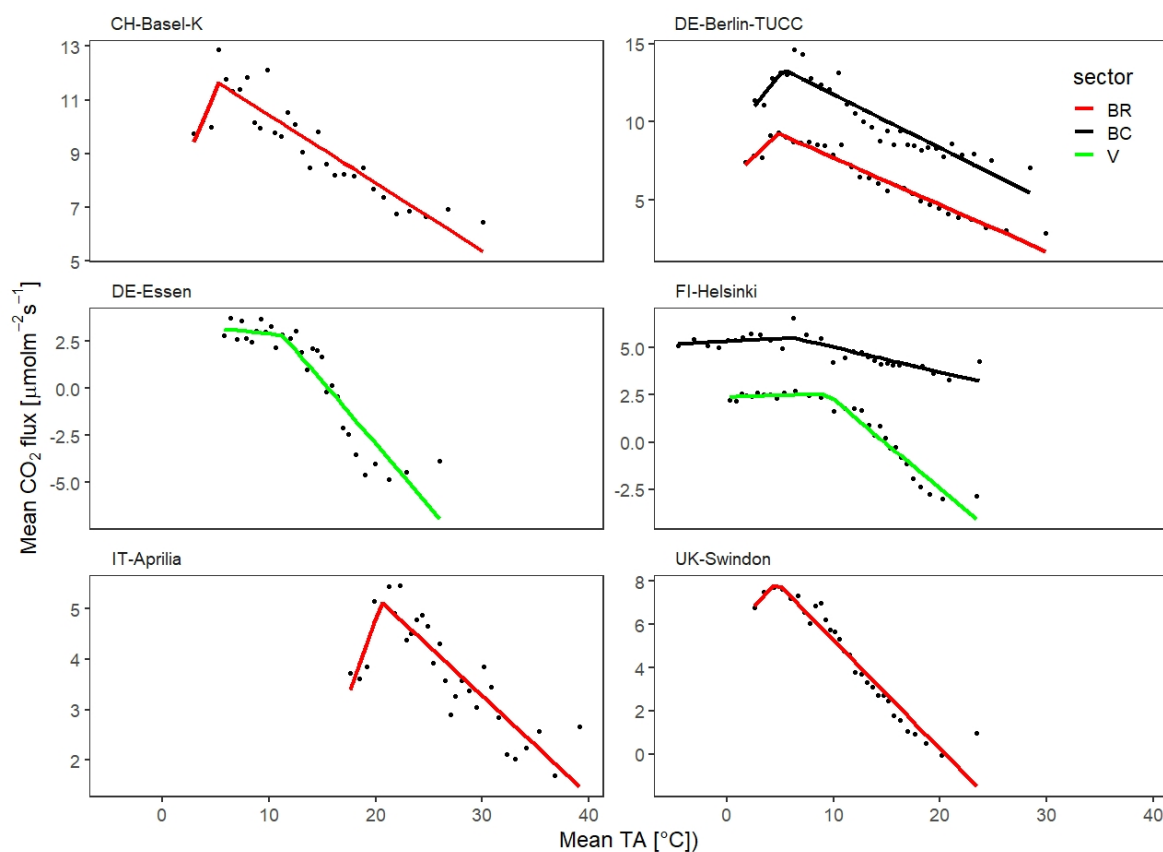


Figure 18. Changepoint detection analysis within the third grouped sites

Site ID	Sector	Multiple R2
CH-Basel-K	BR	0.86
DE-Berlin-TUCC	BC	0.85
DE-Berlin-TUCC	BR	0.96
FI-Helsinki	BC	0.74
FI-Helsinki	V	0.95
IT-Aprilia	BR	0.80
UK-Swindon	BR	0.94

Table 9. Changepoint detection analysis within the first grouped sites

Table 9 shows the determination indexes relative to the last group of sites and relative sectors.

4 Conclusions

This research investigates CO₂ flux emissions drivers within cities, using data from multisite urban EC towers located worldwide. Key inter-site differences in LULC composition were considered the main factor to divide the source areas' emissions in the commercial, residential and vegetated sectors and to study CO₂ fluxes drivers using additional data relative to the urban vegetation and roads. Examination of key parameters such as the percentage of green areas and their photosynthetic potential activity demonstrated the relevance of the urban greenery effect.

The role of urban green areas is strongly linked to the footprint structure, the anthropogenic activities, and other particular characteristics of the urban ecosystem such as the variability in the tree density and species composition, the distribution of vegetation within the footprint, as well as to the criteria used for management (Ferrini et al., 2020). The few experiences carried out in order to investigate the role of vegetation in a single specific urban area using the EC technique suggest the need for allometric equations and relative models to calculate the plant uptake together with ground surveys (Velasco et al., 2013). This study could help to better understand the roles of urban green areas: the sectors with higher vegetation fractions reported consistently smaller intensity of CO₂ fluxes in all the cases available. The effect of photosynthesis becomes visible when the vegetation cover is between a range of 40% and 60% of the considered area with NDVI values between 0.4 and 0.8 which identify dense and high plants.

The linear meter per hectare of primary roads, considered those with a greater impact on CO₂ fluxes, has been used to analyze the correlation between the presence of roads and the intensity of CO₂ emissions. The research undertook the first attempt of using the quantity and quality of roads such as an index of CO₂ emissions suggesting that sectors with major primary roads are also affected by the major intensity of emissions attesting to the high impact of traffic on CO₂ fluxes.

The correlation between temperature and CO₂ fluxes used to characterize the trend of emissions in the various LULC scenario could be applied such as emission partitioning data-driven method if validated against traffic counters and gas consumption data not available in this study.

Finally, the investigation of Covid-19 demonstrates that altering human behaviour has a direct, immediate, and significant effect on the reduction and recovery of urban CO₂ emissions. The

latter research showed the importance of building a network of sites ready to expand the analysis to a system of urban sites at a global scale and showed the potential of local-scale eddy-covariance flux measurements in cities. Indeed, firstly they can detect changes in emission dynamics at high temporal resolution and in almost near real-time. Secondly, they can complement other information on anthropogenic emissions, such as traffic and energy consumption data, high precision measurements of atmospheric concentrations of greenhouse gases, or satellite data. Thirdly, they can help to validate emission scenarios of other atmospheric pollutants.

For what concerns further analysis would be important to complement EC data with additional data such as traffic activity in real-time, heating systems city-specific emissions inventories, and mobility data to monitor people's presence in the footprint in different parts of the year to have a complete view of the urban metabolism and be facilitate for relative fluxes partitioning.

A major weakness in urban EC studies and within this research is the lack of long-term datasets as this can be considered crucial to understanding and monitoring CO₂ metabolism in cities. This research utilized a total of one hundred and sixteen years of data for over a total of twenty-four sites divided unevenly, from sites with fifteen years of data to sites with two years of data. The solution could be to build a network of urban sites able to share and store data in a database by common rules about variable type and names, times units, and measurement units.

Finally, the lack of availability of free additional data to be used together with the EC data is considered one of the most critical points to developing more accurate investigations about CO₂ flux drivers within cities.

5 Published Paper

The next section shows the paper titled “Direct observation of CO₂ emissions reduction due to COVID-19 lockdown across European urban districts” published in the journal of Science of the Total Environment. As mentioned before the paper must be considered as specific research within the broader context of the investigation activities able to highlight the possibility to use the EC technique to provide tracking of CO₂ emissions in near real-time.



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Direct observations of CO₂ emission reductions due to COVID-19 lockdown across European urban districts



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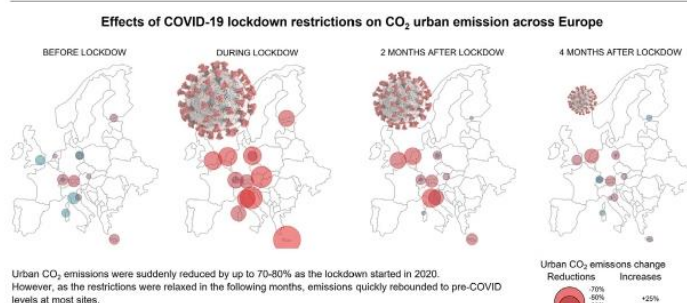
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HIGHLIGHTS

- Following the outbreak of the COVID-19 pandemic in 2020, people's activities drastically changed due to mobility restrictions.
- This affected urban CO₂ emissions and we wanted to quantify its impact during the lockdown and in the following months.
- We analysed eddy covariance measurements of urban CO₂ fluxes over the lockdown in thirteen European city districts.
- Data provided the measured evidence of a consistent reduction of CO₂ emissions, proportional to the stringency of restrictions.
- The reduction was temporary in most of the city districts, as emissions rebounded to usual levels once restrictions were eased.

GRAPHICAL ABSTRACT



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ABSTRACT

The measures taken to contain the spread of COVID-19 in 2020 included restrictions of people's mobility and reductions in economic activities. These drastic changes in daily life, enforced through national lockdowns, led to abrupt reductions of anthropogenic CO₂ emissions in urbanized areas all over the world. To examine the effect of social restrictions on local emissions of CO₂, we analysed district level CO₂ fluxes measured by the eddy-covariance technique from 13 stations in 11 European cities. The data span several years before the pandemic until October 2020 (six months after the pandemic began in Europe). All sites showed a reduction in CO₂ emissions during the national lockdowns. The magnitude of these reductions varies in time and space, from city to city as well as between different areas of the same city. We found that, during the first lockdowns, urban CO₂ emissions were cut with respect to the same period in previous years by 5% to 87% across the analysed districts, mainly as a result of limitations on mobility. However, as the restrictions were lifted in the following months, emissions quickly rebounded to their pre-COVID levels in the majority of sites.

1. Introduction

The large current reliance of urban energy use on fossil fuels makes cities the main contributors to global anthropogenic emissions of carbon dioxide (CO₂) (Oke et al., 2017). Urban CO₂ emissions, being linked to human needs and activities such as mobility, heating, and economic activities, are highly dynamic, varying substantially at sub-hourly, daily, weekly and seasonal time scales. Urban vegetation plays a role in the CO₂ exchange of urban areas with uptake and release of CO₂ also varying at multiple time-scales in response to a range of controls (Ribeiro et al., 2019).

At the scale of large urban areas ($\approx 100 \text{ km}^2$), CO₂ flux budgets can be constrained indirectly by in situ and/or remote sensing measurements of CO₂ concentrations using atmospheric transport models as studied in e.g. Paris (Stauffer et al., 2016) and Indianapolis (Turnbull et al., 2019). At similar or smaller scales, urban CO₂ fluxes can be estimated by combining building energy modules, bottom-up emission inventory models based on activity data and emission factors, and biogeochemical models for urban vegetation (Goret et al., 2019; Gurney et al., 2019). At the neighbourhood or district scale ($\approx 1 \text{ km}^2$), net CO₂ fluxes can be directly inferred from eddy-covariance (EC) measurements of turbulent CO₂ exchange.

EC has been widely used over natural ecosystems to investigate biosphere responses to environmental and biological factors (Baldocchi, 2014), while in urban ecosystems its application has grown steadily over the past 15 years (e.g. Helfter et al., 2016; Nordbo et al., 2012; Pérez-Ruiz et al., 2020; Roth et al., 2017; Salgueiro et al., 2020; Stagakis et al., 2019; Vogt et al., 2006; Ward et al., 2015). Urban EC measurements have been shown to be valuable for detecting short- and long-term changes in fluxes,

and for studying the drivers of local CO₂ emissions and 'urban metabolism' leading to a better understanding of the carbon cycle in cities (Christen et al., 2011; Crawford et al., 2011; Feigenwinter et al., 2012; Velasco and Roth, 2010). The EC method is based on simultaneous high-frequency (e.g. 10–20 Hz) measurements of the vertical wind velocity and CO₂ concentration, or any other scalar entity such as heat, moisture, trace gases, and aerosols, allowing for the estimation of the vertical exchange of such scalars through turbulent motions (eddies) within the mean air flow. Conventionally, positive values represent upward fluxes, i.e. net emissions to the atmosphere, and negative values represent downward fluxes, i.e. net uptake by the underlying surface. Measurements are continuous and representative of a target source area (footprint) typically of the size of a city district (i.e. 10^4 – 10^8 m^2) depending on the measurement height with respect to average building height. For a complete description of the EC flux method see, for example, Aubinet et al. (2012).

The onset of the COVID-19 pandemic in Europe in early spring 2020, caused drastic changes to people's lives and socio-economic activity. The governmental actions taken to break the chain of disease transmission included the closure of schools and non-essential businesses, banning social gatherings, and enforcing home confinement. Such measures reduced mobility and economic activity, and inevitably impacted energy use and anthropogenic CO₂ emissions. It also displaced daytime populations from the work-place to residential areas, which likely impacted the spatial distribution of emissions associated with building energy use, as well as affecting emissions from transport. Assessments of national activity reductions combined with empirical relations to predict emissions suggested that CO₂ emissions of individual countries fell by up to 30% during the peak of the

lockdowns in spring 2020 (Forster et al., 2020; Le Quéré et al., 2020; Liu et al., 2020). Although associated CO₂ emissions reductions at the city scale are to be expected, the magnitude and variability of these reductions cannot be simply determined from national-level changes. Quantitative estimates of urban emission reductions due to COVID-19 restrictions based on atmospheric measurements have so far only been estimated for a few cities worldwide (Gualtieri et al., 2020; Lamprecht et al., 2020; Sugawara et al., 2021; Velasco, 2021; Yadav et al., 2021).

In this study we present CO₂ fluxes measured by a network of 13 EC stations in 11 European cities. These datasets span several years before the pandemic until October 2020. Urban EC stations operating before and during 2020 present a unique opportunity to investigate how the drastic perturbations in human activity caused by the COVID-19 pandemic have impacted local CO₂ emissions. CO₂ flux data at half-hourly resolution allows for temporal changes in CO₂ emissions to be tracked both during the initial lockdown period and during the subsequent recovery phase when economic activities and mobility gradually resumed.

Our analysis focuses on the following questions:

- Do direct flux measurements confirm the emissions reduction predicted by coarse-scale inventory models?
- What was the magnitude of the reduction in emissions at the district scale, and how does this vary from place to place?
- Were reductions in emissions related to the stringency of the restriction measures?
- Were there more substantial reductions for certain hours of the day or days of the week?
- Did emissions return to previous levels after the restrictions were lifted?
- Was this recovery dependent on urban features (e.g. land use type, density of the road network, amount of vegetation)?

2. Methods

Using micrometeorological data (Nicolini et al., 2022) from 13 urban EC stations in 11 cities across Europe (Table 1 and supplementary “Study sites” Section), we evaluated district-scale changes in urban CO₂ fluxes between 2020 and previous years. These changes were analysed in relation to the stringency of the local lockdown rules, taking into consideration the characteristics of each site in terms of local citizens activities (e.g. commuting, economic activities, domestic heating) and urban features.

Each EC station (Table 1) was equipped with a 3D ultrasonic anemometer, a gas analyser for measuring CO₂ concentrations, and meteorological sensors measuring air temperature and humidity, air pressure and solar radiation. All systems collected data at 10 or 20 Hz, which were processed by the researchers in charge of each station according to commonly accepted procedures (Aubinet et al., 2012) to obtain the half-hourly CO₂ fluxes used in the analysis. Data quality assurance was assessed by each group following standard quality control and filtering procedures, albeit with allowances for site-to-site variations (details can be found in the main references for each site which are given in Table 1). For this study, we additionally excluded CO₂ flux data beyond the physically plausible range of -50 to $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, those from wind sectors prone to flow disturbance by physical obstacles (e.g. measurement tower structure) and those outside a site-specific quantile range calculated over a 3 weeks moving window using the 0.5% and the 99.9% probability were excluded. This quantile range was taken asymmetrically because in urban environments sporadic large negative fluxes (sinks) are far less likely than large positive fluxes (emissions). Data were not gap-filled as it was not required for the type of analysis performed.

Flux observations from previous years up to and including 2019 were used as a reference to compare changes before, during, and after the lockdown periods with related restrictions that affected each city district. Pre-2020 records span between 2 and 14 years depending on the station (Table S1). We focused our analysis on four distinct periods defined following the Oxford COVID-19 Government Response Tracker (OxCGRT) Stringency Index (SI) (Hale et al., 2020a, 2020b). The SI quantifies policies that governments have taken to respond to the pandemic; it is calculated as the average of a set of macro-indicators of containment and closure policies including closure of schools, universities and workplaces, cancelling of public events, limits on private gatherings, shutting-down public transport, orders to “shelter-in-place” or otherwise confine to homes, restrictions on internal movement between cities/regions, and restrictions on international travel. The SI ranges between 0 (no restrictions) and 100 (maximum level of restrictions). Although the contributing factors to this index vary between countries and cities, the SI has been shown to provide global insight into the pandemic's evolution and implementation of measures (Cross et al., 2020). We set a minimum threshold of 65 (64.3 is the 60th quantile of the SI values for the analysed cities over the period January–October 2020) to define the lockdown period (LOCK) in each city. The length of this period (and the maximum value of SI reached) varied from 19 days in Helsinki to 75 days in Basel and Amsterdam (Table S2). Then,

Table 1

Summary of the cities and respective EC stations involved in the study. The *station ID* is the naming used in this analysis, containing the names of the respective cities, *z* is the measurement height (m), *z/z_h* is the ratio between *z* and mean building height (*z_h*).

Country	Station ID	Latitude	Longitude	Data range	z	z/z _h	EC system	Main references	
					m		sonic; IRGA		
Austria	AT-Innsbruck	47.26404	11.38571	2017-08-01	2020-10-31	42.8	2.5	CSAT3; EC155	Karl et al., 2020
Austria	AT-Vienna	48.18181	16.39088	2018-01-01	2020-10-01	144.0	7.0	WM Pro; LI-7500	Matthews and Schume, 2022
Switzerland	CH-Basel-A	47.55123	7.59560	2016-01-01	2020-10-19	41.0	2.5	CSAT3; LI-7500	Lietzke et al., 2015
Switzerland	CH-Basel-K	47.56173	7.58049	2016-01-01	2020-10-19	39.0	2.3	HS; LI-7500	Lietzke and Vogt, 2013
Germany	DE-Berlin ROTH	52.45723	13.31583	2018-06-01	2020-09-30	40.0	2.4	Irgason	Vulova et al., 2021
Germany	DE-Berlin TUCC	52.51228	13.32786	2014-07-03	2020-09-30	56.0	2.8	Irgason	Jin et al., 2020; Vulova et al., 2021
Finland	FI-Helsinki	60.20269	24.96231	2014-01-01	2020-09-30	31.0	1.6	USA-1; LI-7200	Järvi et al., 2012; Järvi et al., 2009
Greece	GR-Heraklion	35.33616	25.13282	2016-10-27	2020-09-30	27.0	2.4	Irgason	Stagakis et al., 2019
Italy	IT-Florence	43.77441	11.25511	2005-09-14	2020-10-22	33.0	1.3	81000V; LI-7500	Gioli et al., 2012; Matese et al., 2009
Italy	IT-Pesaro	43.91197	12.90404	2014-08-09	2020-10-20	23.0	1.5	WM Pro; LI-7500	Gioli et al., 2012; Matese et al., 2009
Italy	IT-Sassari	40.71695	8.57593	2016-01-01	2020-10-26	22.0	2.0	HS-50; LI-7200	not available
Netherlands	NL-Amsterdam	52.36654	4.89290	2018-05-01	2020-10-13	40.0	2.8	CSAT3; LI-7500	Steenveeld et al., 2020
United Kingdom	UK-London	51.52140	−0.13881	2011-09-15	2020-09-30	190.0	22.0	R3-50; LI-7500; P1301-f	Helfter et al., 2016, Helfter et al., 2011

EC system instruments: CSAT3, 3-D sonic anemometer (Campbell Scientific, Inc.); EC155, closed-path CO₂/H₂O gas analyser (Campbell Scientific, Inc.); WM Pro, WindMaster Pro 3-axis anemometer (Gill Instruments Limited); LI-7500, LI-7500 open path CO₂/H₂O analyser (LI-COR, Inc.); HS-100, HS-100 horizontal-head ultrasonic anemometer (Gill Instruments Limited); Irgason, Irgason integrated CO₂/H₂O open-path gas analyser and 3-D sonic anemometer; USA-1, USA-1 ultrasonic anemometer (METEK Meteorologische Messtechnik GmbH); LI-7200, LI-7200 enclosed-path CO₂/H₂O gas analyser (LI-COR, Inc.); 81000V, 81000V ultrasonic anemometer (R. M. Young Company); HS-100, HS-100 horizontal-head ultrasonic anemometer (Gill Instruments Limited); R3-50, R3-50 3-axis anemometer (Gill Instruments Limited); 1301-f, Picarro 1301-f flux CO₂, CH₄, and H₂O gas concentration analyser (Picarro, Inc.).

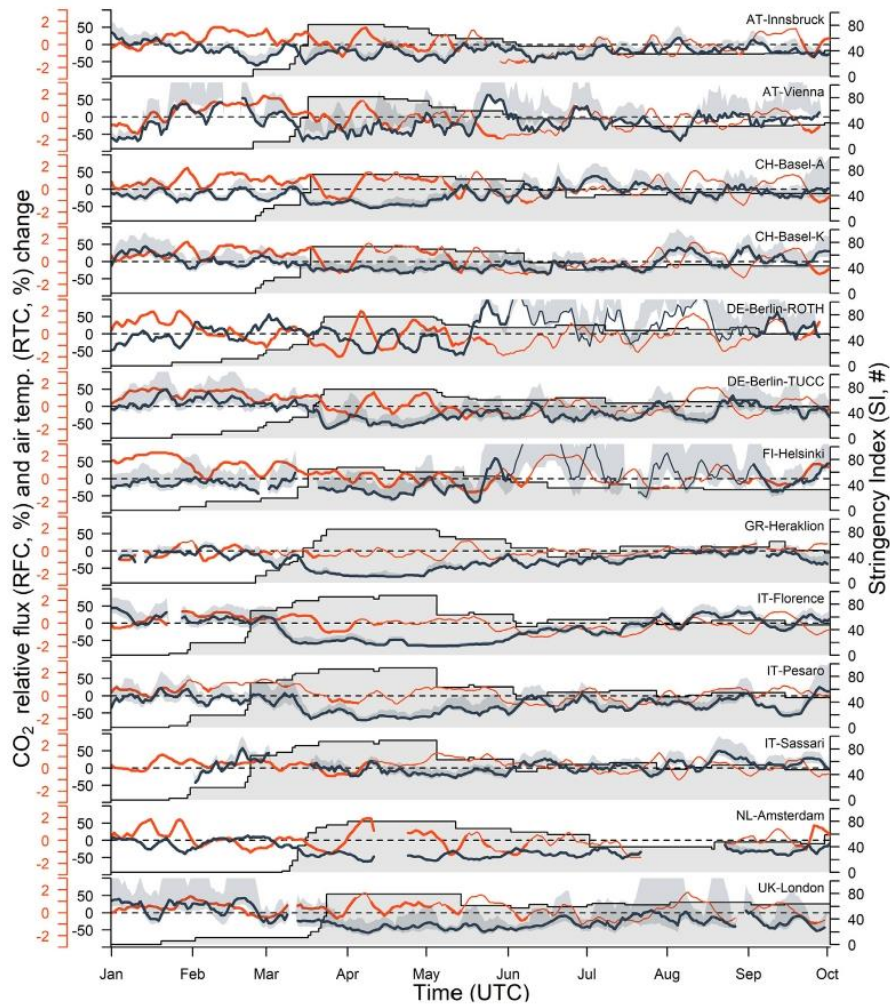


Fig. 1. Daily CO₂ relative flux change (RFC, %, dark grey line, left y-axis) for January to October 2020 relative to the average flux over previous years. Daily fluxes are computed as the median of half-hourly values and smoothed by a 7-day moving window average. Negative RFCs indicate emission reduction. The shaded area around the RFC curve represents the RFC interquartile range calculated using individual previous years as a baseline. The Oxford Stringency Index (SI, 0–100, light grey shaded area, right y-axis) illustrates country-wide levels of restrictions due to the COVID-19 pandemic. The thin line segments of the RFC curves for DE-Berlin-ROTH and FI-Helsinki indicate periods of relevant vegetation activity (assumed to be from June 1st to September 1st). Relative air temperature change (RTC, %, red curve, secondary left y-axis) is computed similarly to RFC, using daily average temperatures (in K). Bold RTC line sections highlight the days with air temperature < 15 °C assumed as a threshold for comfort temperature.

a pre-pandemic period (PRE) was defined lasting from January 1st to the beginning of the lockdown in each location, and two subsequent periods of 60 days each, POST1 and POST2, were identified after LOCK to evaluate the emissions recovery (Table S2).

The anomalies in CO₂ fluxes during each of these periods were quantified in terms of the relative flux changes (RFC, %) computed as:

$$RFC = \frac{x_{2020} - x_{base}}{|x_{base}|} \cdot 100 \quad (1)$$

where x_{2020} and x_{base} are the average fluxes observed for each period in 2020 and for the corresponding period in previous years (considered as the baseline period), respectively. The computation of RFC was based on daily means (Sections 3.1 and 3.2), diel cycles (Section 3.3) or half-hourly means of the CO₂ fluxes (Sections 3.4 and 3.5), depending on the context. Negative values of RFC indicate a reduction of the CO₂ fluxes with respect

to the baseline period, while positive values are associated with increased CO₂ fluxes.

We also calculated the relative air temperature change in a similar way (RTC, %) to evaluate the potential effect of temperature anomalies on the observed fluxes. We assumed that CO₂ emissions from commercial and domestic heating become relevant when the daily mean air temperature is below 15 °C. This threshold is considered as the temperature at which heating in Europe is expected to be switched on (Matzarakis and Balafoutis, 2004; Pigeon et al., 2007).

Uncertainties in CO₂ flux averages, both daily and half-hourly in case of diel cycles, were calculated as the standard error over the single half-hourly values. Non-parametric statistical metrics (Spearman's rank correlation, Kruskal-Wallis test by rank and Wilcoxon rank-sum test) were performed to evaluate the significance of differences in the CO₂ fluxes, and the correlation of RFC with RTC and SI.

To evaluate the contributions to RFC from different land cover categories and emission sources within the footprint of each tower, CO₂ fluxes

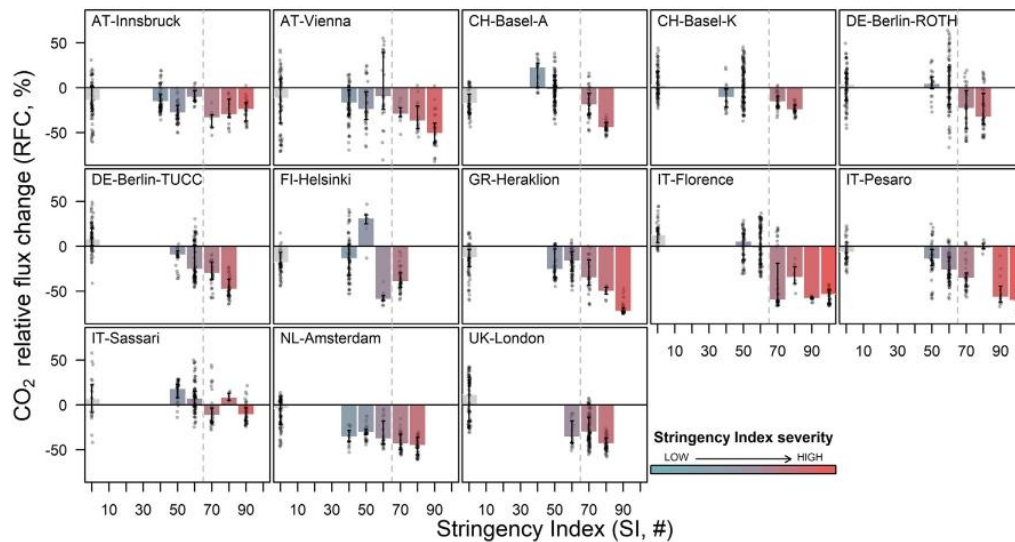


Fig. 2. CO₂ relative flux change (*RFC*, %) as a function of the Oxford stringency index (*SI*). Daily *RFC* values over the whole monitored period, smoothed over a 7-days moving window, are grouped by *SI* classes with a width of 10 points. The bars represent the median of daily *RFC* values, error bars represent their interquartile range, dots represent the individual *RFC* values, the colour gradient represents *SI* severity (low to high, blue to red). *RFC* data up to the first day of lockdown, or when *SI* < 20, are aggregated in the grey bar placed before the *SI* class 0–10 (left-most bar). The dashed vertical line represents the *SI* value we considered as the threshold for the most restrictive measures (i.e. 65). Days with CO₂ fluxes close to zero ($\pm 1 \mu\text{mol m}^{-2} \text{s}^{-1}$) were removed to avoid excessive noise in the ratio calculation of the *RFC*, without affecting the results.

were also analysed by wind sectors (see also the supplementary “Spatial analysis” Section). The land use and land cover (LULC) information was extracted from the European Urban Atlas (UA) 2012 database (Montero et al., 2014), cropping circular areas centred at each flux tower. The radii of these areas were set equal to the median distance of the 70th percentile of the estimated contribution of the cumulative flux footprint (Kljun et al., 2015), irrespective of wind direction. This length represents the distance within which 70% of the measured flux is estimated to originate. It was calculated for 8 sites at which footprint estimates were available whereas, for the other 5 sites, it was estimated according to an average ratio between the calculated distances and measurement heights (Table S1).

To facilitate the interpretation of results, similar UA-LULC classes were combined into broader classes, the main four of which were: (i) predominantly residential areas (RES), consisting mainly of residential structures, but also including downtown areas and city centres (higher storeys of buildings are mostly residential), with various degrees of soil sealing; (ii) non-residential areas (nRES), consisting in industrial and commercial areas, as well as schools and military units; (iii) areas dominated by roads and railway networks (ROD); and (iv) green urban areas (GUA), that include pervious surfaces with vegetation e.g. lawns, parks, greenbelts, farmland, urban forests. We used Google Earth Imagery (© 2020 Google), Sentinel-2 satellite Normalised Difference Vegetation Index (NDVI), and local knowledge of each site, to improve the characterization of districts. At each site, relatively homogeneous wind sectors were associated with single LULC class (supplementary “Spatial analysis” section). The NDVI data were used to determine the extent of green spaces and to track the temporal dynamics in vegetation activity, to minimise the risk of misinterpreting trends in *RFC* arising from year-to-year variations (supplementary “Vegetation analysis” section).

Two independent datasets of city-scale activity, the Carbon Monitor emission inventory (CM, <https://carbonmonitor.org/>) and Google COVID-19 Community Mobility Reports (©2021Google), were used to assist interpretation of the *RFC* at each site. We estimated CO₂ daily emissions from road transportation at the city scale for 2019 and 2020 following the CM methodology (Liu et al., 2020): a sigmoid function describing the relationship between daily mean congestion level (as reported by TomTom's traffic report, <https://www.tomtom.com>) and mean traffic volume data for the city of Paris was used as a proxy to estimate the road-traffic related CO₂

emissions from the other cities using the TomTom's reports for each city. Then, we compared the changes between measured and predicted emissions for residential and non-residential sectors with a substantial presence of roads (20% as minimum).

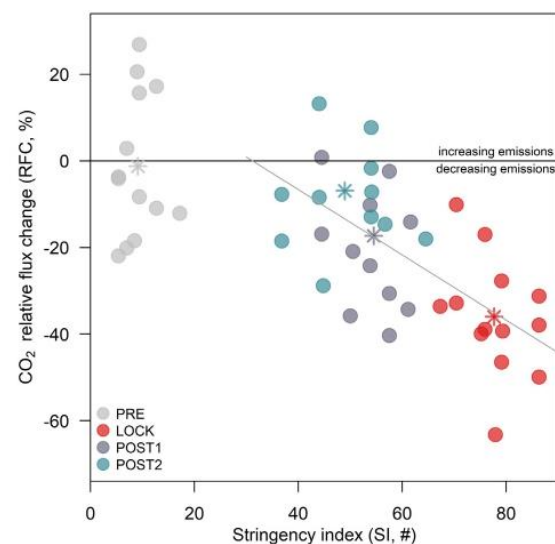


Fig. 3. Average CO₂ relative flux change (*RFC*, %) as a function of the average Oxford stringency index (*SI*) for each period. *RFC* values represent the average of daily *RFC*s obtained from the comparison of CO₂ daily fluxes in 2020 with those from all available previous years. Each dot represents the average *RFC* and *SI* for each period, in each city district. The considered periods are: the period from the beginning of 2020 up to the beginning of the first lockdown (PRE) when social restrictions were not present, the lockdown period (LOCK), and two subsequent periods of 60 days each after the end of the lockdown (POST1 and POST2). Stars represent the average *RFC*s and *SI*s across all the city districts. The *RFC*-*SI* linear regression (grey line) is fitted to the LOCK, POST1 and POST2 data points.

Table 2

CO₂ relative flux change (*RFC*, %), calculated as the average percentage change between 2020 and previous years CO₂ daily fluxes. Minimum (*min*) and maximum (*max*) *RFC*s are calculated over all available years (*Ny*, excluding the 2020 and years with no data for the period of concern). Average *RFC* values are those displayed in Fig. 3. *RFC* values are ranked by colours: from red to green going from higher emission reductions (negative *RFC*) to higher emission increases (positive *RFC*).

station ID	PRE				LOCK				POST1				POST2			
	<i>RFC</i>	<i>min</i>	<i>max</i>	<i>Ny</i>	<i>RFC</i>	<i>min</i>	<i>max</i>	<i>Ny</i>	<i>RFC</i>	<i>min</i>	<i>max</i>	<i>Ny</i>	<i>RFC</i>	<i>min</i>	<i>max</i>	<i>Ny</i>
AT-Innsbruck	-22	-25	-19	2	-28	-35	-20	2	-24	-27	-22	2	-12	-13	-11	2
AT-Vienna	-4	-13	5	2	-47	-50	-43	2	-10	-12	-8	2	-8	-12	-4	2
CH-Basel-A	-20	-25	-12	4	-33	-35	-29	4	1	-7	17	4	-8	-15	-3	4
CH-Basel-K	3	-1	7	4	-10	-20	-2	4	-17	-23	-2	4	13	9	20	4
DE-Berlin-ROTH	-11	-11	-11	1	-17	-17	-17	1	3	-5	11	2	-1	-3	0	2
DE-Berlin-TUCC	17	-2	33	5	-39	-52	-23	5	-14	-24	14	6	-15	-19	-8	6
FI-Helsinki	-12	-37	10	6	-34	-48	-21	5	1	-39	79	5	8	-33	34	6
GR-Heraklion	-18	-20	-16	2	-63	-63	-63	2	-21	-25	-15	3	-7	-12	-1	3
IT-Florence	27	-8	60	10	-38	-53	-32	9	-38	-51	-32	8	-2	-29	22	10
IT-Pesaro	-8	-15	8	5	-50	-54	-45	5	-31	-38	-16	4	-13	-21	-4	3
IT-Sassari	16	9	23	4	-31	-35	-23	4	-2	-8	7	4	8	-3	21	4
NL-Amsterdam	-4	-4	-4	1	-40	-46	-34	2	-36	-36	-36	2	-29	-30	-27	2
UK-London	21	1	68	6	-39	-51	-24	5	-34	-50	-12	6	-18	-51	48	6

Community mobility data released by Google during the pandemic (Google LLC., 2020) were used to track changes in people's mobility, specifically as a measure of the time spent by the population at places of residence. This data source has already been used to estimate changes in CO₂ emissions at the neighbourhood scale (Velasco, 2021). Mobility levels during the LOCK, POST1 and POST2 periods were compared to baseline mobility values calculated as median values of each day of the week over the five weeks between January 3rd and February 6th 2020.

3. Results

3.1. Reduction in daily CO₂ emissions during COVID-19 lockdown

For all sites, we found a clear reduction in CO₂ emissions coinciding with COVID-19 restrictions (Fig. 1), with daily *RFC* values mostly spanning between -5% to -87%. Compared to the same period in previous years, the observed reduction during the LOCK period in which the most restrictive measures were applied, was statistically significant at all sites (Wilcoxon rank-sum test, $\alpha = 0.01$, supplementary Fig. S8). The largest reductions were seen at GR-Heraklion (*RFC* daily means interquartile range IQ = [-75%, -46%]), IT-Pesaro ([-71%, -34%]), IT-Florence ([-66%, -37%]), DE-Berlin-TUCC ([-63%, -36%]), UK-London ([-58%, -33%]) and CH-Basel-A ([-53%, -26%]). In some of the cities (AT-Vienna, GR-Heraklion, NL-Amsterdam, and UK-London), emissions started to decrease 5–7 days earlier than the start of the official lockdowns in response to initial mobility restrictions and recommendations to stay at home.

For most cities, the strictest lockdown measures were gradually reduced in early May (Fig. 1 and Table S2). For the post lockdown periods (POST1, POST2), daily CO₂ fluxes returned to levels similar to previous years in most of the city districts (DE-Berlin ROTH, GR-Heraklion, IT-Florence, IT-Sassari, CH-Basel-A, CH-Basel-K, AT-Innsbruck, AT-Vienna, FI-Helsinki). In the others CO₂ fluxes remained 13% to 30% below the baseline values.

The dynamics of the *RFC* roughly followed those of the SI at all sites, with stronger emission reductions (negative *RFC*) observed during more stringent confinement periods. Over the whole monitored period, the correlation between *RFC* and SI was statistically significant (see Table S7, Spearman ρ varying between -0.65 and -0.14, $p < 0.05$) except at DE-

Berlin-ROTH and FI-Helsinki ($\rho = -0.12$, $p > 0.05$), both characterized by abundant vegetation cover (> 60% of the land cover, Figs. S3 and S4). The correlation became statistically significant at both sites however ($\rho = -0.18$ and -0.28 , respectively, $p < 0.01$) when the analysis was done excluding the data collected during the vegetation growing season (approximately from June, thin lines in Fig. 1, see the Supplementary "Vegetation analysis" Section) that could have acted as a confounding factor.

Since the lockdown period began in early spring, CO₂ emissions from building heating contributed to total CO₂ fluxes at most sites. As a result, synoptic variations in weather patterns and associated temperature changes impact CO₂ emissions and are responsible for some of the variability in the *RFC*. For relatively cold days (mean air temperature < 15 °C) without strong restrictions (SI < 40), a negative correlation was found between *RFC* and *RTC*, in particular at CH-Basel-A, DE-Berlin-ROTH and NL-Amsterdam (Spearman ρ correlation coefficient between -0.33 and -0.44, $\alpha = 0.05$), probably due to a reduction in heating-related emissions. This aspect is further analysed in Section 3.3.

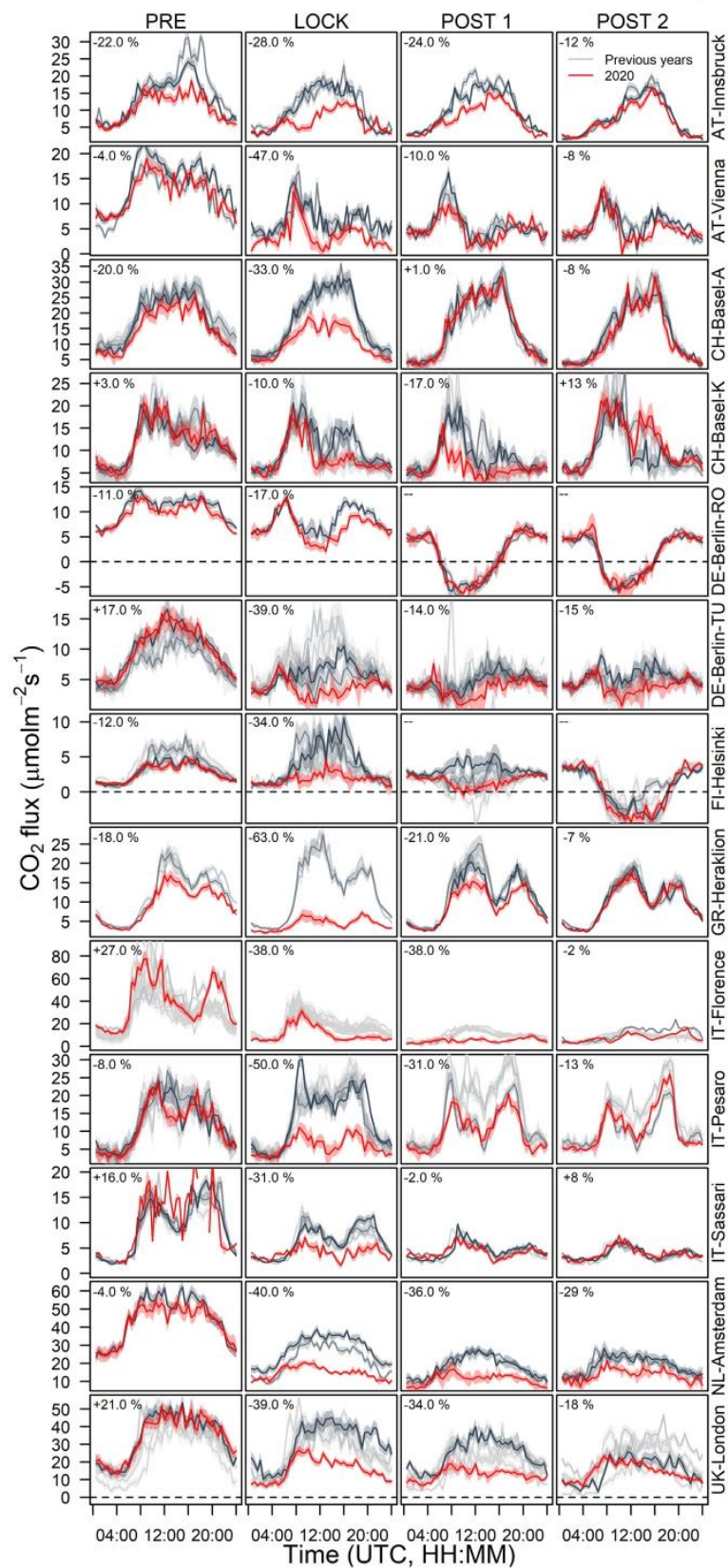
3.2. Relation between reduction of emissions and severity of restrictions

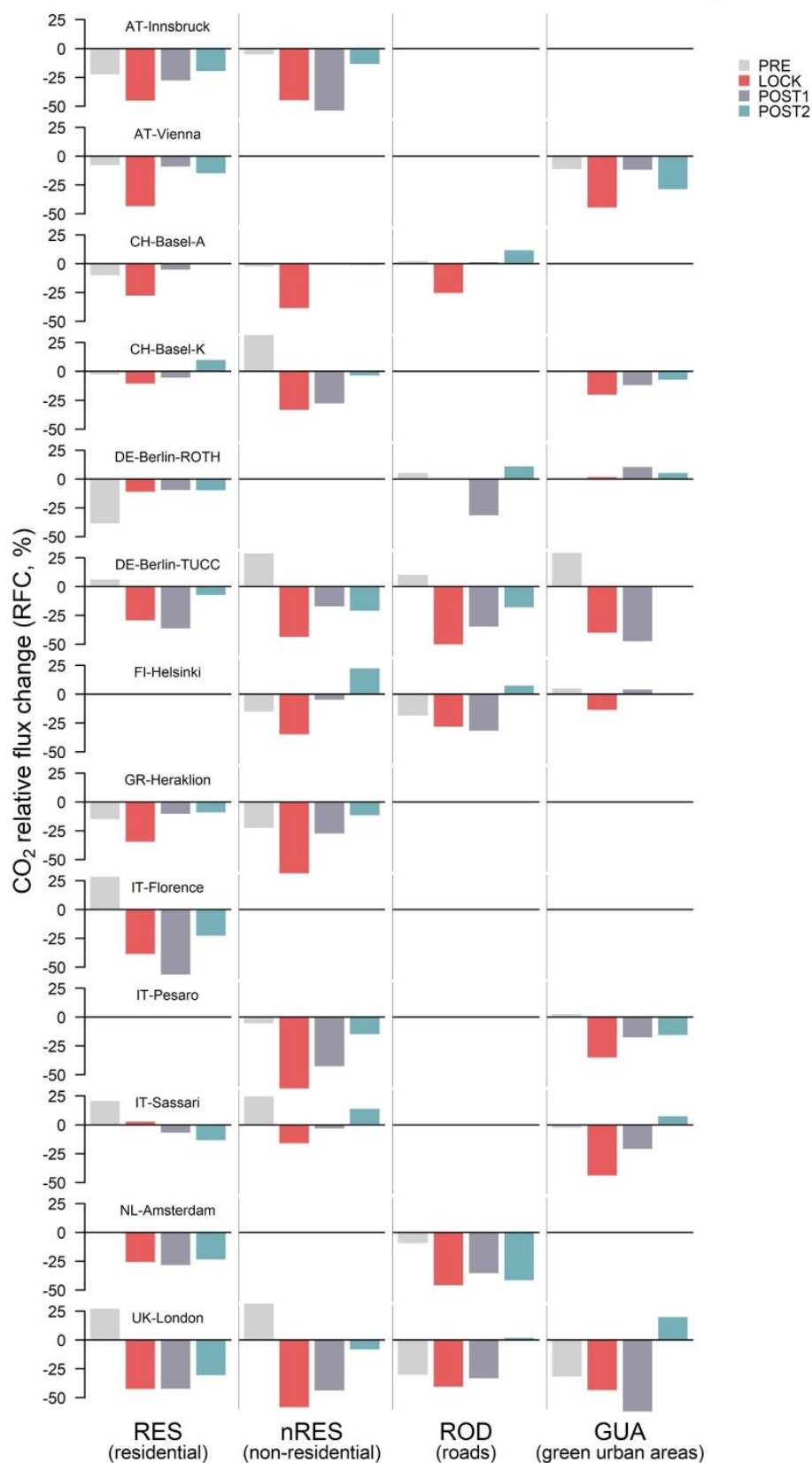
All cities had a significant reduction in emissions during the most restrictive measures (LOCK, SI > 65), and several cities also reported reduced emissions in the subsequent months (POST1 and POST2) during which some restrictive measures remained in place. The relation between *RFC* and SI is examined in more detail in Fig. 2 (the statistical significance is shown in Fig. S9). In almost all cities the *RFC* reached its minimum (< -50%) for the highest values (SI > 70–80), when the most restrictive measures were in place.

There were however two districts where emissions were only slightly reduced even under the most stringent restrictions (IT-Sassari and CH-Basel-K), suggesting that the main emission sources of those districts were partly decoupled from the lockdown severity, for example if the measured fluxes were not strongly affected by traffic reductions. Some cities showed a clear and consistent decrease in *RFC* with SI (e.g. AT-Vienna, GR-Heraklion, IT-Pesaro) while others show more variability (e.g. AT-Innsbruck, FI-Helsinki) hinting at a more complex situation in which other drivers contributed to the emission reductions (further detail in Section 3.3).

When analysing all districts together (Fig. 3), a consistent and significant correlation between *RFC* and SI was found (slope = -0.75, $p < 0.001$). The average *RFC* during the LOCK period across all sites was

Fig. 4. Diel patterns of CO₂ fluxes during the initial COVID-19 lockdown restrictions (LOCK), before (PRE), and afterward (POST1 and POST2). Fluxes measured in 2020 (red lines) and previous years (grey lines) are included for comparative purposes. Shaded areas represent the standard error of the mean of the individual half-hourly fluxes. The relative flux change (*RFC*) is reported as the average percentage change between 2020 and previous years. The individual daily patterns of previous years are presented in grey colours: dark grey 2019, and greyscale (direction dark to light) for 2018 and earlier. Average *RFC* values are those reported in Table 2.





– 36%, and decreased to – 17% and – 7% in the POST1 and POST2 periods, respectively (star symbols in Fig. 3). In the period before the restriction or with $SI < 20$ (PRE, grey dots and stars in Fig. 3), the average RFC was not significantly different from zero.

3.3. Diel pattern of CO_2 fluxes

3.3.1. Effects of restrictions on diel CO_2 flux magnitudes

The analysis of diel CO_2 flux cycles established significant reductions in emissions in all districts during the LOCK period compared to each previous years (Table 2, LOCK period, min and max RFC values always negative), ranging from – 10% at CH-Basel-K to – 63% at GR-Heraklion. In all cases the reductions occurred mainly during daytime (Fig. 4), except for larger cities (AT-Vienna, NL-Amsterdam, UK-London), where restrictions had a clear effect also at night. Significant emission reductions during LOCK were observed at different hours of the day across districts, e.g. mainly in the morning at AT-Innsbruck and GR-Heraklion, and in the afternoon in CH-Basel-K and DE-Berlin-ROTH (Fig. 4).

During the PRE period, despite a normal interannual variability at all sites, emissions below the baseline values over previous years were already registered at AT-Innsbruck, CH-Basel-A and GR-Heraklion (Table 2, min and max always negative in the PRE period). This result is unlikely related to COVID-19 since no restrictions were in place for most of this period and the pandemic was not yet thought to have reached Europe. In Innsbruck and Basel, these lower than average emissions were attributed to especially warm temperatures in February 2020 (see Fig. S1). This likely caused a decrease in the use of domestic heating of which about 70% is by fossil fuel in Innsbruck and 25% in Basel. As a result, CO_2 emissions were reduced, in particular in the afternoon (Fig. 4, PRE column). In Heraklion, the temperature during this period was close to normal (supplementary “Air temperature analysis” section) and heating for this district is mainly from electricity. The reduction seen in early 2020 affected both the morning and afternoon peaks (Fig. 4 LOCK column), and this could be due to changes in the traffic regulations imposed by the city authorities in the city centre (Politakos et al., 2020).

The partial lifting of restrictions (periods POST1 and POST2) led to a general recovery of the emissions, which reached baseline levels during POST2 in 9 out of 13 districts (Table S8 for statistical analysis). In four cities (DE-Berlin-TUCC, IT-Pesaro, NL-Amsterdam and UK-London) emissions remained statistically lower during POST2, with RFC ranging between – 13% and – 29% (see Fig. 4, POST2 column and Table S8 for statistical significance). At NL-Amsterdam the emissions remained below baseline level throughout the day (Fig. 4, last two columns), although social restrictions were not particularly stringent during POST2 ($SI = 44.8$, Table S2). However, this district is characterized by a strong presence of tourists, which the pandemic reduced drastically (Amsterdam saw a 60% reduction in tourism in July and August 2020, CBS Statistics Netherlands, 2021). This could also be the reason for the reductions observed at UK-London and IT-Pesaro during the POST periods. However, at UK-London, the restriction level remained high both during POST1 and POST2 ($SI = 64.5$ during POST2) compared to other cities, and the uptake of voluntary home-working was relatively high. These factors would also have contributed to keeping levels of socio-economic activities below the seasonal baseline in central London where the EC tower is located.

3.3.2. Effects of restrictions on diel CO_2 flux patterns

The diel patterns of the CO_2 fluxes in the different districts (Fig. 4) fall into two main categories: a bimodal emission pattern typical of districts with heavy traffic and accompanying rush-hour peaks (e.g. DE-Berlin-ROTH, GR-Heraklion, IT-Pesaro, IT-Sassari), and a monomodal pattern with a single maximum at midday (e.g. AT-Innsbruck, NL-Amsterdam and UK-London). At some sites the temporal pattern and the magnitude of the

baseline fluxes remain similar over the different periods from PRE to POST2 (e.g. AT-Innsbruck, CH-Basel-A, GR-Heraklion, IT-Pesaro, compare grey lines in the four sub-plots per site in Fig. 4), while in other cases the flux magnitude and/or pattern changed over the different periods suggesting a seasonal change in the CO_2 fluxes, independently from the pandemic. For example at the IT-Florence site, fossil fuel combustion for building heating results in large emissions and hence large net CO_2 fluxes in winter. Later on in the year during POST1 and POST2 (late spring to summer), the magnitude of the emissions is substantially reduced and the two emission peaks seen in winter are replaced by a single peak around midday. This midday peak is related to emissions from traffic and commercial activities that in the centre of this touristic city are not characterized by commuter traffic (see also Fig. S7).

By comparing emissions from paired EC observations in residential and non-residential areas of the same city, it is possible to infer qualitative information on the dominant driver. For example, single peak emission patterns are observed at CH-Basel-A and DE-Berlin-TUCC, both sites dominated by non-residential areas (see Fig. S5) where emissions are more evenly distributed during the business hours. In contrast, bimodal emission patterns are seen at CH-Basel-K and DE-Berlin-ROTH, which are more representative of residential areas.

For most of these urban sites, the observed CO_2 fluxes are positive throughout the day and across the January to October period considered (Fig. 4). However, net CO_2 uptake was observed at DE-Berlin-ROTH and FI-Helsinki during POST1 and POST2, and attributed to vegetative drawdown. Potential confounding effects of vegetation drawdown on the analysis of net reductions in anthropogenic CO_2 emissions as a result of lockdown can be ruled out because the vegetation was not active during the PRE and LOCK periods (see the Vegetation Analysis section in the Supplement).

3.4. Role of urban features: land use type analysis

Wind sectors classified as non-residential areas (nRES) showed the largest emission reduction during the LOCK period in all cities (Fig. 5, second column red bars). The other land use types also showed reductions during LOCK in almost all districts, but those reductions persisted at least in part during the following POST1 and POST2 periods (recovery phase), while a quicker recovery of emission levels was experienced in nRES after starting POST1. The emissions recovery in residential areas (RES, Fig. 5 first column) was less clear, and followed different temporal dynamics across cities; this was likely due to pandemic-related changes in vehicular traffic, and emissions associated with domestic heating, cooking, and human respiration, which are functions of population density and other specific characteristics of each district. Similarly, sectors dominated by roads and green urban areas (ROD and GUA respectively, third and fourth column in Fig. 5) also showed site-specific emission dynamics during the recovery phase.

3.5. Comparison with city-scale activity data

Despite differences in spatial scales, there was a clear link between reductions in road traffic emissions estimated by the CM method using traffic congestion data (city scale), and lower measured CO_2 emissions in the ROD, RES and nRES sectors (neighbourhood scale) in all cities during LOCK (Fig. 6b, all points in the third quadrant). During the POST1 period (Fig. 6c), the correlation progressively decreased and disappeared during POST2 (Fig. 6d) when traffic emissions according to the CM are close to pre-pandemic levels. The negative RFC values still observed at many of the sites are thus thought to be related to other factors or specific local conditions. Similarly for the PRE period (Fig. 6a), as expected in the absence of mobility restrictions, no relationship was found between RFC and changes in traffic emissions.

Fig. 5. CO_2 relative flux change (RFC , %) as a function of the district's land use and lockdown period. For each period RFC was calculated for each half-hour and wind direction (2° bins) between CO_2 fluxes in 2020 and previous years and then averaged by sector. District sectors are defined as residential (RES), non-residential (nRES), roads, and green dominated (ROD and GUA respectively). Negative RFC means emission reduction.

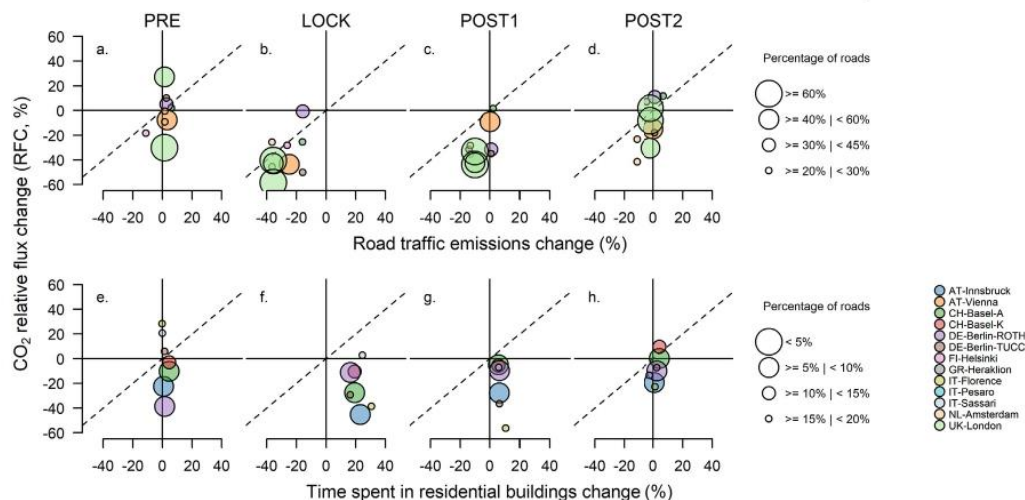


Fig. 6. Comparison of CO₂ relative flux change (RFC, %) and city-scale inventory data. Top panels (a–d): RFCs obtained from the EC flux measurements are compared against the road traffic emission change estimated using the Carbon Monitor (CM) modelling approach. RFC data used refer to district sectors covered mostly by residential buildings (RES), non-residential buildings (nRES), and roads (ROD). Data from sectors with less than 20% of roads were excluded from the analysis. Bottom panels (e–h): RFC compared to the COVID-19 Google community mobility trends in residential areas (as average duration spent in places of residence). RFC data used refer to district sectors covered mostly by residential buildings (RES), and having less than 20% of road coverage. The dashed lines represent 1:1 relationships. The comparison was done for the four COVID-19 periods (PRE, LOCK, POST1, POST2). As with RFC data, the daily city-scale emission estimates were smoothed using a 7-day rolling mean.

CO₂ emissions did not increase significantly in residential areas (with less than 20% of road cover) during the LOCK period, despite a mean 20% increase in time spent at home according to Google mobility data, and some instances of net reductions in emissions were recorded. This suggests that vehicular traffic is the main factor driving CO₂ fluxes in the monitored districts, with emissions from heating, cooking and human respiration playing a lesser role. The negative RFC in the three districts with less than 10% of roads during the PRE period (Fig. 6e, largest dots) could instead respond to a reduction in heating emissions due to anomaly warmer weather in these cities (e.g. Basel, Berlin, Innsbruck, see also Fig. 1 red lines and Fig. S1).

4. Conclusions

Direct CO₂ flux measurements from 13 eddy covariance (EC) stations across Europe reveal the effect of the COVID-19 pandemic restrictions on district level CO₂ emissions. At all sites, CO₂ emissions were significantly reduced during the strictest lockdown measures. In contrast to other approaches, the fine temporal resolution of EC data allows the evolution of the emissions to be analysed (at sub-daily to seasonal time-scales) and the changing response to restrictions to be quantified. For most sites CO₂ emissions returned to pre-pandemic levels by autumn of 2020. The emission reductions occurred mainly during daytime, principally as a consequence of limitations on mobility, and particularly reductions in vehicular traffic. In contrast, emissions related to home confinement (heating, cooking, human metabolism) did not increase enough to compensate for the reductions in emissions from road traffic; this was true in all neighbourhoods studied, even in the more residential ones where the workforce was displaced during lockdown periods.

The substantial emission reduction recorded through the first COVID-19 pandemic wave was temporary in most of the city districts and emissions rebounded to previous levels once restrictions were eased in the following months. The speed and extent of the emission recovery varied from district to district, with the fastest and most complete recovery seen mainly in the non-residential areas and attributed to re-established vehicular traffic.

This study demonstrates that the EC method is a valuable tool for monitoring continuously and almost in real-time the short- and long-term changes in urban trace gas emissions, and, potentially, for assessing the

effectiveness of climate change mitigation policies (for example limiting traffic emissions versus reducing building heating demand). Of great importance to this aim is the availability of auxiliary data such as detailed traffic data, inventories of emission sources related to human activities, and data on city urban features. This study highlights the additional advantages of monitoring networks, where data collected from individual stations can be synergistically combined for long-term monitoring activities such as the Integrated Carbon Observation System (ICOS, www.icos-ri.eu).

Our results demonstrate that altering human behaviour has a direct, immediate and significant effect on the reduction and recovery of urban CO₂ emissions. The temporary nature of the observed emission reductions emphasises the need to implement systemic changes in the city ecosystem and people's lifestyles to achieve effective and sustained climate change mitigation. To reach the target of climate-neutrality in 2050, cities need to take action across multiple sectors but, according to our data, this must include interventions on private and public mobility aimed at reducing associated emissions.

CRedit authorship contribution statement

Giacomo Nicolini: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft. **Gabriele Antoniella:** Conceptualization, Data Curation, Investigation. **Federico Carotenuto:** Investigation, Writing - Review & Editing. **Andreas Christen:** Investigation, Writing - Review & Editing. **Philippe Ciais:** Investigation, Resources, Writing - Review & Editing. **Christian Feigenwinter:** Investigation, Writing - Review & Editing. **Beniamino Gioli:** Investigation, Writing - Review & Editing. **Stavros Stagakis:** Methodology, Investigation, Writing - Review & Editing. **Erik Velasco:** Methodology, Investigation, Writing - Review & Editing. **Roland Vogt:** Investigation, Writing - Review & Editing. **Helen C. Ward:** Methodology, Investigation, Writing - Review & Editing. **Janet Barlow:** Writing - Review & Editing. **Nektarios Chrysoulakis:** Investigation, Writing - Review & Editing. **Pierpaolo Duce:** Investigation, Writing - Review & Editing. **Martin Graus:** Investigation, Writing - Review & Editing. **Carole Helfter:** Investigation, Writing - Review & Editing. **Bert Heusinkveld:** Investigation, Writing - Review & Editing. **Leena Järvi:** Investigation, Writing - Review & Editing. **Thomas Karl:** Investigation, Writing - Review & Editing. **Serena Marras:** Investigation, Writing - Review &

Editing. **Valéry Masson**: Writing - Review & Editing. **Bradley Matthews**: Methodology, Investigation, Writing - Review & Editing. **Fred Meier**: Investigation, Writing - Review & Editing. **Eiko Nemitz**: Investigation, Writing - Review & Editing. **Simone Sabbatini**: Writing - Review & Editing. **Dieter Scherer**: Investigation, Writing - Review & Editing. **Helmut Schume**: Investigation, Writing - Review & Editing. **Costantino Sirca**: Investigation, Writing - Review & Editing. **Gert-Jan Steeneveld**: Methodology, Investigation, Writing - Review & Editing. **Carolina Vagnoli**: Writing - Review & Editing. **Yilong Wang**: Investigation, Writing - Review & Editing. **Alessandro Zaldei**: Investigation, Writing - Review & Editing. **Bo Zheng**: Investigation, Writing - Review & Editing. **Dario Papale**: Conceptualization, Methodology, Writing - Review & Editing, Validation, Supervision.

Data availability

All the eddy covariance datasets used in the study are available in Figshare under CC-BY licence (DOI: <https://doi.org/10.6084/m9.figshare.13686292>), together with the buildings and road traffic daily emissions as estimated by the CarbonMonitor method.

Other data that support the findings of this study are available at the following links:

- Oxford COVID-19 Government Response Tracker (OxCGRT) data are available at <https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker#data>
- Urban Atlas 2012 data are available at <https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012?tab=download>
- Google Community Mobility Reports data are available at <https://www.google.com/covid19/mobility/index.html?hl=en>

Code availability

Data in this study were analysed using R (R Core Team, 2019) version 3.6.2 (2019-12-12, Dark and Stormy Night) and RStudio (RStudio Team, 2021) version 1.4.1717 (Juliet Rose). The custom code used for the analysis is available at: https://github.com/Giacomo-Nicolini/UrbanFluxes_COVID19.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2022.154662>.

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