

Long-term land-atmosphere carbon monoxide exchange from a tall tower in a rural Central European region

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Abstract. ~~Carbon monoxide (CO) is a crucial~~The atmospheric trace gas, carbon monoxide (CO) significantly influences the atmosphere's oxidative capacity and indirectly affecting climate. However, the net land-atmosphere exchange of CO remains highly uncertain due to the scarcity of long-term monitoring. This study presents and analyses a 10-year-long CO flux data series from a tall-tower eddy covariance (EC) system operated in a rural Central European region. The measured fluxes were evaluated separately for ~~cases when the flux footprint of the measurement covered almost exclusively quasi-natural areas (arable land, forests), and for cases when the footprint of the measurement covered populated areas (villages, roads)-vegetation-covered, (quasi)natural areas and for populated areas.~~ The estimated monthly mean emissions from the populated areas varied between 12 and 110 nmol m⁻² s⁻¹, with the lowest value observed in July and the highest in January, respectively. The measured wintertime emissions from the populated areas significantly exceed the activity-based estimations, presumably due to underestimated emissions factors for residential heating. The vegetation-dominated sector (agricultural fields and forests) acted as a weak net CO source from April to September with an average emission of 0.58 nmol m⁻² s⁻¹ (monthly range 0.31–0.91 nmol m⁻² s⁻¹), with the highest value occurring in July. The diurnal peaks of the median hourly emissions can be observed around noon, and they range from 1.59 to 2.66 nmol m⁻² s⁻¹. The nighttime (20-04 h LST) hourly median values range from -1.01 to +1.17 nmol m⁻² s⁻¹. Their deviations from zero are not statistically significant at a p<0.05 probability level. Solar radiation was identified as the primary driver of CO exchange. ~~The measured emissions from the populated areas significantly exceed the activity based estimations, presumably due to the underestimation of the emissions from residential heating. This study also presents~~This study also demonstrates the advantages and challenges of tall-tower EC flux measurements.

1 Introduction

35 For ~~a long time~~many decades, carbon monoxide (CO) was primarily considered a dangerous, toxic component of urban and indoor air pollution (Horner, 2000). With the introduction of three-way catalytic converters in gasoline-powered vehicles and advances in combustion technologies, ~~carbon monoxide~~CO pollution has become less of a problem in cities, at least in the more developed parts of the world (Hedelius et al., 2021). However, ~~carbon monoxide~~CO is also an important trace component of the global atmosphere, playing a significant role in atmospheric chemical processes, governing ~~its~~the oxidative capacity, and, through these, indirectly influencing the atmospheric greenhouse effect and climate change (Szopa et al., 40 2023).

Carbon monoxide is oxidized by the hydroxyl radical (OH). The product of this chemical reaction is carbon dioxide (CO₂), which is the second most important greenhouse gas in the atmosphere after water vapor (Schmidt et al., 2010). The oxidation of ~~carbon monoxide~~CO by OH is a concurrent chemical reaction with the oxidation of methane (CH₄) by OH, which is the 45 dominant sink of ~~methane~~CH₄ in the troposphere. One of the reaction products is carbon monoxide itself (Gaubert et al., 2017). The reaction of OH with ~~carbon monoxide~~CO consumes about 40 % of OH radicals (Lelieveld et al., 2016; Zhao et al., 2020). Hence, any change in the atmospheric ~~carbon monoxide~~CO concentration influences the lifetime of ~~methane~~CH₄, the third most important greenhouse gas after water vapor and ~~carbon dioxide~~CO₂, and thus, CO could be considered an indirect greenhouse gas. The oxidation of ~~carbon monoxide~~CO by OH also results in hydroperoxyl radicals. Hydroperoxyl 50 radical is one of the key components of ozone formation in the troposphere (Crutzen et al., 1999). In addition to being a greenhouse gas, ozone is also a phytotoxic substance of environmental concern. All this underscores the importance of research focusing on the sources, sinks, and processes of atmospheric ~~carbon monoxide~~CO.

Almost half of the carbon monoxide in the atmosphere is derived from the oxidation of ~~methane~~CH₄ and ~~other~~ volatile organic compounds. One quarter comes from direct anthropogenic sources, and a roughly similar amount from biomass 55 burning, which has large interannual variability. The source inventory is completed by a minor (~7 %) biogenic and a practically negligible (<1 %) oceanic release (Zheng et al., 2019). In the recent compilation of Zheng et al. (2019), oxidation by OH is the only globally notable sink of ~~carbon monoxide~~CO. Other authors (e.g., Khalil et al., 1999; Pihlatie et al., 2016; Liu et al., 2018; and references from therein) suppose that soils are globally a small but not negligible sink of CO due to microbial oxidation processes (Ragsdale, 2004; King and Weber, 2007). Duncan et al. (2007) list several inversion studies, a 60 part of which attributes up to 10 % of the global CO-sink to the soil, while the others did not indicate a net soil sink. Their own model supposes that biogenic emissions are roughly balanced with the amount consumed by soils, and that these emissions exert no significant net influence on the global CO budget.

The scarce availability of in-situ CO flux data comes from relatively few, mostly short-term measurements performed ~~at~~in a limited spatial context (using e.g. chambers and short (<5 m) eddy covariance (EC) towers), which cannot represent the wide 65 variety of ecosystems, soil types, and climate conditions, and regional scale fluxes. The rate at which microorganisms consume ~~CO-consuming microbial activity~~ may depend on the soil's organic ~~fraction of the soil, content,~~ porosity,

temperature, ~~and~~ water content, ~~etc., while~~among other factors. Meanwhile, the production rate of ~~carbon monoxide~~CO via thermal- or photodegradation of ~~the~~ living or dead organic matter may depend on ~~plant~~the species of plant (Bruhn et al., 2013). Bruhn et al. (2013) conducted a 2-month survey over a grassland in Denmark using UV-transparent Plexiglas chambers and found that the grassland was a net sink in darkness and a net source in natural sunshine. Constant et al. (2008) came to the same conclusion after one year of CO-flux measurement over a grassland in Canada using the vertical gradient method at a 3 m-tall tower. However, the 20-month-long survey of Cowan et al. (2018) over a grazed grassland in Scotland indicated net emission from the soil-vegetation system. The nighttime fluxes were around zero. The measurements did not supporting the reflect a net soil sink hypothesis., but the EC system used did not allow the separation of the fluxes from the vegetation and from the soil. Laasonen et al. (2025) performed a 2-year-long measurement series over an Arctic peatland in Sweden and concluded that part of the peatland could act as either a net source or sink, depending on soil moisture levels. However, the area as a whole, as represented by the measurements, acted as a net CO source. Laasonen (2021)~~Laasonen~~ studied three different ecological systems in Finland (6–23 months) and one in Kenya (1 month), and found all to be net CO sources, as the soil uptake was ~~overcompensated~~offset by ~~the~~emissions mainly driven by incoming solar radiation~~driven~~ ~~emission.~~. The 22-month-long measurement by Murphy et al. (2023) over a fertilized and grazed grassland in Ireland did not show net CO uptake by soil either. Pihlatie et al. (2016) reported on a single season (from snowmelt to snowfall) of CO-flux measurements over an area cultivated with a perennial reed canary grassland in Finland. They found a seasonally variable net flux direction (net source/net sink). The represented area was a net source from mid-April to mid-June, and a net sink from mid-June to November. Integration of the fluxes over the 7 months of the measurements indicated a weak net soil uptake. Pihlatie et al. (2016) also list several earlier CO-flux monitoring projects from different parts of the world, which indicate a mixture of positive and negative CO fluxes between the surface and the atmosphere. Sun et al. (2018) also recorded net soil uptake during a project covering a late growing season (July–November) in a Scots pine forest in Finland. Based on two short measurement campaigns, van Asperen et al. (2024) concluded that soil sources dominate over soil sinks in tropical rainforests in Brazil.

The general conclusion is that the net biogenic CO exchange between the land surface (soil + vegetation) and the atmosphere is highly uncertain due to the limited number of measurement projects and the rather short (from a few days to about 2 years) monitoring periods. Although the biogenic surface-atmosphere exchange is not the major contributor to the atmospheric CO budget, due to the wide-ranging effects of carbon monoxide in the global environment, it is ~~worth clarifying~~nevertheless important to clarify this contribution.

Most of the historic measurements applied the so-called chamber method, which involved open or closed, opaque or transparent chambers of various sizes. This labor-intensive method cannot cope with the heterogeneity of the soil; moreover, its spatial representativeness is rather limited. The micrometeorological methods suitable for continuous monitoring of CO-fluxes only appeared about a decade ago (Blomquist et al., 2012; van Asperen et al., 2015; Pihlatie et al., 2016). To date, only a few, mostly short-term projects lasting from a few days to a maximum of two years, have been published (Blomquist et al., 2012; van Asperen et al., 2015; Pihlatie et al., 2016; Cowan et al., 2018; Murphy et al., 2023; Laasonen et al., 2025).

These studies used short, 2–4 m tall towers and focused on specific ecological systems. The use of taller towers comes with significant benefits, but also poses challenges (see e.g. Berger et al., 2001; Davis et al., 2003; Desai et al., 2015; Chi et al., 2019; Coimbra et al., 2024; Hilland et al., 2025; and several other publications). Tall-tower measurements can provide landscape-scale surface-atmosphere exchange values over heterogeneous regions of up to 100 km² or more, ~~depending on~~depending on the height of the tower (Kljun et al., 2002; Kljun et al., 2004; Barcza et al., 2009; Desai et al., 2015; Chi et al., 2019; Barcza et al., 2020). ~~Depending on topography and these values~~Depending on topography ~~land cover patchiness, flux measurements on tall towers~~and these values can be more robustly upscaled than the data from specific ecosystems. At the same time, the ~~se~~se flux ~~measurement on a tall tower~~measurement on a tall tower ~~measurements~~measurements may become decoupled from the surface during low-level temperature inversions, and temporary accumulation of ~~material~~material ~~trace gases~~trace gases in the atmospheric layer below the measurement level („storage”) may also cause methodological challenges (Haszpra et al., 2005).

This study focuses on a tall tower site in western Hungary. Here, atmospheric ~~carbon monoxide~~CO concentration monitoring started already in 2015. The high-frequency data acquisition and the availability of a co-located EC system for CO₂ ecosystem exchange measurements (Barcza et al., 2020) ~~raised~~motivated the ~~idea that exploration of~~idea that exploration of these measurements ~~could also be used~~could also be used to determine the flux of ~~carbon monoxide~~CO between the surface and the atmosphere. We are aware of only a few recent short-term (<1 year) attempts to measure CO ~~-fluxes~~-fluxes on tall towers (Coimbra et al., 2025; Hilland et al., 2025). These measurements were performed in urban or semi-urban environments. ~~As the original purpose of the measurements was the long term monitoring of the concentration trends, local auxiliary measurements for the interpretation of the flux measurements are limited. Despite these challenges, this~~As the original purpose of the measurements was the long term monitoring of the concentration trends, local auxiliary measurements for the interpretation of the flux measurements are limited. Despite these challenges, this ~~Our~~Our study presents the first long-term, tall-tower-based, regionally representative CO flux data series for a rural environment (agricultural fields, small villages) for the 2015–2025 period.

The main goals of the present study are 1) to synthesize and interpret the 10-years long CO flux observations at the Hegyhátsál tall tower site; 2) to distinguish areas that are more influenced by anthropogenic activity from those that are mainly associated with vegetation by applying a footprint model; 3) to quantify fluxes from these two land cover types; and 4) to identify environmental variables that might explain the observed CO emissions from the vegetation-dominated, (quasi)natural areas. We focused primarily on analyzing anthropogenic surface-atmosphere CO fluxes during winter and natural CO fluxes during summer. The study provides a unique dataset for the observation-based, regional-scale estimation of the CO budget, where the results can be used to refine emission inventories in Central Europe.

2 Measurements and methods

2.1 Site location ~~and instrumentation~~

The Hegyhátsál tall-tower greenhouse gas monitoring station is located in a rural environment in western Hungary (46.956°N, 16.652°E, 248 m asl). It was established in 1993 and provides data for the Global Atmosphere Watch of the

World Meteorological Organization (WIGOS ID: 0-348-4-16307)), and weekly air samples are taken here for NOAA's Global Cooperative Flask Air Sampling Network (NOAA station ID: HUN). Since 2024, the site has also been operating as an ICOS Class 2 atmospheric site. The station is a 117 m-tall TV/radio transmitter tower (operated by Antenna Hungária Corp.), equipped with meteorological sensors and air intake tubes ~~at different elevations (10 m, 48 m (50 m from 2022), 82 m, 96 m, 115 m above. The mean annual temperature in the ground)-region was 10.4 °C in 1991–2020 and increasing rapidly with time (0.54±0.13 °C per decade). The average annual precipitation is 690 mm, showing no significant trend but a wide range of variation between 475 and 939 mm yr⁻¹ during the indicated period.~~

The station is located in a fairly flat region, in the vicinity of a small village called Hegyhátsál. During the 10 years of this study (July 2015 – June 2025), the population of the settlement, accommodating with no industrial or commercial activities, gradually decreased from 160 to 141 people (Hungarian Central Statistical Office, 2025). The village, a potential anthropogenic ~~carbon monoxide~~CO source, is located in the northwest sector of the station, at a distance of 400–1200 m, while the prevailing wind ~~direction is~~directions (NNE and SSW) are perpendicular to this direction. Apart from the village, the tower is surrounded by a regionally typical mixture of agricultural fields (dominantly corn, winter wheat, and rape in crop rotation with small plots of other cultivars) and forest patches. For the identification of the land cover types, the National Ecosystem Base Map of Hungary (NÖSZTÉP) (Tanács et al., 2021) was used. This dataset classifies 56 land cover type categories and provides land cover information with a spatial resolution of 20 m×20 m (Fig. 1). The soil type in the region is 'Lessivated brown forest soil' (Alfisol, according to the USDA system). The upper layer is generally 10–20 cm thick and has an organic matter content of 5–8 %.

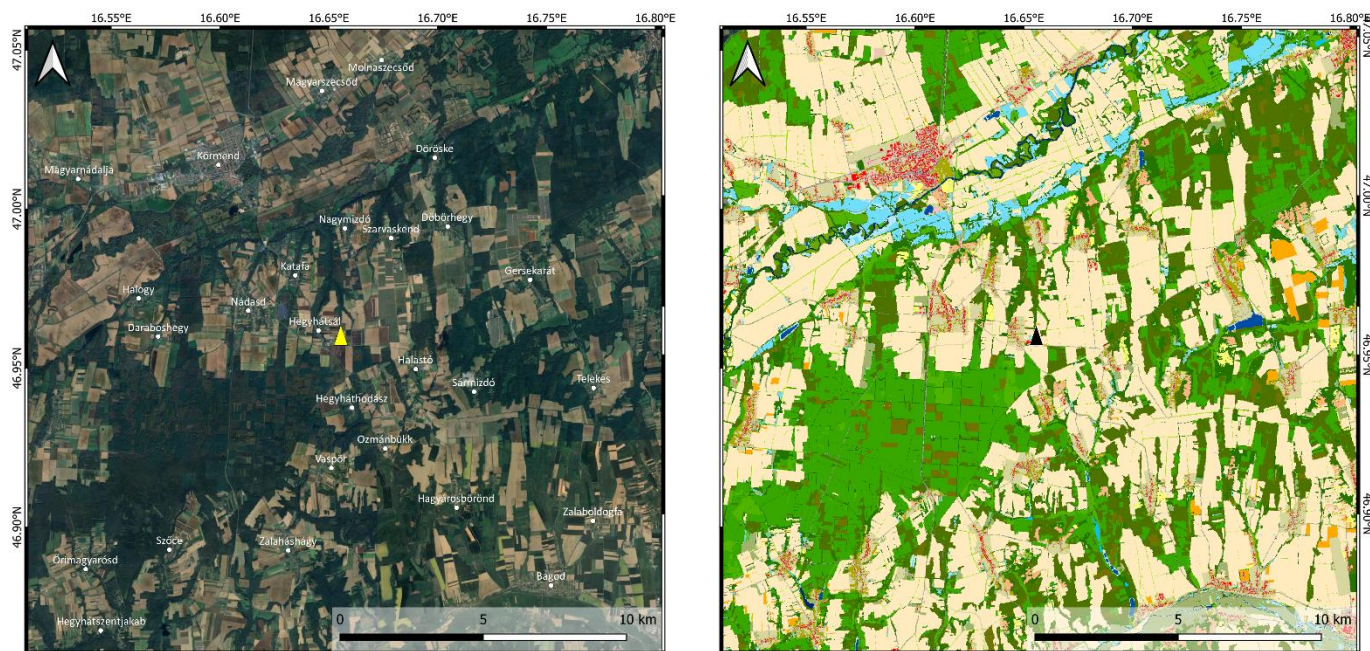


Figure 1: Google Earth satellite image (left – © Maxar Technologies/Google, 2025) and the NÖSZTÉP land cover map (right) of the region of the monitoring site (colors: shades of green – different types of forests and grasslands, yellow to pale orange – agricultural lands, bluish – wetlands, rivers, lakes, red/pink – buildings/urban residential areas, olive – green areas in urban residential environment; for detailed description see Tanács et al., 2021). The location of the tower is indicated by a yellow (left) and black (right) triangle.

The neighboring villages near Hegyhátsál are about 3 km away from the tower to the northwest (Katafa), west (Nádasd), and south (Hegyháthodász). The nearest settlement worth mentioning in the eastern sector is Gersekarát, located more than 7 km from the tower (Fig. 1). There is hardly any commercial or industrial activity in this predominantly agricultural region. The local roads connecting the small settlements carry little traffic (300–600 vehicle units per day). The only major road in the region is the 2×1-lane trans-European E65 running northwest–southeast with 5200 vehicle units per day (Magyar Közút, 2025). Its closest point to the monitoring site is about 500 m to the southwest (Fig. 1).

Carbon monoxide2.2 Instrumentation

CO concentration has been monitored using an Enhanced Performance fast-response N₂O/CO/H₂O analyzer (Model 913-0014, Los Gatos Research Ltd., San Jose, CA, U.S.A.) with fast-flow optional accessories, which records at 5 Hz frequency continuously since July 2015. The analyzer is located at ground level in an air-conditioned room of the transmitter building. Air to be analyzed is taken from 82 m on the tower through an approximately 100 m-long 3/8” OD Synflex 1300 tube (Eaton Corporation Plc, Dublin, Ireland). The flow rate at of about 3.5 L/min is maintained by a diaphragm vacuum pump (KNF

170 Type N 880.3 AN.22E, Neuberger, Inc., Trenton, NJ, U.S.A.). The analyzer is regularly calibrated against four CO-in-
natural air standards ($48\text{--}513\text{ nmol mol}^{-1}$) produced and certified by Max Planck Institute for Biogeochemistry, Jena,
Germany, to meet the high accuracy requirements of the monitoring of the temporal variation in the concentration (long-term
trend, seasonal and daily variations, etc.) (WMO, 2024). The standards are traceable to the WMO CO X2014A scale. The
drifts of the standards were linearly corrected between the recalibrations of the standards, and we continuously compared the
175 measurement results with those obtained from NOAA flask air samples to detect any significant drift. The ~~platform at 82 m
elevation also hosts an~~ EC system ~~for the long term monitoring of surface atmosphere CO₂ exchange, consisting of also
includes~~ a GILL R3-50 research ultrasonic anemometer ~~and a LI-COR Model LI 6262 CO₂/H₂O analyzer (LI-COR Inc.,
Lincoln, Nebraska, USA; . The temporal synchronization of the monitoring systems and the close mounting of the intake
tube of the N₂O/CO analyzer to~~. The ultrasonic anemometer ~~(~50~~ and the air inlet are mounted at the end of a 4.4 m long
180 ~~north-looking instrument arm at 82 m above the ground, where the diameter of the steel-tube tower is 1.8 m. The distance of
the air inlet from the center of the ultrasonic anemometer is 80 cm)~~ allow us to use the analyzer not only for concentration
~~monitoring but also to estimate the surface atmosphere carbon monoxide exchange.~~ Considering the high elevation of the
EC system above the ground ~~(82 m)~~, where the characteristic size of the eddies is larger than that at the elevation of the
usual EC systems (typically a few meters above the ground), the 5 Hz sampling frequency and the 3.5 L/min flow rate
185 ~~are~~proved sufficient for reliable flux calculations: (Haszpra et al., 2018).

2.23 Auxiliary data

Since the monitoring system was ~~not~~ originally designed for CO concentration rather than for a carbon monoxideCO
exchange study; ~~therefore~~, only somea few CO-flux-relevant auxiliary measurements are available from the site.
Instead of the standard height of 2 m, air temperature is ~~measured~~available at 10 m elevation above the ground (until
190 November 2022: Vaisala Model HMP35D; from December 2022: Vaisala Model HMP155; Vaisala Oyj, Helsinki, Finland),
~~matching the lowest measurement elevation of the vertical CO₂ concentration profile~~following the requirements of another
research project (Haszpra et al., 2001). A Model LI-190SZ (LI-COR Inc., Lincoln, Nebraska, USA) quantum sensor was
available until March 2021, followed by an Apogee SQ-100X-SS sensor (Apogee Instruments, Inc., Logan, Utah, USA)
from December 2022 for recording of the incoming photosynthetically active radiation ($0.4\text{--}0.7\text{ }\mu\text{m}$) at 2 m above the
195 ground.
UV -radiation and soil water content (SWC) ~~may also influence~~measurements are not available at the ~~carbon
monoxide~~tower. These variables are mentioned in the literature as potential drivers of the CO exchange between the surface
(vegetation+soil) and the atmosphere (Bruhn et al., 2013; Murphy et al., 2023; Laasonen et al., 2025). ~~These data (downward
UV radiation at the surface [0.20–0.44 μm], volumetric soil water content in layer 0–7 cm) were downloaded from;~~
200 therefore, we turned to the ERA5 reanalysis dataset of the European Centre for Medium-Range Weather Forecasts
(Copernicus Climate Change Service, 2022). Downward UV radiation at the surface (0.20–0.44 μm) and volumetric soil

water content in layer 0–7 cm data were downloaded for the nearest two grid points to the monitoring station (47.0°N, 16.5°E; 47.0°N, 16.75°E), and were then averaged.

A disadvantage of tall-tower EC systems is that they may be decoupled from the surface by low-level inversions from time to time (Desai et al., 2015; Chi et al., 2019). In these situations, the EC systems cannot provide the actual surface–atmosphere flux data. To remove decoupled measurements in cases of low-level inversion, information on the height of the boundary layer was also derived from the ERA5 reanalysis dataset.

2.34 Flux calculation

The basic theory of the EC flux measurement technique is discussed in the scientific literature in detail (see e.g. Aubinet et al. (2012) for summary and review). The methodology applied for the calculation of the ~~raw~~-hourly turbulent fluxes of CO at our tall tower monitoring site ~~is practically identical to that used~~was originally developed for CO₂ flux derivation (Barcza, 2001; Haszpra et al., 2005; Barcza et al., 2020)~~calculation at this site, and is described in detail in~~has been adapted to calculate the exchange of CO. In the following, we provide a brief summary of the methodology. For more details, the reader is referred to Barcza (2001), Haszpra et al. (2018), and Barcza et al. (2020).

As a first step, the lag time caused by the ~100 m long air intake tube is determined. The H₂O lag time is used as an indicator for the identification of the CO lag time. It is typically 5-10 seconds longer than the lag time for CO due to the adsorption/desorption of water vapor on the inlet tube wall. For each day, the lag time is manually determined by visualizing the lagged covariance data for all 24 hours. This method was chosen because the covariance maximization would frequently lead to erroneous lag time values for days with low turbulent flux (cf. Supplementary material S2 in Haszpra et al. 2018). The turbulent flux calculation starts with the determination of the lag time caused by the ~100 m long air intake tube. For each day, lag time estimation was done interactively by visualizing the lagged covariance data for predefined time windows. Angle-of-attack dependent calibration was). Assuming a constant lag time for each particular day is supported by the relatively constant performance of the pump and the visual inspection of the dataset over the 10-year-long measurement period. For low flux days, the lag time can be determined from the lag time from previous days with larger fluxes, and with careful visual selection of some of the lagged covariance curves that correctly indicate the true value (e.g. associated with occasional higher fluxes).

Angle-of-attack dependent calibration is applied to the raw sonic anemometer data (van der Molen et al., 2004).~~Three-dimensional wind vector rotation was applied.~~ Since the EC system is located at a height of 82 m, the slight tilt of the sonic anemometer, the tower body structure, and the surrounding terrain can affect the mean airflow that is sampled by the anemometer. We hence chose the three-dimensional wind vector rotation to align the coordinate system with the prevailing streamlines (Lee, 1998). This method performed better for our site than the popular planar fit method and the simple 2D rotation (Aubinet et al., 2012). Using the technique detailed in Barcza (2001), rotation coefficients are calculated for each 3° wind direction sector using data from long time periods. The length of the time periods is determined by the timing of interventions when the tilt of the anemometer might have changed due to maintenance work. These coefficients are used to

235 determine the rotation angle of the 3D wind for a given wind direction (see Fig. 2.12 in Barcza, 2001), which means that the rotated coordinate system matches the mean streamlines (but allows non-zero mean vertical wind speed – Lee, 1998). Linear detrending is applied to the wind and CO mole fraction time series.

The hourly means of the turbulent fluxes ~~we~~are calculated taking into account the predetermined lag times ~~and rotated 3D wind data described above~~. As the system ~~calculates~~derives fluxes from dry air mole fractions of CO, the Webb-Pearman-Leuning correction (Webb et al., 1980) was not applied. As part of the postprocessing, spectral corrections ~~we~~are applied to account for flux losses caused by the fluctuation damping caused by the intake tube, lateral sensor separation, sensor line averaging, etc. (Moore, 1986; Massman, 1991). Finally, several quality control indicators are derived (Vickers and Mahrt, 1997; Kroon et al., 2010).

245 An EC system measures the mass transport through a horizontal plane at its elevation above the ground, which is 82 m in our case. In situations of limited vertical mixing, the EC system may become decoupled from the surface, ~~causing the leading to measurements to fail to reflect that are no longer representative of the actual surface processes taking place at the surface~~. To avoid ~~the unrepresentative such~~ values, we ~~did not calculate rejected fluxes for those hours~~ when the boundary layer height was below 100 m. The layer below the EC system may become enriched (surface source) or depleted (surface sink) in the trace gas studied without recording. After the decoupling (i.e., during the breakup of the nighttime inversion after sunrise), 250 the accumulated excess or deficiency in the surface layer appears in the measured flux (storage flux). Although the temporary decoupling may distort the measured diurnal variation, the daily total flux ~~usually~~ properly reflects the daily surface-atmosphere exchange (as there is no long-term accumulation or depletion below the measurement level); cf. Haszpra et al., 2005). Unlike in the case of CO₂, we ~~suppose~~hypothesize that emitted CO is neither taken up nor reemitted during the time of decoupling, i.e., there should not be any distortion of the net ~~exchange estimations. Due to the absence of vertical concentration profile measurements, we have to accept the aforementioned limitations and assumptions~~CO exchange estimations.

To test this hypothesis, we calculated the single-point concentration-based CO storage flux (assuming a constant vertical CO mole fraction profile up to the measurement level – Greco and Baldocchi, 1996). The result showed that the CO storage term at 82 meters has relevance for the CO fluxes only in the winter season, redistributing the hourly fluxes slightly, but not 260 affecting the total flux. It is important to mention that the variability of the fluxes is high (see Results), and as the single-point-based storage flux calculation is only a simple approximation of the true storage flux (where the latter is supposed to take into account the non-linear shape change of the CO profile as well), consideration of the storage flux increases the uncertainty. As the analysis is restricted to turbulent conditions ($u^* \geq 0.2 \text{ m s}^{-1}$, PBLH $\geq 100 \text{ m}$ – see Section 2.5), to ensure that the surface fluxes are identical with the measured CO flux measured at 82 m elevation, the storage-prone hours are 265 largely excluded beforehand. Thus, it seems reasonable to accept the aforementioned hypothesis on the negligible effect of CO storage flux on the results.

Considering quality control and data flagging based on the calculated quality indicators (Vickers and Mahrt, 1997; Kroon et al., 2010) ~~We expect that due to the heterogeneous landscape surrounding the tower, the different land cover sections (arable~~

lands, forests, villages, etc.) may contribute significantly different fluxes to the measured signal. Hence, no outlier filtering was applied during the flux calculation.

2.4, an attempt was made to check their applicability to filter outliers. However, as there was no detectable relationship between the magnitude of the CO fluxes and the indicators, this filtering was not applied. Another approach would have been to filter the data based on statistical measures (e.g. removing data outside the ± 3 standard deviation threshold or using percentile-based filtering, etc.). We rejected this approach because we expect significantly different fluxes from the different land cover types (arable lands, forests, villages, etc.) in the heterogeneous landscape surrounding the tower. Hence, no outlier filtering was applied during the flux calculation. It is important to note that the prerequisites for the footprint calculations inherently filter out low wind speed conditions (i.e. strong inversion during nighttime), which represents an alternative quality control.

2.5 Flux footprint calculation

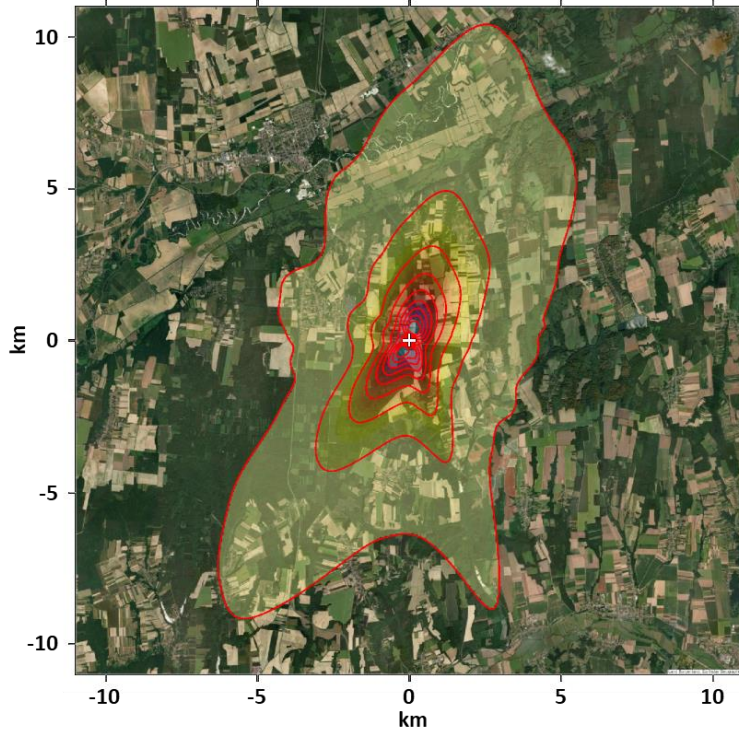
The flux footprint function quantifies the relative contribution of each element of the upwind surface area to the measured flux as a probability density function. For the calculation of the source area (footprint) of the flux measurements, the two-dimensional Flux Footprint Prediction (FFP) model developed by Kljun et al. (2015) ~~Kljun et al.~~ was applied. This model performed amongst the best in a test against data from a tracer release experiment involving several footprint models (Heidbach et al., 2017); and is, unlike other models, valid for tall tower fluxes.

The input parameters of the model are the measurement height above displacement height (z_m), the roughness length (z_0), the Monin-Obukhov length (L), the standard deviation of the lateral wind speed (σ_v), the friction velocity (u_*), and the height of the boundary layer (h). The wind direction is an optional input parameter, but it is needed here for the spatial attribution of the source areas. As wind direction is affected by the tower body (see Barcza, 2001), we developed a wind direction correction method based on the co-located short-tower (3 m) EC system documented in Barcza et al. (2003). The wind direction measured at the height of 82 m is empirically adjusted based on the wind direction climatology of the short tower (3 m), taking into account the changes in wind direction with height. This method was successfully used in earlier studies (Barcza et al., 2009; Gelybó et al., 2013)~~geographical localization of the source areas, focusing on footprint analysis based on the tower data.~~ Displacement height was considered to be negligible relative to the height of the measurements; thus, the observation height was used to approximate z_m . The listed parameters were either directly measured or could be calculated from the measurements. The boundary layer height was available from the ERA5 reanalysis dataset (see Section 2.23) for the region of the tower. The roughness length was assumed to be equal to 0.15 m based on estimates from an earlier study (Barcza et al., 2009).

In this study, following the recommendations for the application of the FFP model (Kljun et al., 2015), the model was used with the following restrictions: $20z_0 < z_m < h_e$, $-15.5 \leq z_m/L$, and $u_* \geq 0.2 \text{ m s}^{-1}$, where h_e is the height of the entrainment

300 layer. h_e is typically around $0.8 h$ (Holtslag and Nieuwstadt, 1986), ~~-. We also applied $u_* \geq 0.2 \text{ m s}^{-1}$ to ensure turbulent forcing.~~

An example footprint climatology of the station for the year 2020 is presented in Fig. 2. It demonstrates that the prevailing wind directions at the station are northeasterly and southwesterly, and that the footprints for these wind directions typically extend up to 10 km from the tower.



305 **Figure 2: Flux footprint climatology of the monitoring site in 2020.** For data selection, see Section 2.56. The footprint contour lines (red) show a 10 %–90 % contribution to the flux measurement in 10 % steps. The tower is at the origin (0,0) of the map, and it is indicated by a white + sign. Sources base map: ESRI | Powered by ESRI.

2.56 Data availability statistics

310 The measurements started on 1 July 2015, and the present study evaluates the data until 30 June 2025. The 10-year-long data series comprises 87,672 hourly values. During a total of 21,802 hours, predominantly summer nights and at any time of day in winter (see the boundary layer height statistics in Haszpra and Barcza (2010)), the boundary layer height was below 100 m. Due to the potential decoupling of the EC system from the surface, we rejected these data points for surface flux estimation. In the case of an additional 16,499 hours, fluxes could not be calculated for technical reasons- (instrument malfunction, data acquisition gaps, maintenance, etc.). Finally, 14,068 hours did not satisfy the conditions for footprint

315

calculations. In the absence of a solid theoretical basis, and also ~~in order~~ to avoid inclusion of modelled data, data gap filling was not applied.

Far-reaching flux footprints are increasingly uncertain and may cover distant anthropogenic sources, distorting the regional emission estimations. To decrease attribution uncertainty, we selected only those footprints for which the integral of the footprint transfer function over a radius of 5 km from the tower was ≥ 0.8 , i.e., the footprint contribution to the fluxes measured at the tower was $\geq 80\%$. Altogether, we had to exclude 70.4 % of the hourly data; that is, 25,917 hourly data remained available for the actual study.

2.67 Flux map, and separation of populated and (quasi)natural areas

~~Using the filtered CO fluxes, footprint-weighted flux maps were calculated. In these maps, each grid cell contains the average of the fluxes measured at the tower weighted by the value of the footprint transfer function at the given grid cell. This approach only indicates the direction of the sources/sinks due to the so-called "blurring effect", and is not suitable on its own for determining the exact location of the sources/sinks.~~

In the case of most conventional ~~eddy covariance~~EC towers, which are only a few meters tall, the heterogeneity of the footprint area is generally small. However, in the case of tall towers with an extensive footprint area, it can be significant. While tall towers are great for determining the average emissions of heterogeneous areas (Desai et al., 2015; Peltola et al., 2015; Chi et al., 2019) and allow more reliable upscaling of the results, attempts can also be made to separate fluxes from areas with different land cover types (Barcza et al., 2009; Helbig et al., 2017; Tuovinen et al., 2019; Hernandez Rodriguez et al., 2023; Tikkasalo et al., 2025; Molinier et al., 2026).

In this study, we use a simple method to determine the ~~carbon monoxide~~CO flux of populated grid cells and (quasi)natural grid cells separately. A grid cell is considered „populated” if it belongs to one of the following NÖSZTÉP land use categories: buildings, roads, other paved or unpaved artificial surfaces, as well as green fields in an artificial environment. The term “(quasi)natural grid cell” or “vegetation-covered grid cell” (these terms are used as synonyms in this paper) refers to the categories of arable land, forest, grassland, and wetland, where the anthropogenic emissions are assumed to be minimal. Due to the relatively small amount of data, we did not attempt to separate the fluxes from agricultural fields and forests.

Using the filtered CO fluxes, footprint-weighted flux maps were calculated. In these maps, each grid cell contains the average of the fluxes measured at the tower weighted by the value of the footprint transfer function at the given grid cell. To provide a robust estimation at low data availability, the quantification of CO flux from the populated areas and from the (quasi)natural areas was performed in monthly time steps. The hourly CO fluxes were combined with the footprint analysis and the land cover map to quantify the percentage of contribution from both the populated and (quasi)natural areas. At any time, the measured flux (f) is assumed to be the sum of the flux from the populated areas (F) and that from the non-populated, (quasi)natural areas (f_{bg}). For the determination of the emissions from the populated areas, the following model was used:

$$F = (f - f_{bg}(1 - \alpha)) / \alpha, \quad (1)$$

350 where α is the contribution of the populated grid cells. Assuming at least an order of magnitude difference between the fluxes from the populated areas and from the (quasi)natural areas (“background flux”), we used the initial guess of $f_{bg} = 0$ for the calculation. We used the emission density estimated this way for the populated grid cells (F) to make a more realistic estimation of f_{bg} using an iterative procedure.

355 Using the estimated emission value from the populated grid cells (F), and rearranging equation (1), we can express the CO exchange of the (quasi)natural grid cells (f_{bg}):

$$f_{bg} = (f - \alpha F) / (1 - \alpha) \quad (2)$$

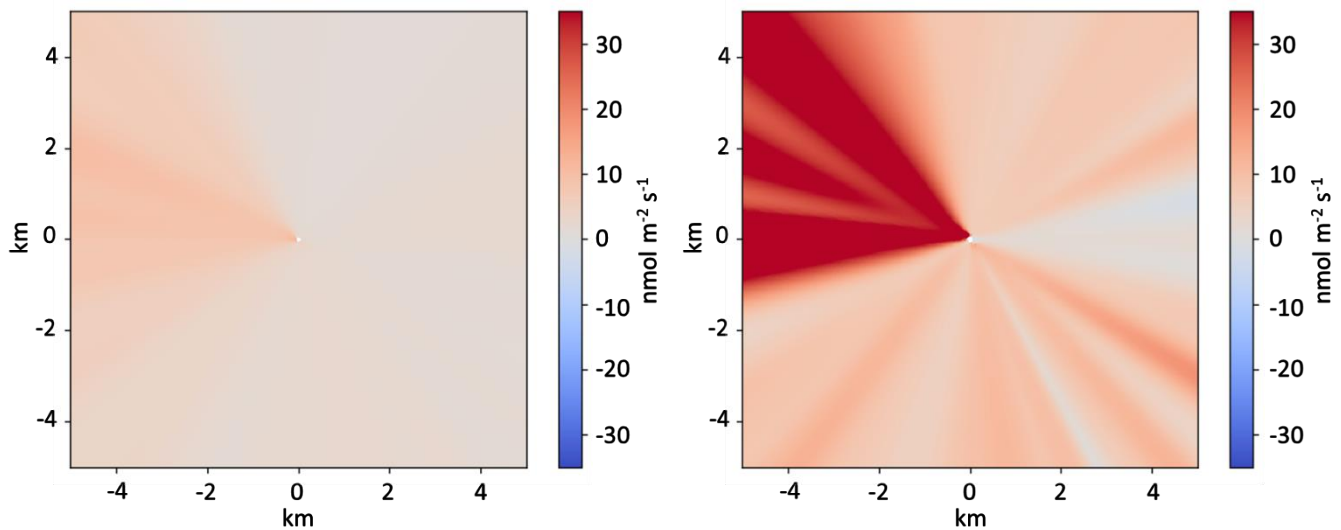
Substituting the calculated f_{bg} value back into Eq. (1) yields a modified F value, which is then used again in Eq. (2). We repeated the process until F and f_{bg} no longer changed significantly from one iteration to the next.

360 If there are only a few populated grid cells within the footprint, they are not necessarily representative of the populated areas in general. Therefore, the higher the α -value, the more robust the estimation. On the other hand, a higher α -value implies that less data are available for the calculations, which reduces the accuracy of the estimations. To find a compromise, we examined how the value of F depends on the α -value. What is the α -value such that, if increased further, the value of F no longer changes significantly? This threshold value and the related F values were used in the further calculations.

3 Results

365 3.1 Directional distribution of carbon monoxide flux

Figure 3 shows the footprint-weighted flux maps for the summer and winter months separately for the entire measurement period. The figure shows that the flux is higher from the direction of the village (west-northwest) than from the sector dominated by agricultural fields and forests. This result provides a solid basis for the separation of the populated (i.e. anthropogenic emission related) and dominantly natural areas with vegetation cover.



370 **Figure 3: Footprint-weighted flux maps for the summer (Jun–Aug, 2015–2025, left) and winter months (Dec–Feb, 2015–2025, right).** The maps are based on cases in which the footprint contribution over a radius of 5 km from the tower is at least 80 % ~~to~~^{of} the measured fluxes. The tower is at the origin (0, 0).

3.2 Carbon monoxide emission from the populated areas

375 Based on the ~~footprint-selections~~^{data selection} described in Section 2.56 and source area separation presented in Section 2.67, the flux contribution from the populated area of the nearby small village of Hegyhátsál can be up to 42 %. High values are typical when the wind blows from the ~~275–290°~~^{west-northwest} sector. In the same sector but farther from the tower (2.5–3.5 km), there is a larger village called Nádasd (population: 1,300). In the case of far-reaching footprints in this direction, the flux contribution from this settlement may reach 14 %. Hegyháthodász, similar in population to Hegyhátsál, is located 1.8–2 km south of the tower. The flux contribution from this village may also reach 17 % during southerly winds. Neither of these settlements has notable industrial or commercial activities. ~~Hence, carbon monoxide~~^{Western Hungary, where the monitoring site is located, is not a fire-prone area; forest fires are rare, and open burning is prohibited in agricultural areas. Since CO measurements began in 2015, the closest fire event revealed by satellites (MODIS MCD64A1 Burned Area and MOD14 Active Fire products) was more than 20 km from the monitoring station, and even that was small in scale. Hence, CO}

380 emissions should primarily originate from domestic activities, such as residential heating, which is typical in winter, and from ~~the~~^{traffic} year-round. Due to the absence of hot spots, it is assumed that anthropogenic emissions are uniformly distributed in the populated areas. Thus, the integrals of the footprint transfer function over these areas directly give their contributions to the measured flux.

385 ~~The measured flux (f) is~~^{Using the simple model presented in Section 2.7 (Eq. 1) to calculate monthly aggregated fluxes, a sensitivity analysis was performed to check the effect of flux contribution threshold selection on the aggregated CO flux. ~~the~~}

390

sum of the flux from the populated areas (F) and that from the non populated, (quasi)natural areas (f_{bg}). For the determination of the emissions from the populated areas, the following model was used:

$$F = (f - f_{bg}(1 - \alpha))/\alpha, \tag{1}$$

where α is the contribution of the populated grid cells. Assuming at least an order of magnitude difference between the fluxes from the populated areas and from the (quasi)natural areas (“background flux”), we used the initial guess of $f_{bg} = 0$ for the calculation. The emission density estimated this way for the populated grid cells will be used in the next section for a more realistic estimation of f_{bg} , which will then be used iteratively to refine the emission density of the populated cells.

If there are only a few populated grid cells, they are not necessarily representative of the populated areas in general. Therefore, the higher the α value, the more robust the estimation. On the other hand, a higher α value implies that less data are available for the calculations, which reduces the accuracy of the estimations. As a compromise, and to demonstrate the robustness of the estimation,

The calculated median emissions for the populated areas are presented in Fig. 4 for the cases when the flux contribution from the populated grid cells is $\geq 20\%$, $\geq 25\%$, $\geq 30\%$, and $\geq 35\%$, respectively. As can be seen in the figure, the differences are minimal. The significant seasonal variation and the small amount of available data for each month prevent the estimation of the diurnal variation of the fluxes. For the same reason, we could not estimate the 2015-2025 trend either. In the following, the calculations are based on the 2015-2025 median value calculated for those cases when the flux contribution from the populated grid cells is $\geq 25\%$.

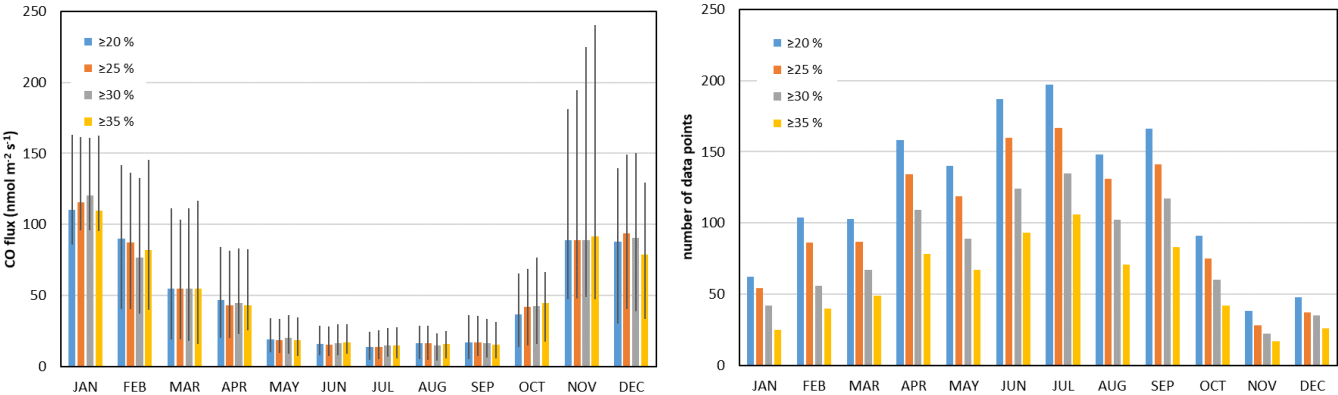
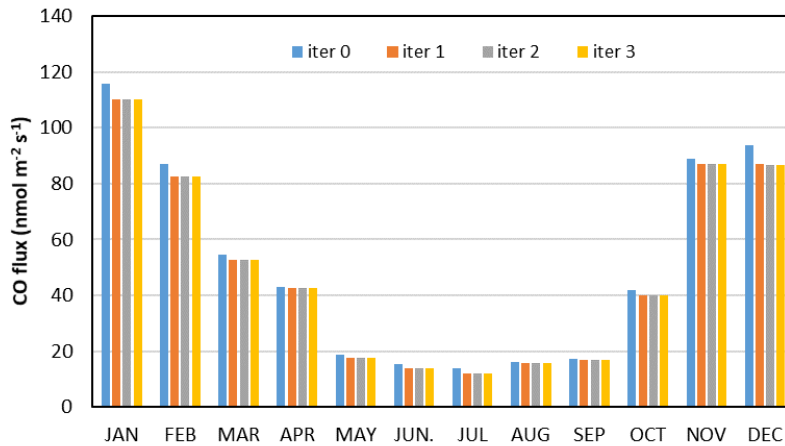


Figure 4: 2015-2025 monthly mean carbon monoxide fluxes from the populated areas (left panel) and the number of data available for the calculations (right panel). The flux values are calculated for $\geq 20\%$, $\geq 25\%$, $\geq 30\%$, and $\geq 35\%$ flux contribution from the populated grid cells, (α -value), assuming zero net flux from the (quasi)natural grid cells. The whiskers indicate the lower and upper quartiles. The right panel shows the decreasing data availability with the increasing flux contribution- (α -value).

3.3 Carbon monoxide exchange of the vegetation-dominated landscape, and the refinement of the emissions from populated areas

415 For flux measurements at a height of 82 m in a densely populated Central European region, it is practically impossible to exclude roads and small agricultural buildings from the footprints of the measurements in any direction. For the determination of the ~~carbon monoxide~~CO exchange of the vegetation-dominated, (quasi)natural landscape (agricultural fields, forests), we selected those hourly ~~footprints~~data points for which ≥ 80 % of flux ~~footprint~~ contribution came from within a 5 km radius of the tower (see also Section 2.56), and ~~where~~ the flux contribution from the so-called populated grid cells did not exceed 2.5 %. The median contribution of the populated grid cells to the measured fluxes over the 12,347 selected hours was 1.74 %. The contribution of arable land to the measured flux varied between 11 % and 78 %, while the corresponding values for forested areas were 7 % and 68 %, depending on the location and extent of the actual footprint. This sector characteristically corresponds to the wind directions of $350\text{--}150^\circ$ and $190\text{--}230^\circ$ (see Fig. 3).

425 ~~Even if the populated grid cells cover only a small portion of the footprint area, their high emission density may still significantly influence the measured fluxes. To reduce this influence, an iterative process was applied. At any time, the measured flux is the combination of the flux from the populated grid cells and that from the cells of agricultural fields or forests. Using an estimated emission value from the populated grid cells (see Section 3.2 Using the iterative method described in Section 2.7, Fig.), and rearranging equation (1), we can express the CO exchange of the (quasi)natural grid cells~~

$$(f_{bg})^*$$


430
$$f_{bg}^* = (f - \alpha F) / (1 - \alpha) \quad (2)$$

For the populated grid cells, the emission density (F) calculated in the previous section for ≥ 25 % footprint flux contribution (cf. Fig. 4) was assumed for each month. Substituting the calculated f_{bg} value into equation (1) yields a modified F value, which is then used in equation (2) again. The results indicated that this iterative procedure quickly converges. Even after the

~~2nd round, the calculated fluxes hardly change.~~ Figure 5 shows the changes in the calculated emissions from the populated grid cells in each month and in each iteration step. While the change in F was up to 13 % in the 1st iteration step, it was less than 0.4 % in the 2nd step, and less than 0.02 % in the 3rd step. It means that even after the 2nd round, the calculated fluxes for the populated areas hardly change. The results obtained in the 3rd iteration step are considered the actual emission densities of the populated grid cells, and are discussed further in Section 4.1. Using a ≥ 25 % threshold, the monthly CO fluxes range from 82–110 nmol m⁻² s⁻¹ in winter to 14–16 nmol m⁻² s⁻¹ in summer. Summer values are 85 % lower on average than the winter values, demonstrating the significant contribution from heating in the cold season.

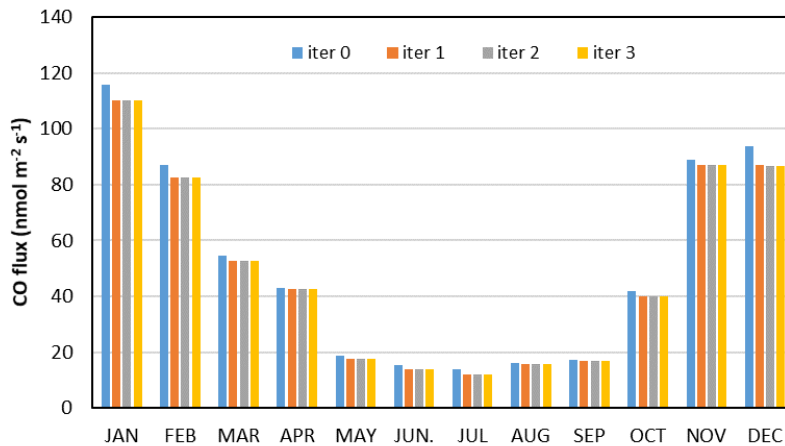


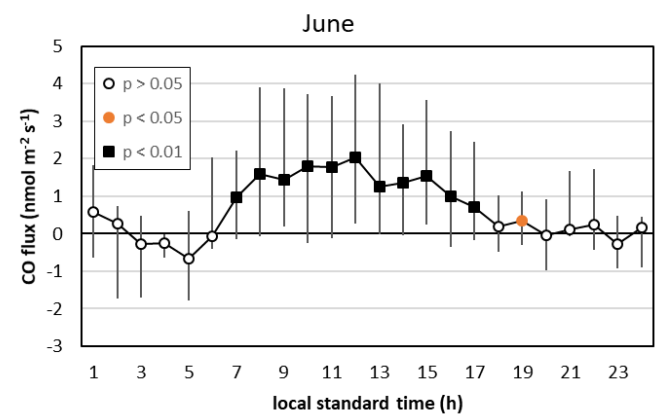
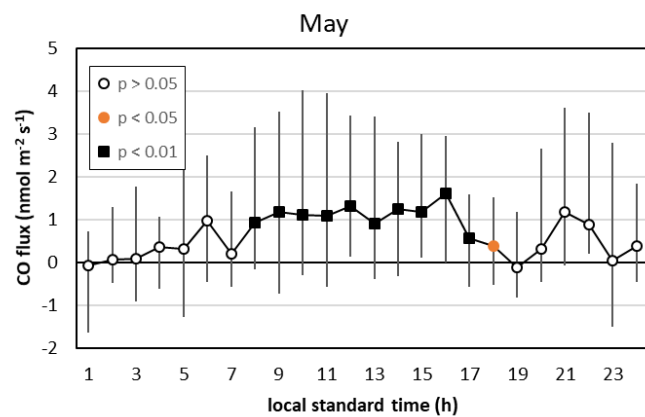
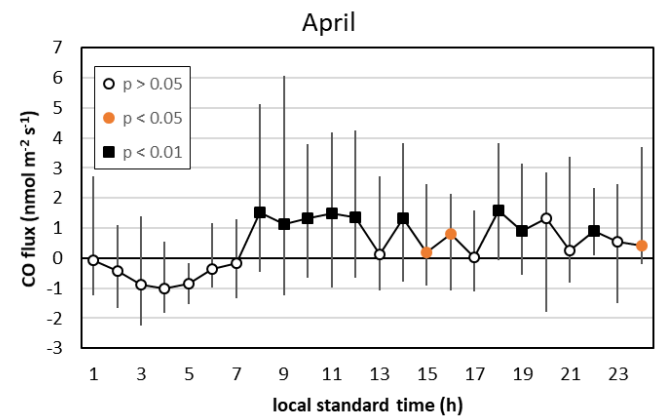
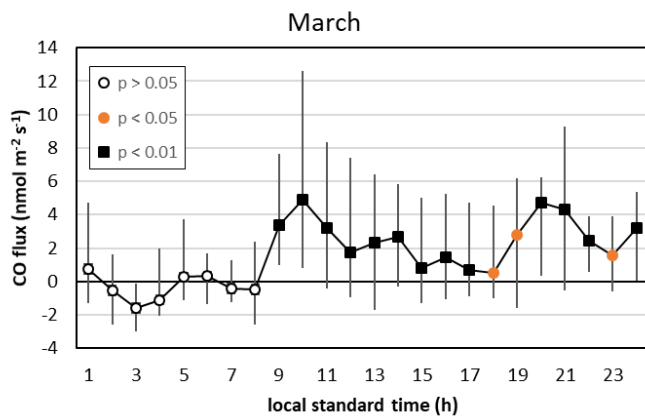
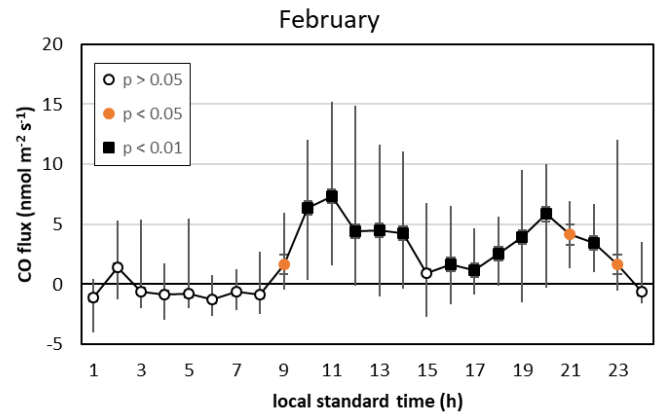
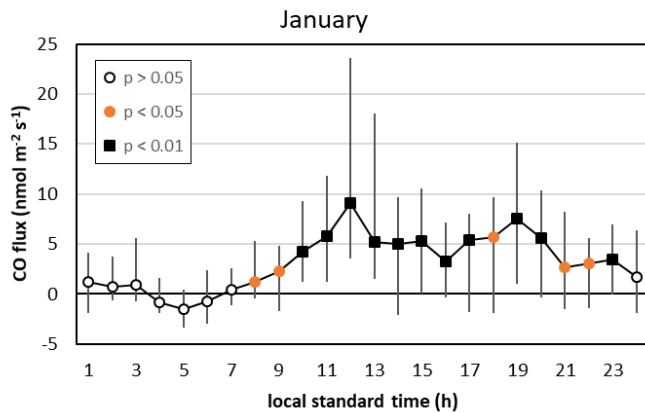
Figure 5: Iterative approximation of the emission density from the populated areas using the method described in the text. Iteration 0 (iter 0) represents the uncorrected data calculated in Section 3.2 (see Fig. 4). The flux values are calculated for the cases when the contribution of the populated grid cells to the measured fluxes at the tower is at least 25 %.

Figure 6 shows the mean diurnal variation of net CO exchange over the (quasi)natural grid cells for each month based on the converged data. Lacking an objective criterion for defining a data point as „extreme”, outlier removal was not applied during the quality control of the data- (cf. Section 2.6). However, outliers (whether extreme or not) may distort the averages; therefore, Fig. 6 shows the median value for each hour of each month. The symbols in the figures indicate the confidence level of the deviations of the values from zero as determined by the Wilcoxon hypothesis test. It should be noted that significantly fewer data were available for nighttime hours than for daytime hours (especially in summer), affecting the confidence limits. As mentioned earlier, the limited data availability meant that the diurnal variation of the emission of the populated grid cells could not be derived. Therefore, the monthly average emissions were used to derive the natural CO flux, which can affect the estimated diurnal variation of the latter. Presumably, both anthropogenic and natural CO emissions are lower during night than during day; therefore, the limitation in the correction algorithm does not significantly alter the diurnal shape of the CO exchange over the arable land/forests.

~~Whiskers indicate the lower and upper quartiles, while the symbols give the probability level of the deviation of the median from zero. Note the different y axes.~~

The mean daily flux for each month can be calculated from the monthly mean diurnal variations of the hourly median fluxes (Fig. 7). Fluxes from the (quasi)natural grid cells are only a few percent (1-8 %) of those from the populated grid cells (Fig. 5). The winter maximum in the net exchange over the vegetated landscape cannot be explained by natural processes alone. It is hypothesized that our simple method cannot completely filter out the anthropogenic emissions. This question will be discussed further in Section 4.2.

The diurnal variation of the CO exchange in the arable land/forest (i.e. vegetation-covered) sector shows a daytime maximum, which is more pronounced during the summer half-year (Fig. 6). The nighttime net flux tends to be negative, though it does not deviate statistically significantly from zero throughout the year. The average emission for the summer half-year (April–September), when the unavoidable anthropogenic influence is the lowest, is 0.58 nmol m⁻² s⁻¹ based on the monthly averages calculated from the hourly median values. The range is 0.31–0.91 nmol m⁻² s⁻¹, with the highest value occurring in July. The daily peaks of the median hourly emissions range from 1.59 to 2.66 nmol m⁻² s⁻¹. The nighttime (20-04 h LST) hourly median values range from -1.01 to +1.17 nmol m⁻² s⁻¹, respectively.



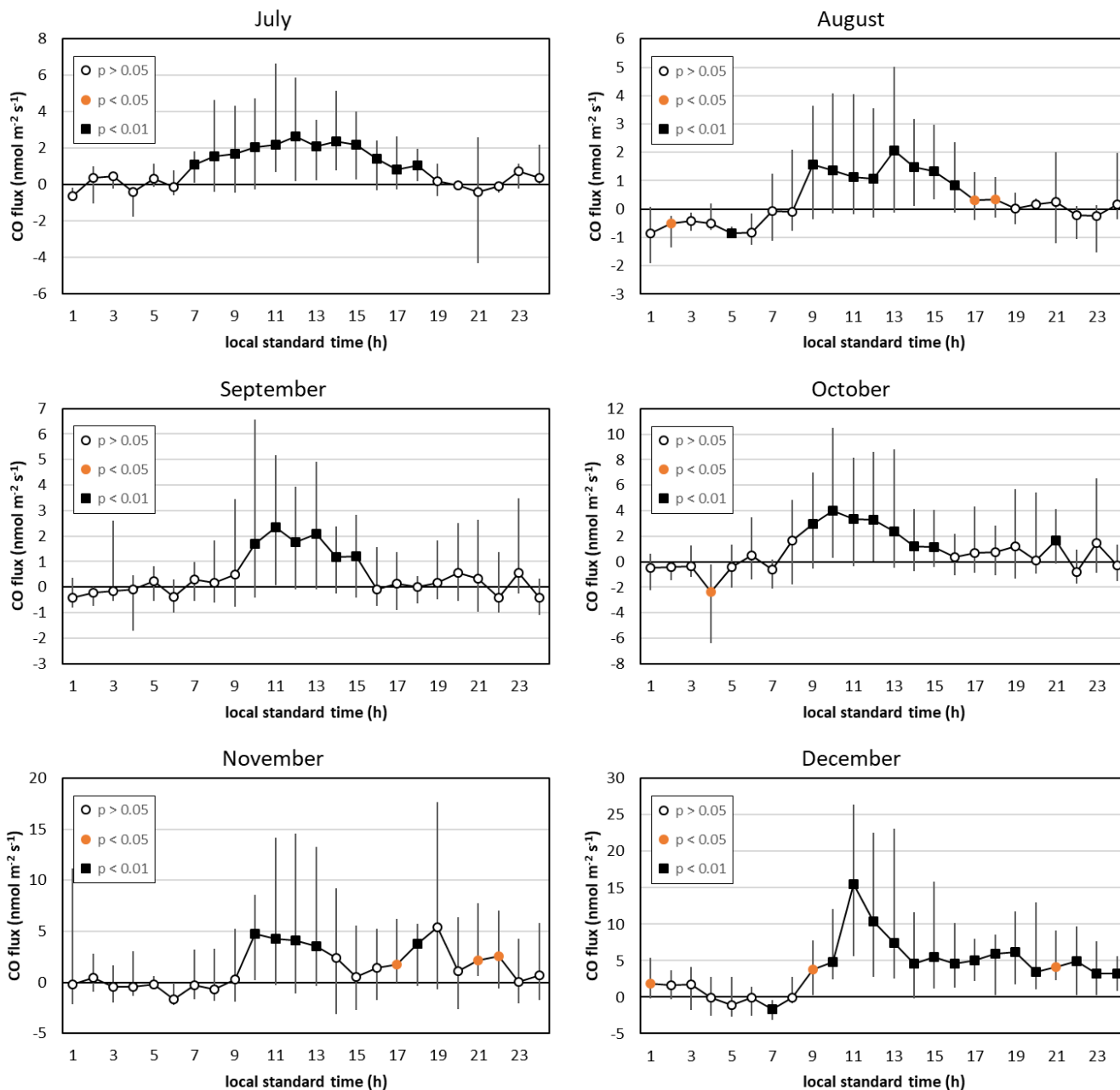


Figure 6: Mean diurnal variation of net CO exchange in the (quasi)natural grid cells (2015-2025) based on the converged data ($\alpha < 2.5\%$). Whiskers indicate the lower and upper quartiles, while the symbols give the probability level of the deviation of the median from zero. Note the different y-axes.

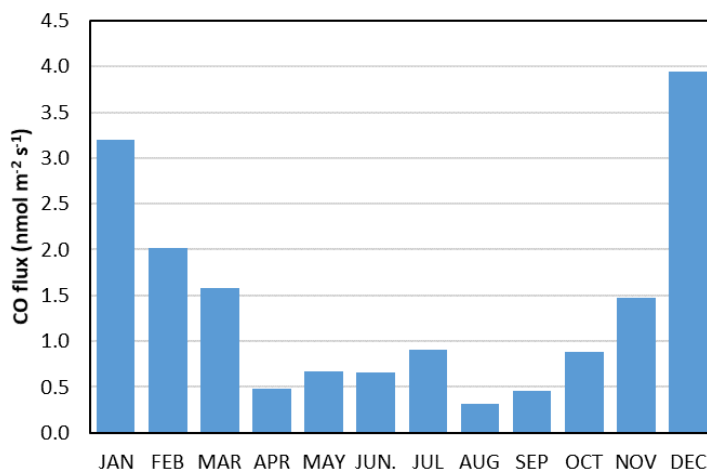


Figure 7: Seasonal variation of the monthly mean ~~carbon monoxide~~CO flux from the (quasi)natural grid cells- ($\alpha < 2.5\%$).

3.4 Possible drivers of the ecosystem carbon monoxide budget

~~To identify the processes controlling the carbon monoxide exchange of ecological systems, We considered footprints in which at least 80% of the measured flux contribution came from within a 5 km radius of the tower and within which the contribution of populated grid cells was no more than 2.5 % (see Section 3.3). The correlation coefficients between UV~~ radiation, photosynthetically active radiation, daytime/nighttime air temperature, ~~and~~ soil water content as possible drivers. The correlation coefficients between these drivers and CO flux, as well as their probability levels, are presented in Fig. 8. The results suggest that solar radiation plays an important role in the CO emission of the soil/vegetation system. The correlation with air temperature at 10 m is not statistically significant at a reasonable probability level for most of the year (standard air temperature measurements or soil temperature data were not available at our site). The nighttime correlations

between CO net flux and temperature are not significant either (Fig. 8), suggesting that the summer daytime correlation is the result of the high correlation between ~~the~~ temperature and radiation (Fig. 9). Soil moisture or soil water content is occasionally also mentioned as one of the drivers of CO exchange (Laasonen et al., 2025). However, herein our study, the correlation between CO flux and local soil water content (SWC) in the top 0-7 cm layer is not statistically significant (Fig. 8). This suggests that SWC may not be an important driver, at least at the given soil/vegetation characteristics with the given soil/vegetation characteristics. It should be emphasized, however, that we used data from the ERA5 database with a resolution of 0.25×0.25 degrees for the calculation, while there may be very significant variations in soil moisture content, soil types, and structure within an area of this size. Therefore, the fact that we do not observe a correlation between flux and soil moisture content in the present study does not mean that such a correlation cannot exist.

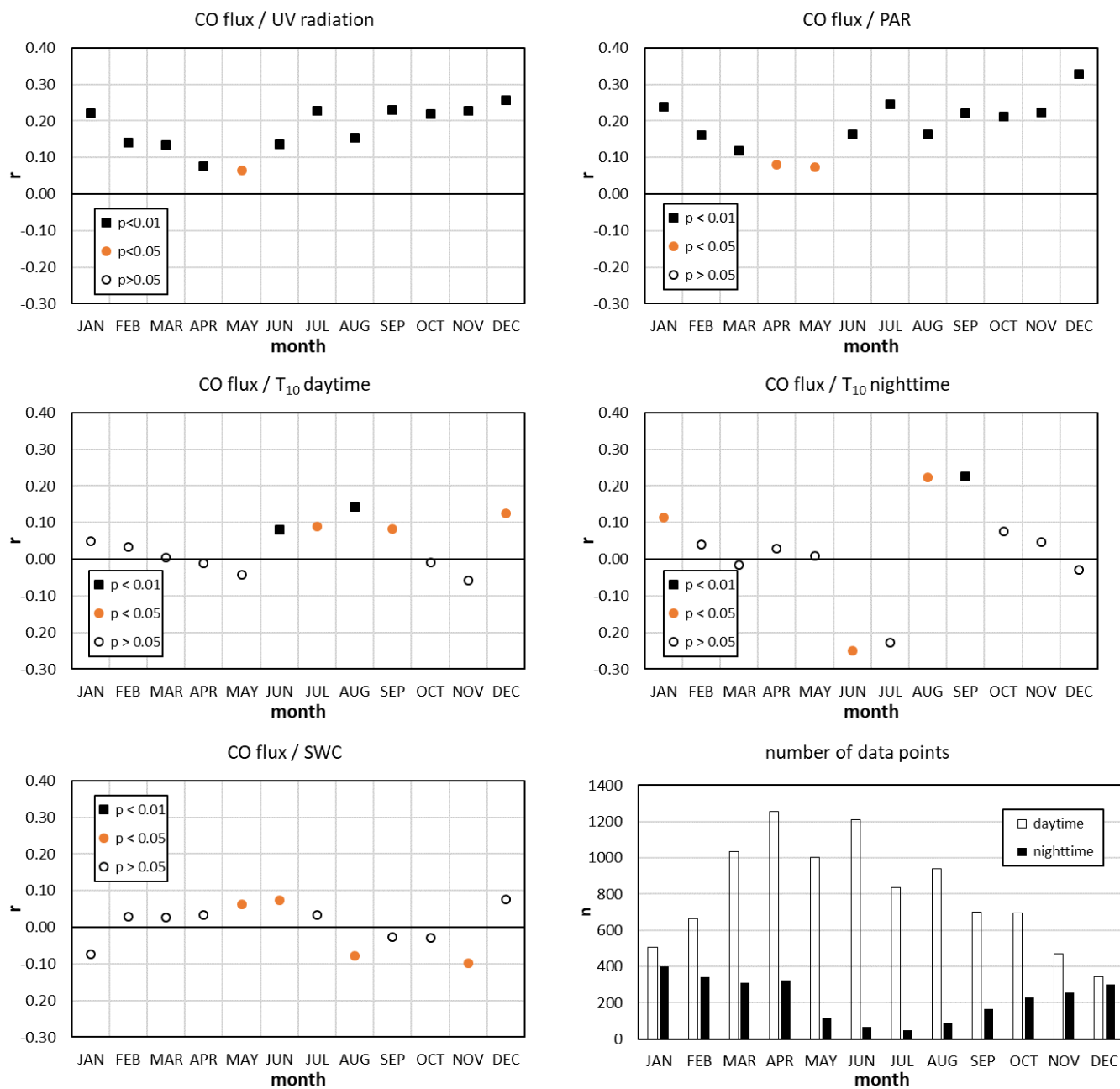


Figure 8: Monthly correlations (2015-2025) of CO fluxes with UV radiation, photosynthetically active radiation (PAR), air temperature at 10 m (T₁₀ – day and night), and soil water content, as well as the number of data points available for the correlation calculations. The different symbols indicate the confidence level of the correlation coefficients.

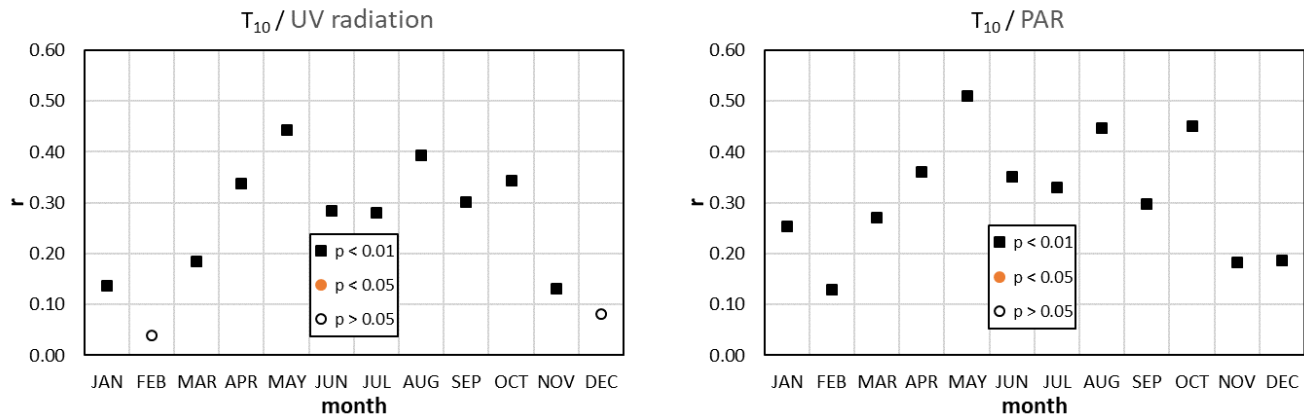


Figure 9: Correlations between air temperature and solar radiation. The wintertime low level of correlation is not a surprise. ThatAt this time of the year, clear sky is usually comesobserved together with cold air mass intrusions.

4 Discussion

4.1 Carbon monoxide emission from the populated areas

515 The fluxes originating from the populated grid cells show a remarkable seasonal variation: the winter values are an order of magnitude higher than the summer onesvalues (Fig. 5). Since traffic-related emissions may be similar throughout the year, and since there is no notable industrial activity in the region, the additional winter emissions can be reasonably attributed to residential heating in the villages with relatively high confidence. Although natural gas is available for residential heating, many households in this relatively poor, slowly depopulating region use biomass (wood, agricultural waste) or low-quality

520 coal in technologically outdated, inefficient, poorly ventilated heating appliances. Unfortunately, illegal household waste burning is also rather common in such regions with poor socioeconomic conditions (Haszpra et al., 2022; Balogh et al., 2025). These circumstances can result in high carbon-monoxideCO emissions.

According to the EDGAR v8.1_AP database (European Commission and Netherlands Environmental Assessment Agency, 2024) containing 0.1°x0.1° gridded CO emission data up to 2022, approximately 98 % of anthropogenic emissions from the

525 EDGAR grid cell surroundingincluding the monitoring site originated from road transport (IPCC 2006 category: 1.A.3.b (IPCC, 2006)) and residential (IPCC 2006 category: 1.A.4) emissions in 2015–2022. Transport emissions hardly change throughout the year. According to the database, the residential emissions in summer are only about 10 % of the transport emissions. Our measurement recorded 15.2 nmol m⁻² s⁻¹ CO emissions for May–September (non-heating season) on average, of which 13.7 nmol m⁻² s⁻¹ may be attributed to the transport sector- (90 % of the total). The populated grid cells for which

530 this value was calculated cover 12.8 % of the EDGAR grid cell (84.3 km²) surroundingincluding the tower. Considering the summer value to be valid for the entire year, the total CO emissions of transport origin are 131 Mg yr⁻¹ from the EDGAR grid cell. This value is twice as high as the EDGAR v8.1 average for the years 2015–2022 (60 Mg yr⁻¹).

~~The total measured anthropogenic emissions~~The annual average flux over a populated grid cell is $48.1 \text{ nmol m}^{-2} \text{ s}^{-1}$ (see Fig. 5). Taking into account the total area of the populated grid cells within the EDGAR grid cell ($84.3 \text{ km}^2 \times 0.128 = 10.8 \text{ km}^2$), and summing up the emissions for a year, we obtain that the total measured anthropogenic emissions expressed in mass of CO are around 460 Mg yr^{-1} , from which 330 Mg yr^{-1} can be attributed to residential activity, primarily heating. Although we neglected small terms in the above estimation, including the few percentage shares of non-transport/non-residential emissions and the anthropogenic emissions recorded in the agricultural/forest areas, the EDGAR data for the residential sector (83 Mg yr^{-1} , averaged for 2015–2022) seems far too low. In addition, we cannot see the reasons for the 30 % reduction in emissions reported by EDGAR for the period from 2015 to 2022. Given the economic stagnation and deterioration between 2015 and 2022, including the impact of the COVID pandemic, we would expect an increase in the burning of biomass and other waste, and thus an increase in carbon monoxideCO emissions, although this cannot be substantiated in the absence of surveys. Unfortunately, the small share of the populated grid cells in our monitoring area and the resulting limited amount of data prevent us from determining the actual emission trends.

4.2 Carbon monoxide exchange of the vegetation-dominated landscape

The dominant role of photodegradation in natural CO emission and the less intensive solar radiation during the winter months should result in less positive net CO exchange, even if the microbiological CO uptake must also be lower due to the lower temperature. However, the seasonal variation of CO exchange in the agricultural/forested areas shows a maximum in winter (Fig. 7). ~~Murphy et al. The elevated winter emissions over the vegetation-dominated areas are also reflected in Fig. 6.~~ Murphy et al. (2023) also observed a winter increase in the CO fluxes over a grassland. Despite performing EC measurements on a 2.2-meter-tall tower with a limited footprint, they identified the influence of distant anthropogenic sources. The area influencing our measurements performed at 82 m elevation can be about two orders of magnitude larger, and may cover different distant anthropogenic sources. This is true even when the "clean air" sector is carefully selected and constrained to footprints for which the contribution of the distant sources (outside of the 5 km radius of the tower) to the flux measured at the tower is less than 20 %. The wintertime emission in the populated grid cells can be two to three orders of magnitude larger than in the (quasi)natural grid cells. Even if the weighted footprint contribution from a distant grid cell is minor, the potentially huge emission from that cell may ~~significantly~~substantially influence the measured fluxes. This effect cannot be completely eliminated with our rather simple correction algorithm.

~~Not forgetting about~~However, even with the unavoidable seasonally varying anthropogenic influence in mind, our measurements show that agricultural fields and forests are net sources of carbon monoxideCO throughout the year.

~~The diurnal variation of the CO exchange in the arable land/forest (i.e. vegetation covered) sector shows a daytime maximum (Fig. 6), which is more pronounced during the summer half year. The nighttime net flux tends to be negative, though it does not deviate statistically significantly from zero throughout the year. The average emission for the summer half year (April–September), when the unavoidable anthropogenic influence is the lowest, is $0.58 \text{ nmol m}^{-2} \text{ s}^{-1}$ based on the monthly averages calculated from the hourly median values. The range is $0.31\text{--}0.91 \text{ nmol m}^{-2} \text{ s}^{-1}$, with the highest value~~

occurring in July. The daily peaks of the median hourly emissions range from 1.59 to 2.66 nmol m⁻² s⁻¹. The nighttime (20–04 h LST) hourly median values range from -1.01 to +1.17 nmol m⁻² s⁻¹, respectively. ~~These values~~Our measurement results fall within the range of other measurements of -3 – +14 nmol m⁻² s⁻¹ over grasslands and arable lands (van Asperen et al., 2015; Pihlatie et al., 2016; Cowan et al., 2018).

570 ~~The~~Earlier longer-term EC measurements recorded diurnal CO flux variations similar to our measurements. ~~Pihlatie et al.~~ Pihlatie et al. (2016) reported a distinct diurnal pattern with uptake at night and emission during the day, ~~with maximum emissions at noon. The. Their~~ daytime maximum median emissions over the perennial reed canary grass ~~field monitored~~ reached 2.7 nmol m⁻² s⁻¹ around noon, while the nighttime values varied around -0.77 nmol m⁻² s⁻¹ throughout the measurement period. Cowan et al. (2018) also measured fluxes that showed a regular diurnal cycle peaking at noon (1–
575 4 nmol m⁻² s⁻¹) and falling to around zero (>-1 nmol m⁻² s⁻¹) at night. Laasonen (2021) recorded daytime net emission up to 3 nmol m⁻² s⁻¹ in forest, wetland, and cropland ecosystems in summer. These ecosystems showed zero flux or small uptake during nighttime. Murphy et al. (2023) observed a similar diurnal pattern, also in summer. During daytime, the measured fluxes were 1–5 nmol m⁻² s⁻¹, while the nighttime values were near zero or slightly negative (>-2 nmol m⁻² s⁻¹). Recent measurements of Laasonen et al. (2025) over peatland also showed the characteristic daily cycle with a daytime maximum of
580 1.1 nmol m⁻² s⁻¹ and a nighttime minimum of -0.44 nmol m⁻² s⁻¹.

EC measurements at an elevation of 82 m would require the calculation of the storage term, i.e., the amount of ~~carbon monoxide~~CO accumulating below the measurement elevation in the cases of decoupling from the surface due to low-level temperature inversions (Haszpra et al., 2005). Ignoring the storage term can result in unrealistic flux values when the inversion layer breaks up, ~~and also can cause a slight bias during the formation of the nighttime inversion.~~ Due to the lack of
585 concentration profile measurements, we could not calculate the storage term. ~~This could increase the uncertainty of the diurnal variation of the fluxes in the winter months during the hours when stable stratification forms or the inversion is breaking up.~~ However, ~~the lack of a negative or positive peak in the fluxes measured during the break up of the inversion layer indicates that as there is no significant long-term accumulation or depletion occurs in of CO below the surface layer, and EC level, the net emission storage flux is negligible already at the surface at night is close to zero indeed daily scale, and~~
590 ~~the missing storage term does not affect the total fluxes.~~

4.3 Drivers of the ecosystem carbon monoxide budget

~~Scientific publications widely complain that we know very little about~~Despite ongoing research, substantial uncertainty remains regarding the soil and vegetation processes that ~~can produce or absorb carbon monoxide~~contribute to CO emission and uptake (King, 2000; Constant et al., 2008; Bruhn et al., 2013; Liu et al., 2018; Sun et al., 2018; Laasonen et al., 2025).
595 This ~~knowledge gap~~ also ~~hinders~~the development of process-based ~~biogeochemistry~~biogeochemical models of CO exchange ~~models~~ (Liu et al., 2018). From the atmospheric point of view, the commonly studied drivers are solar radiation (see e.g. Bruhn et al., 2013; van Asperen et al., 2015; Pihlatie et al., 2016; Cowan et al., 2018; Murphy et al., 2023; Laasonen et al., 2025; and references therein), temperature (Constant et al., 2008; van Asperen et al., 2015; Murphy et al., 2023; van

Asperen et al., 2024), and soil moisture (Cowan et al., 2018; Murphy et al., 2023; Laasonen et al., 2025). However, the results are uncertain and partly controversial, presumably due to the different climate and soil conditions, different vegetation types at the measurement sites, as well as the short measurement durations.

Most previous studies agree that photo and/or thermal degradation of organic substances is/are the main driver(s) of the ecosystems' CO emissions. The key role of solar radiation (global radiation, UV or PAR spectra of the visible range) in CO emission has been ~~well-established since~~confirmed already in the early studies on natural CO flux (see e.g. Seiler and Giehl, 1977; Tarr et al., 1995; Schade et al., 1999; Bruhn et al., 2013; Pihlatie et al., 2016; Murphy et al., 2023; Laasonen et al., 2025; and references therein). However, the importance of the role of thermal degradation is somewhat controversial. One of the reasons is that both emissions resulting from the abiotic thermal degradation and microbiological uptake are temperature dependent (Whalen and Reeburgh, 2001). Some of the methods applied in the field (e.g. micrometeorological methods) measure the net surface-atmosphere exchange and cannot separate the emission and uptake processes. On the other hand, temperature is strongly correlated with solar insolation. According to the measurements of Laasonen et al. (2025)~~Laasonen et al.~~, solar radiation is the primary driver of CO flux; the role of the air temperature is limited. Murphy et al. (2023)~~Murphy et al.~~ and ~~Cowan et al.~~ Cowan et al. (2018) found a variable relation between CO flux and temperature. On the contrary, the laboratory and field measurements of van Asperen et al. (2015)~~van Asperen et al.~~ indicated ~~the~~a higher importance of thermal degradation than of photodegradation in CO flux ~~relative to photo degradation~~.

Our measurements support the assumption that thermal decomposition either plays a minor role in CO emissions or is largely compensated by the microbiological uptake. The collinearity between temperature and solar radiation can lead to the incorrect identification of the causal relationships that may explain the controversy in the literature.

The role of SWC as a driver cannot be confirmed by our results. However, it should be noted that SWC may vary greatly within the footprint area due to the diversity of land use (presence of summer and winter crops with different phenophases, associated rooting depths, evapotranspiration rates, etc.). Therefore, the above conclusion should be treated with caution.

5 Conclusions

The evaluation of ~~the~~ 10-year-long tall tower EC-based carbon monoxide flux measurements has revealed the advantages and challenges of such monitoring projects. The tall-tower EC measurements and their associated large flux footprints can provide information on heterogeneous, regionally characteristic landscapes that help the upscaling of the results. However, the high elevation ~~and the~~causes gaps in the data series due to occasional decoupling from the surface ~~cause gaps in the data series~~. In principle, footprint modelling can separate the flux contribution from different land cover types. However, the emissions from populated areas are magnitudes larger than the ~~carbon monoxide (CO)~~CO exchange of natural or quasi-natural (agricultural fields, grasslands, forests) areas. Therefore, even distant anthropogenic sources can significantly influence measurements with footprints in areas covered almost exclusively by vegetation. This makes it difficult to study the dynamics of the CO exchange of the soil-vegetation system.

Despite the above-mentioned difficulties, our measurements support the theory that the primary driver of the CO exchange of the (quasi)natural ecosystems is solar radiation. The maximum emission can be observed in summer daytime (up to 2.66 nmol m⁻² s⁻¹, July hourly median at noon), while the nighttime exchange does not deviate statistically significantly from zero.

635 The measured emissions from the populated areas significantly exceed the emissions calculated using activity statistics. The ~~factors~~discrepancies, ranging from a factor of 2– to 4, are far too large to be ~~attributable to the uncertainty explained by~~uncertainties in the methodology ~~and the uncertainty of or~~ the input data, ~~but certainly reflect the underestimation of the~~alone and instead suggest that the real-world emission factors ~~are substantially underestimated~~. It is hypothesized that the bottom-up method underestimates the fact that ~~in this despite the supply of~~ natural gas ~~supplied in this~~ region, a significant
640 proportion of the population heats their homes with technologically outdated heating appliances using wood, low-quality coal, ~~or~~ agricultural or household waste for economic reasons, ~~in some cases also burning household waste. Atmospheric effects. As the atmospheric impacts of CO~~ depend on the amount of ~~carbon monoxide~~CO actually released into the air, ~~so it would be necessary~~is of high importance to refine the emission factors applicable in real-life situations ~~throughby~~ field measurements. If the anthropogenic emission density recorded in the region of our measurement site were representative of
645 the other rural regions in the country, the national total emissions reported to international organizations would need to be modified upward.

Data availability

The data used in the study are available at <https://doi.org/10.5281/zenodo.20025124>.

Author contributions

650 L.H. designed the study, performed the calculations, and wrote the original manuscript; Z.B. performed the eddy covariance calculations; A.K. provided the land use information and visualization; N. Z contributed to the eddy covariance data interpretation; N.K. supported the footprint calculations. All authors read and edited the original and revised manuscript.

Competing interests

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

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