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Does increased spatial replication above heterogeneous agroforestry improve the representativeness of eddy covariance measurements?

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Abstract. Spatial heterogeneity in terrestrial ecosystems compromises the accuracy of eddy covariance measurements. An example of heterogeneous ecosystems are temperate agroforestry systems, that have been poorly studied by eddy covariance. Agroforestry systems get an increasing attention due to their potential environmental benefits, e.g. a higher carbon sequestration, enhanced microclimate and erosion reduction compared to monocropping agricultural systems. Lower-cost eddy covariance setups might offer an opportunity to reduce this bias by allowing for more spatial replicates of flux towers. The aim of this study was to quantify the spatial variability of carbon dioxide (*FC*), latent heat (*LE*) and sensible heat (*H*) fluxes above a heterogeneous agroforestry system in northern Germany using a distributed network of three lower-cost eddy covariance setups across the agroforestry systems. Fluxes from the three towers in the agroforestry were further compared to fluxes from an adjacent monocropping site. The campaign took place from March 2023 until September 2024. The results indicated that the spatial variability of fluxes was largest for *FC*, attributed to the effect of different crops (rapeseed, corn and barley) within the flux footprints contributed to the measured fluxes. Differences between fluxes across towers were enhanced after harvest events. However, the temporal variability due to the seasonality and diurnal cycles during the campaign was larger than the spatial variability across the three towers. When comparing fluxes between the agroforestry and the monocropping systems, weekly sums of carbon and evapotranspiration fluxes followed similar seasonality, with peak values during the growing season of -50 g C m^{-2} $week^{-1}$ and 40 mm $week^{-1}$, respectively. The variation of the magnitude depended on the phenology of the different crops. The effect size, which is an indicator of the representativeness of the fluxes across the distributed network of three eddy covariance towers against only one, showed in conjunction with the other results that the spatial heterogeneity across the agroforestry was better captured by the network of three stations. This supports previous findings that spatial heterogeneity should be taken into account in eddy covariance studies, and that lower-cost setups may offer the opportunity to bridge this gap and improve the accuracy of eddy covariance measurements above heterogeneous ecosystems.

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1 Introduction

The eddy covariance (EC) technique is the central approach to measuring the exchange of energy, trace gases and momentum between terrestrial ecosystems and the atmosphere (Baldocchi, 2014). The EC technique has been established as a standard method within the scientific community when rapid-response instruments, capable of measuring wind speed, temperature, and gas concentrations over the major frequency ranges of the turbulent energy spectrum became commercially available (Rebmann et al., 2012; Wohlfahrt et al., 2009). These instruments provided the capability to measure the exchange of energy and matter between the land surface and the atmosphere, driven by eddies of diverse sizes and frequencies (Kaimal and Finnigan, 1994).

At a majority of flux sites, a single EC station is installed (Hill et al., 2017) and measurements are made based on the ergodic hypothesis. The ergodic hypothesis states that covariances (fluxes) calculated over the time domain are equivalent to covariances calculated over the spatial domain (Higgins et al., 2013). The measured turbulent fluxes and carbon and water balances, when integrated over a defined time interval, are representative of the tower footprint area corresponding to the averaging interval (Vesala et al., 2008). This is true for homogeneous sites where the spatial representativeness of fluxes within the ecosystem of interest is guaranteed with a high degree of confidence (Hurlbert, 1984). However, these conditions of homogeneity are often not met in many ecologically and socioeconomically interesting sites, such as mixed forests, wetlands, urban forest interfaces or small-scale farmlands (Finnigan et al., 2003; Hill et al., 2017).

Agroforestry (AF) systems are an example of heterogeneous agroecosystems. They combine trees and crops on the same agricultural land in order to benefit from the presence of trees on the land (Veldkamp et al., 2023; Kay et al., 2019). These systems offer several benefits, including the potential to prevent wind erosion over crops (van Ramshorst et al., 2022; Böhm et al., 2014), improve soil fertility (Kanzler et al., 2021), or reduce water loss through evaporation in crops (Kanzler et al., 2019). Short Rotation Alley Cropping systems, a type of agroforestry, represent an alternative land use practice with the potential to increase carbon sequestration and improve water use efficiency (WUE) in comparison to conventional monocropping (MC) agriculture (Markwitz et al., 2020; Veldkamp et al., 2023). These AF systems consist of alternating rows of trees and crops. The trees employed in these systems are typically fast-growing species, such as poplar (*Populus*) or willow (*Salix*), and are harvested in cycles of 5-6 years for biomass production. Crops are cultivated in an annual rotation.

The spatial configuration of the AF system influences the wind flow regimes within the ecosystem, thereby affecting the development of turbulence. In many cases, such as over tall vegetation, EC measurements are made within the roughness sub-layer (RSL), which is, by definition, the atmospheric layer whose dynamics are influenced by the roughness elements and is located below the inertial sub-layer (Katul et al., 1999). At the AF, the trees act as an effective wind barrier (van Ramshorst et al., 2022), thus modifying the RSL, creating internal boundary layers (Markwitz, 2021), and changing the characteristics of turbulence over the field. In addition, the alternation of trees and crops with differing phenologies and canopy heights creates a heterogeneous distribution of carbon and water vapor sources and sinks. This spatial variability is likely to have an impact

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on the measured fluxes, as shown by other authors who have studied the spatial variability of fluxes over different ecosystems, such as pine forest (Katul et al., 1999; Oren et al., 2006) or managed grassland (Peltola et al., 2015).

The location of the EC station within a land use system has been demonstrated to potentially introduce a bias in the measured fluxes (Chen et al., 2011), indicating that a single EC station may not be sufficient to properly account for the spatial variability of fluxes induced by landscape heterogeneity (Katul et al., 1999). The high cost and labor intensity of deploying an EC station are the main reasons for the lack of spatial replicates of EC measurements in many studies (Hill et al., 2017). The infrared gas analyzer (IRGA), the crucial component to measure trace gases, typically accounts for a large proportion of the total installation costs associated with an EC station. Lower-cost EC (LC-EC) setups represent a potential solution to the spatial replication problem of EC measurements, as several EC stations could be deployed for the cost of a single conventional station. LC-EC employ a more economical infrared gas analyser and a sonic anemometer, though these instruments necessitate more rigorous post-processing corrections. Notably, previous studies have demonstrated that LC-EC setup can yield comparable results to those of conventional EC (CON-EC) setups. Hill et al. (2017) compared a custom-built LC-EC setup for CO_2 and H_2O measurements with a CON-EC, with very good agreement in CO_2 and H_2O fluxes. In addition, a different LC-EC setup for H_2O flux measurements was compared with a conventional setup Markwitz and Siebicke (2019), resulting in good agreement in H_2O fluxes. Furthermore, another version of the LC-EC setup deployed in Hill et al. (2017) was extensively validated in the studies of Callejas-Rodelas et al. (2024) and van Ramshorst et al. (2024), with very good agreement in CO_2 fluxes and good agreement in H_2O fluxes.

The LC-EC setups can allow for a higher degree of spatial replication of EC and support conventional EC setups. In addition, they provide a powerful tool for the verification of carbon and water balances in the agricultural and forestry sectors in developing carbon credit markets (Trouwloon et al., 2023). However, the increased uncertainty associated with these setups must be taken into account when calculating balances of energy, carbon, or other variables, and when comparing different land uses. One of the main differences between LC-EC and CON-EC setups is the spectral response of the sensors. The LC-EC setups used in the Callejas-Rodelas et al. (2024), Cunliffe et al. (2022), Hill et al. (2017) and van Ramshorst et al. (2024) studies were characterized by a slower frequency response in CO_2 and H_2O measurements, which induces a higher spectral attenuation in the high-frequency range of the turbulent energy spectrum, compared to CON-EC. The higher attenuation introduces a greater degree of uncertainty when applying spectral corrections, as observed by Ibrom et al. (2007) and Mammarella et al. (2009), among others.

The impact of landscape heterogeneity within a AF system on turbulence, latent heat flux (*LE*), sensible heat flux (*H*) and carbon dioxide flux (*FC*) remains to be examined. Markwitz and Siebicke (2019) and Markwitz et al. (2020) conducted evapotranspiration (*ET*) measurements across multiple AF and MC systems in Northern Germany; however, their measurements were not replicated within a single site. In contrast, in the study of Cunliffe et al. (2022) a total of eight LC-EC setups were deployed in different locations across a landscape of ecological interest (Cunliffe et al., 2022). The objective of this study was to capture the heterogeneity of CO_2 and *ET* fluxes across a semiarid ecosystem, with low magnitude of both CO_2 and *ET* fluxes. To the best of our knowledge, replicated measurements in heterogeneous agroforestry systems are so far lacking.

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In the present study, a network of three LC-EC setups was deployed, analogous to those utilized in the studies of Callejas-Rodelas et al. (2024), Cunliffe et al. (2022) and van Ramshorst et al. (2024), above an AF site, and one additional LC-EC setup above an adjacent MC site in northern Germany. To the best of our knowledge, this was the first time a distributed network of EC towers has been installed above a temperate agroforestry system. With one and a half years of concomitant flux data from the four EC setups, the objective was to quantify the spatial and temporal variability of *FC* and *LE*, as well as the statistical effect of the increased spatial replication of EC measurements above a heterogeneous site. According to Hill et al. (2017), it is possible to estimate the sampling variability and total uncertainty for an ecosystem with independent spatial replication of EC measurements. This allows for the estimation of the effect size (see Section 2). The present study tested the hypothesis that the increased uncertainty inherent to the use of slower-frequency response sensors in EC measurements can be counteracted by the improvement of spatial replication of EC, which increases its statistical robustness. The objectives of this study were threefold: (i) to quantify the spatial and temporal variability of turbulent fluxes and parameters above AF; (ii) to calculate the effect size of the experimental site, following Hill et al. (2017); and (iii) to compare the ecological functioning of the AF to the MC in terms of carbon and *ET* balances.

2 Methods

2.1 Site description

The measurements were conducted from 1 March 2023 to 19 September 2024 at an agroforestry system located in Wendhausen (Lehre), Lower Saxony, Germany (52.63° N, 10.63° E). Elevation above sea level is 80 m. The field is divided into two distinct systems: an AF system in the north and a MC system in the south (see Fig. 1). The AF system covers an area of 17.3 ha and the MC covers an area of 8.5 ha. The crops cultivated within both systems kept a similar distribution from west to east. In 2023, rapeseed was cultivated at the western side, barley at the eastern side, and corn at the center (Fig. 1a). In 2024, rapeseed was cultivated at the eastern side, barley at the center, and corn at the western side (Fig. 1b). The management of the crops was similar at both AF and MC sites and crops were fertilized. The mean long-term annual precipitation is 617 mm, and the mean annual air temperature is 9.9 °C, for the reference period 1981-2010 at Braunschweig airport ((DWD, 2024)). The soil at both AF and MC sites was classified as a Clay Cambisol, with an organic carbon (SOC) content of 5.8 kg C m^{-2} at the MC and and 6.75 kg C m^{-2} at the AF. Additionally, the soil bulk density was determined as 1.0 g cm^{-3} at both AF and MC (Veldkamp et al., 2023). Soil characteristic were last measured in 2019.

The harvest of rapeseed, barley and corn in the 2023 campaign season occurred on 13 July, 22 August and 26 and September. The harvest of rapeseed, barley and corn in the campaign of 2024 took place on 15 July, 5 August and 13 September, respectively. In 2024, rapeseed did not grow well and a mulch cut was carried out, therefore the eastern part of the field was covered by a combination of grasses, bare soil and mulch. Canopy height was estimated from pictures taken during field visits. The maximum height attained by the crops at the peak of their development stage was around 1.5 m for rapeseed, 2.5 m for corn and 1.3 m for barley. The trees present at the AF system are fast-growing poplar (*Populus nigra* × *Populus maximowiczii*) and are typically harvested every 4 to 5 years. The most recent harvest of these trees occurred in 2019. Trees grew from around

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4.0 m till 5.5 m on average across the measurement period. Further details on the site are provided in Callejas-Rodelas et al. (2024).

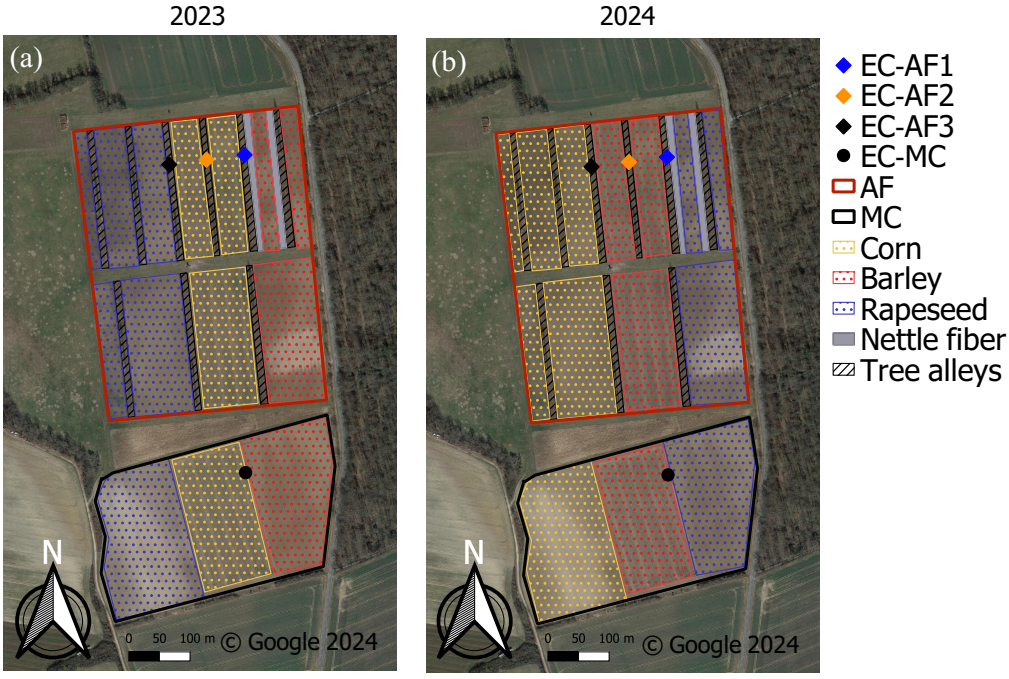

Figure 1. Satellite view and land cover classification of the experimental site for 2023 (a) and 2024 (b), together with the location of the EC stations (blue diamond for EC-AF1, orange diamond for EC-AF2, black diamond for EC-AF3 and black circle for EC-MC). The area bordered red corresponds to the AF system and the area bordered blue to the MC system. Figure created with QGIS v. 3.22, aerial map by Google Satellite Maps. © Google 2024.

2.2 Experimental setup

Measurements were made at four EC stations, one located at the MC site and three located at the AF site (Fig. 1). The stations are designated as MC, AF1, AF2 and AF3. Each station was equipped with a complete set of meteorological sensors and a LC-EC setup (see Table 1 in Callejas-Rodelas et al., 2024). The measured meteorological variables were air temperature (*TA*), relative humidity (*RH*), atmospheric pressure (*PA*), precipitation (*P*), global radiation (*SW_IN*), outgoing shortwave (*SW_OUT*) and longwave radiation (*LW_OUT*), and net radiation (*NETRAD*. The EC measurement heights were 10 m above ground for AF1, AF2 and AF3, and 3.5 m for MC. Only one photosynthetic active radiation (*PPFD_IN*) sensor was installed at AF1, and two barometers for atmospheric pressure measurements were installed at AF1 and AF2. All the stations were equipped with two soil heat flux plates to measure soil heat flux (*G*) at 5 cm depth. Only one soil heat flux plate was installed at AF3. Radiation sensors were placed in a beam facing south at 9 m height at AF1, AF2 and AF3 and at 3 m height at MC. *TA* and *RH*

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measurements were taken at 2 m height at all stations. Meteorological data were recorded on CR1000X dataloggers (Campbell Scientific Inc., Logan, UT, USA).

The LC-EC setups consisted of a three-dimensional sonic anemometer for wind measurements (uSonic3-Omni, METEK GmbH, Elmshorn, Germany) and a gas analyzer enclosure. The enclosure consisted of an IRGA for CO_2 mole fraction measurements (GMP343, Vaisala Oyj, Helsinki, Finland), and a *RH* capacitance cell for *RH* measurements (HIH-4000, Honeywell International Inc., Charlotte, North Carolina, USA) and was installed at the bottom of the tower. Air was drawn through a 9 m tube at the AF stations and 2.5 m tube at the MC station. Two temperature sensors were installed, one inside the IRGA measuring cell and one inside the enclosure; and two pressure sensors, one to measure differential pressure inside the enclosure and another to measure absolute pressure inside the IRGA measuring cell. Measurements from all components were recorded at 2 Hz frequency on a CR6 datalogger (Campbell Scientific Inc., Logan, UT, USA). A more detailed description of the setup can be found in Callejas-Rodelas et al. (2024).

The GMP343 sensors were calibrated in February 2023 and February 2024. Frequent inspections were performed to clean the tubing, replace filters, measure flow rate, and clean the lens of the GMP343. The nominal flow rate was 5.0 L· min^{-1} at all AF stations, with some drops due to filter clogging, and 2.2 L· min^{-1} at the MC before March 14th 2023 and 5.0 L· min^{-1} thereafter, due to the replacement of the pump by a more powerful one.

During the study period, there were generally large percentages of missing data. Missing data were either short gaps (a few 30-minute periods or a few hours) caused by data filtering during the quality control after flux processing (see Section 2.3.3), or longer gaps (hours to a few days) due to power outages during the winter, mostly at night, at all stations. Due to other technical problems, there were few larger gaps at some stations, in particular a gap of three months from mid-July to early October 2023 at AF3, for *FC* and *LE*.

Although generally recommended in EC studies (Aubinet et al., 2012), no storage terms were considered in the calculation of *FC* and *LE* because no concentration profiles were installed at the stations.

2.3 Flux computation

2.3.1 Pre-processing

Data processing prior to flux calculation included (i) the calculation of CO_2 dry mole fraction measurements from the CO_2 molar density provided by default by the instrument, using some sensor-specific parameters and the observed values of pressure and relative humidity in the measurement system (Callejas-Rodelas et al., 2024); and (ii) the calculation of the H_2O dry mole fraction from relative humidity, temperature and pressure measurements inside the measurement cell using the derivation of Markwitz and Siebicke (2019). More details on the pre-processing steps are given in Callejas-Rodelas et al. (2024) and van Ramshorst et al. (2024).

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2.3.2 Flux processing

H, *LE*, *FC* and momentum flux were calculated using the EddyUH software (Mammarella et al., 2016) in its Matlab version (MATLAB®R2023a, The Mathworks, Inc., Natick, MA, USA). Raw data were de-spiked using limits for absolute differences between consecutive values. Detrending was performed by block averaging. Wind coordinates were binned into eight sectors and rotated according to the planar fit correction procedure of Wilczak et al. (2001). Time-lag optimization was performed through cross-covariance maximization, using predefined windows of 2 to 10 s for CO_2 and 2 to 20 s for H_2O (Callejas-Rodelas et al., 2024). Low-frequency losses were corrected after Rannik and Vesala (1999) and high-frequency losses after Mammarella et al. (2009). The latter is based on the determination of the time response of CO_2 and H_2O separately, calculated from measured co-spectra. In the case of CO_2 the time response determined by the experimental method was similar to the nominal time response of 1.36 s calculated in Hill et al. (2017) for the GMP343. This time response was used for all flux calculations for all the three towers. In the case of H_2O the time response was estimated by a exponential fit as a function of relative humidity. Data quality was flagged from 1 to 9 following Foken et al. (2005).

2.3.3 Filtering and gap filling

Fluxes were filtered using data with quality flags < 7 to avoid periods with poorly developed turbulence (Foken et al., 2005). Outliers were removed using a running median absolute deviation (MAD) filter, based on the approach by Mauder et al. (2013), with a window of two weeks. The *q* parameter in Eq. (1) of the paper by Mauder et al. (2013) was set as 7.5. The MAD filter was iterated three times over each time series. Hard upper and lower limits were applied afterwards to remove any additional outliers not detected by the MAD filter. Values outside the ranges from -100 W m^{-2} to 700 W m^{-2} for *H*, from -20 W m^{-2} to 700 W m^{-2} for *LE*, and from -55 µmol $m^{-2}s^{-1}$ to 55 µmol $m^{-2}s^{-1}$ for *FC*, were discarded. Additional hard limits were applied specifically to winter (November to February) and transition periods (March and October) separately. The aim was to avoid outliers that went through the previous filters which might bias the application of the gap-filling algorithms. For *LE* and *H*, these limits were of 50 W m^{-2} during winter, and 100 W m^{-2} in March and October. For the *FC*, these limits were ± 10 µmol m^{-2} s^{-1} during winter, and ± 15 µmol m^{-2} s^{-1} in March and October. Finally, a friction velocity (*USTAR*, m s^{-1}) filter was applied to remove periods with non-existent or weak turbulence. The filter of *USTAR* was applied using REddyProc (Wutzler et al., 2018), which removed values based on a *USTAR* threshold calculated as the maximum of the seasonally derived *USTAR* values. These seasonal values were calculated based on Papale et al. (2006). The average *USTAR* thresholds for the stations were 0.21, 0.21, 0.18 and 0.16 m·s^{-1} for AF1, AF2, AF3 and MC, respectively.

The total available data before filtering accounted for 63.4 % (AF1), 80.0 % (AF2), 76.2 % (AF3) and 61.5 % (MC) for *FC* and *LE*, and 85.7 % (AF1), 86.0 % (AF2), 83.1 % (AF3) and 75.9 % (MC) for *H*, relative to the duration of the whole measurement campaign. These gaps were due to instrumental or power failure. After filtering, the available data accounted for 36.5 % (AF1), 44.8 % (AF2), 31.3 % (AF3) and 29.2 % (MC), for *FC*; 41.6 % (AF1), 50.1 % (AF2), 36.1 % (AF3) and 38.5 % (MC) for LE; and 61.4 % (AF1), 60.0 % (AF2), 56.4 % (AF3) and 52.3 % (MC) for *H*. Additional gaps in filtered data were introduced by rejecting data.

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Meteorological data were gap-filled at the 30-minute time scale in order to provide complete time series for the variables acting as predictors for the flux gap-filling, with slight differences in the procedure for the different variables of interest. Short gaps of up to one hour were filled using linear interpolation, except for *P*. Missing data at the AF1 station that were available at the MC station, were filled using linear regression models using as predictors the data from the MC, and viceversa. Missing data at AF2 and AF3, but available at AF1, were filled using a similar procedure with AF1 as the reference. Finally, *P*, *TA*, RH, vapor pressure deficit (*VPD*), *SW_IN*, wind speed (*WS*) and wind direction (*WD*) were filled at the stations using ERA5-Land re-analysis data (Muñoz-Sabater et al., 2021) as predictors, following the approach implemented in Vuichard and Papale (2015). Linear regression models were derived from the ERA5-Land data and the station data, using the library *pylr2* in Python. The coefficients (slope and intercept) from the linear models were used to calculate the missing values. *PPFD_IN* was filled based on global radiation (*SW_IN*), by multiplying *SW_IN* by the average ratio between *PPFD_IN* and *SW_IN* for the available periods at the site. *P* was filled by multiplying the ERA5-Land data by the ratio between the station data and the re-analysis data, as done in Vuichard and Papale (2015). Possible inaccuracies resulting from this replacement did not contribute to an additional bias in the gap-filled flux time series, as precipitation was not used for gap-filling purposes. A quality flag was developped for meteorological data, with 0 being measured data, 1 being interpolated data, 2 being data filled using the nearby station as a reference, and 2 being data filled with ERA5 as a reference.

Gaps in the flux time series were filled using a double-step procedure, analogous to the approach applied in Winck et al. (2023). Short gaps were filled using the Marginal Distribution Sampling method (Reichstein et al., 2005) with the online version of the REddyProc package (Wutzler et al., 2018). Short gaps were considered by taking the filled data with quality flags of 0 (originally measured data) or 1 (highly-reliable filled data). Subsequently, the remaining gaps (flagged with 2 or 3 in REddyProc) were filled using a machine learning (ML) tool based on the Extreme-Gradient-Boosting (XGBoost) algorithm (Chen and Guestrin, 2016). The code was adapted from Vekuri et al. (2023) to include *H*, *LE* and *FC*. The predictor variables of the model were the previously filled *TA*, *VPD*, *SW_IN*, *WS* and *WD*. The inclusion of *WD* followed the recommendation of Richardson et al. (2006) to account for the heterogeneity of the site, with different land covers depending on wind sectors potentially contributing to flux variability. A quality flag was developped for flux variables, being 0 measured data, 1 data filled with REddyProc, and 2 data filled with XGBoost. There were two very long gaps, one for AF3 during summer 2023 (mid July until beginning of October) and another for AF1 during winter 2023/24 (beginning of December 2023 until beginning of March 2024), besides gaps of few days duration. Because such long gaps would induce very large uncertainty in any gap-filling method, the analysis considered only measured data and gap-filled data for gaps not exceeding two weeks duration.

The error in gap-filled fluxes with XGBoost was taken as the root mean squared error (RMSE) of the modelled data. Table 1 shows the RMSE scores for *FC*, *LE* and *H* for all four stations. RMSE was taken as the error attributed to each individual gap-filled 30-minute flux value.

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Table 1. Root mean squared error (RMSE) of modeled and measured data, for *FC*, *LE* and *H*, for the four stations used in this study. Note that the error in *FC* was slightly different across the stations, but the displayed values are similar due to the effect of decimal rounding.

	AF1	AF2	AF3	MC
FC (µmol $m^{-2}s^{-1}$)	2.8	2.8	2.8	2.8
LE (W m^{-2})	23.2	32.8	19.7	25.7
H (W m^{-2})	14.5	15.2	13.0	14.1

2.3.4 Footprint calculation.

A footprint climatology was calculated for all stations, for five different periods considered in the study: (i) growing season 2023: from March to 13 July 2023, with the latter being the harvest date of rapeseed; (ii) harvest period 2023: from 13 July to 22 September 2023, with the latter being the harvest date of corn; (iii) winter 2023/24: from 22 September 2023 to 1 March 2024; (iv) growing season 2024, from 1 March to 15 July 2024, with the latter being the harvest date of the rapeseed; and (v) harvest period 2024, from 15 July to 19 September 2024. The footprint climatology was calculated using the Python version of the model by Kljun et al. (2015).

The input data to the footprint model comprised non gap-filled wind data (*WS*, m s^{-1}, and WD, °), roughness length (z_0, m), *USTAR*, Obukhov length (L, m), the standard deviation of lateral wind speed (*V_SIGMA*, m s^{-1}), boundary layer height (*BLH*, obtained from ERA5, Hersbach et al. 2023), measurement height (z_m, m), displacement height (d_h, m) and aerodynamic canopy height (h_a, m). Only daytime values were selected based on values of *SW_IN* higher than 10 W m^{-2}. The aerodynamic canopy height was calculated during near-neutral conditions (stability parameter $ZL \leq 0.1$) based on the procedure by Chu et al. (2018). The complete time series of h_a were estimated as described in more detail in van Ramshorst et al. (in prep.). This allowed for a more comprehensive representation of the roughness effects of a varying canopy, therefore it can be considered as a more precise representation compared to the use of a single value representing the average canopy height for the whole site for each time step. d_h and z_0 were estimated as 0.6 and 0.1 times the aerodynamic canopy height, following Chu et al. (2018). The mean values of d_h were 3.1 m at the AF and 0.6 m at the MC, while the mean values of z_0 were 0.5 at the AF and 0.1 m at the MC. A thorough discussion on the uncertainties of the footprint model can be found in Section 4.4.

2.4 Spatial and temporal variability of fluxes and turbulence parameters and effect size

In order to disentangle spatial and temporal variability of fluxes and turbulence parameters across the site, the data were classified in two different ways. Firstly, data were aggregated according to different wind sectors of 30° each, and separated into five time periods as described in the previous paragraph. Secondly, data were grouped in periods of one week, along the whole measurement campaign, without the division into wind sectors. For each of these classifications, coefficients of spatial variation (CVs) were calculated and the variance was partitioned into temporal and spatial components.

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The *CVs* were defined as follows

$$CV_x = \overline{\left[\frac{< [x(t) - X(t)]^2 >^{\frac{1}{2}}}{X(t)}\right]} \quad (1)$$

based on Katul et al. (1999) and Oren et al. (2006). *X* is the spatial average of variable *x* across the three towers in the AF for the respective averaging time interval. Angular brackets (<>) denote the spatial averaging operator and the overbar denotes temporal average across all the individual time steps *t*. This formula was applied to *H*, *LE* and *FC*, and to the standard deviation of the vertical wind velocity (*W_SIGMA*, m s^{-1}), *USTAR* and *WS*. The coefficients of variation are dimensionless, normalized by the spatial average of variable *x*, such that they can be compared for different variables. Lower limits were set for some of the variables, in order to avoid biasing the coefficients of variation by some very low fluxes in the denominator of Equation 1. These limits were 10 W m^{-2} for *H* and *LE*, ± 2 µmol m^{-2} s^{-1} for *FC*, and 0.5 m s^{-1} for U.

The partitioning of the variance into temporal and spatial components was done as presented in Peltola et al. (2015) (Eq. 2 therein) based on Sun et al. (2010):

$$\sigma_{tot}^2 = \frac{m(n-1)}{m \cdot n - 1}\bar{\sigma_s^2} + \frac{n(m-1)}{m \cdot n - 1}\sigma_t^2(\xi) = \sigma_s + \sigma_t \quad (2)$$

with *m* the number of temporal data points, *n* the number of measurement locations, $\bar{\sigma_s^2}$ the time average of the spatial variance, and $\sigma_t^2(\xi)$ is the temporal variance of the time series of spatial averages ξ. Consequently, the first term on the right hand side of the equation is equivalent to the spatial variance (σ_s), which includes as well the instrumental variance, while the second term is equivalent to the temporal variance (σ_t) (Peltola et al., 2015).

Furthermore, the effect size (*d*) was calculated in order to assess the statistical robustness of our distributed network, in accordance with the hypothesis of Hill et al. (2017) that the enhanced error observed in LC-EC setups can be counteracted by an improved statistical representativeness of the measurements, provided that the effect size is sufficiently large. In our case, with the three towers network we calculated *d* across the three towers inside the AF and between the AF and the MC. *d* was calculated, following Hill et al. (2017), as

$$d = \frac{f_1 - f_2}{\sigma} \quad (3)$$

where f_1 is the flux from ecosystem 1, f_2 is the flux from ecosystem 2 and σ is the pooled standard deviation of data from both ecosystems. *d* can be positive or negative. We used daily cumulative sums of gap-filled *FC* and *LE*. The value f_1 in Eq. 3 refers to the daily cumulative sums of C (g C m^{-2}) or *LE* (W m^{-2}) at the AF, as an average across the three stations, while f_2 corresponds to the daily cumulative sum of C or *LE* for AF1 or for MC, depending on the case under study. We calculated *d* for two different cases: (i) to test whether fluxes over AF (average across the three towers) were significantly different from fluxes over MC, in order to compare both ecosystems; and (ii) to test whether fluxes over AF were significantly different from fluxes from the reference tower AF1, in order to compare the increase in statistical robustness of the distributed network to the hypothetical case in which only one station was installed at the AF. AF1 was selected as the reference tower because it was the oldest running tower on site, having been in operation since 2016. σ was calculated as in Hill et al. (2017)

$$\sigma = \sqrt{\frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2}} \quad (4)$$

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where σ_1 and σ_2 are the standard deviations of both datasets being compared, and n_1 and n_2 are the number of data points in each of the datasets. σ was calculated as the error of the daily cumulative sum, from the individual 30-min error in the fluxes (see next section). Afterwards Eq. 4 was applied to get the error for the ensemble of stations being compared.

2.5 Uncertainty of the LC-EC setups

The uncertainty in *FC* and *LE* was considered by assigning an error to each 30-min flux value. This error was propagated later on when aggregating data to daily cumulative sums for the effect size calculations. The error was considered differently for measured and gap-filled data. In the case of measured data, the error in the 30-min *FC* and *LE* was obtained from the inter-comparison of LC-EC and conventional EC setups in the studies of Callejas-Rodelas et al. (2024) and van Ramshorst et al. (2024). The error was taken as the worst-case slope of the linear regression models between LC-EC and conventional EC setups, separately for *FC* and *LE*. It was of 5% for *FC* and 22% for *LE*, considered as a relative error for each individual flux value. It is important to note that the error is a systematic deviation from the conventional EC setup, and no random error was considered in these calculations. Therefore, the uncertainty associated with a given flux value is determined by the product of this error value and the magnitude of the flux itself. As an example, a *FC* of 10 µmol m^{-2} s^{-1} would be expressed as 10 $\pm$ 0.5 µmol m^{-2} s^{-1}, and a *LE* of 100 W m^{-2} would be expressed as 100 $\pm$ 22 W m^{-2}.

In the case of the gap-filled data, the error was addressed differently for the two gap-filling steps. For the data filled with REddyProc, the error was defined as the standard deviation of the data points used for gap-filling (Wutzler et al., 2018), provided as an output from the REddyProc processing. In contrast, for the data filled with XGBoost, the individual error in the fluxes was assigned as the RMSE of the modelled data (Table 1). The uncertainty in a cumulative sum was then calculated using error propagation from the single 30-minute uncertainties to the daily sums.

3 Results

3.1 Meteorological conditions

SW_IN followed a seasonal cycle, with the maximum magnitude observed at the end of June 2023 (daily means above 300 W m^{-2}), followed by a radiation intensity decrease, reaching the minimum values in winter close to 0 W m^{-2}, and then again increasing until similar maximum values in June 2024 (Fig. 2a). Monthly values of *P* were large, especially from June to December in 2023, and in July of 2024, with values up to 125 mm (Fig. 2d). There were some very dry months, with *P* sums lower than 20 mm, especially from March to June in 2024. Compared to the climatological averages (Table 2), all seasons during the measurement period were more rainy than the period 1981-2010, especially during summer and autumn of 2023, when the recorded precipitation was more than three times the reference one (272 mm vs. a reference value of 65 mm for summer 2023, and 218 mm vs. a reference value of 52 mm for autumn 2023). Only spring 2024 was slightly dryer than the climatological reference, with a record of 30 mm of rain instead of 49 mm.

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Table 2. Measured and reference climatological averages of *TA* and *P* by seasons. Measured seasonal values were calculated as averages across all four stations at the site. Reference values were taken as the seasonal 1981-2010 climatological average from the German Weather Service (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/, last accessed 25-09-2024) from the nearby station at Braunschweig airport (ID 662).

Season	Measured *TA* (°C)	Measured *P* (mm)	*TA* reference (°C)	*P* reference (mm)
Spring 2023	9.1	102.5	9.1	48.7
Summer 2023	18.7	272.3	17.4	65.0
Autumn 2023	11.9	218.5	9.8	52.0
Winter 2023/24	4.3	198.0	1.7	46.7
Spring 2024	11.8	30.1	9.1	48.7
Summer 2024	18.6	165.8	17.4	65.0

TA followed a seasonal cycle, with the lowest values in winter (daily means between 0 and 10 °C, with occasional lower values) and the highest values in July and August of both 2023 and 2024 (daily means around 20 °C). *TA* was slightly larger at the MC tower than at the other three AF towers during most of the campaign, with enhanced differences in summer and very small differences in winter. The mean *TA* during the campaign was 12.86 °C at the MC, while it was 12.49 °C at the AF. The three AF stations showed very similar *TA*. *TA* was higher in all seasons compared to the climatological averages (Table 2), except in spring 2023 in which both values were similar (9.1 °C). Summer 2023 and summer 2024 were slightly warmer (18.7 and 18.64 °C, respectively) than the reference value (17.4 °C). Autumn 2023, winter 2023/24 and spring 2024 were clearly warmer than the climatological averages, with 11.9, 4.3 and 11.8 °C vs. the reference values of 9.8, 1.7 and 9.1 °C, respectively. The absolute difference between measured and historical data was largest in winter.

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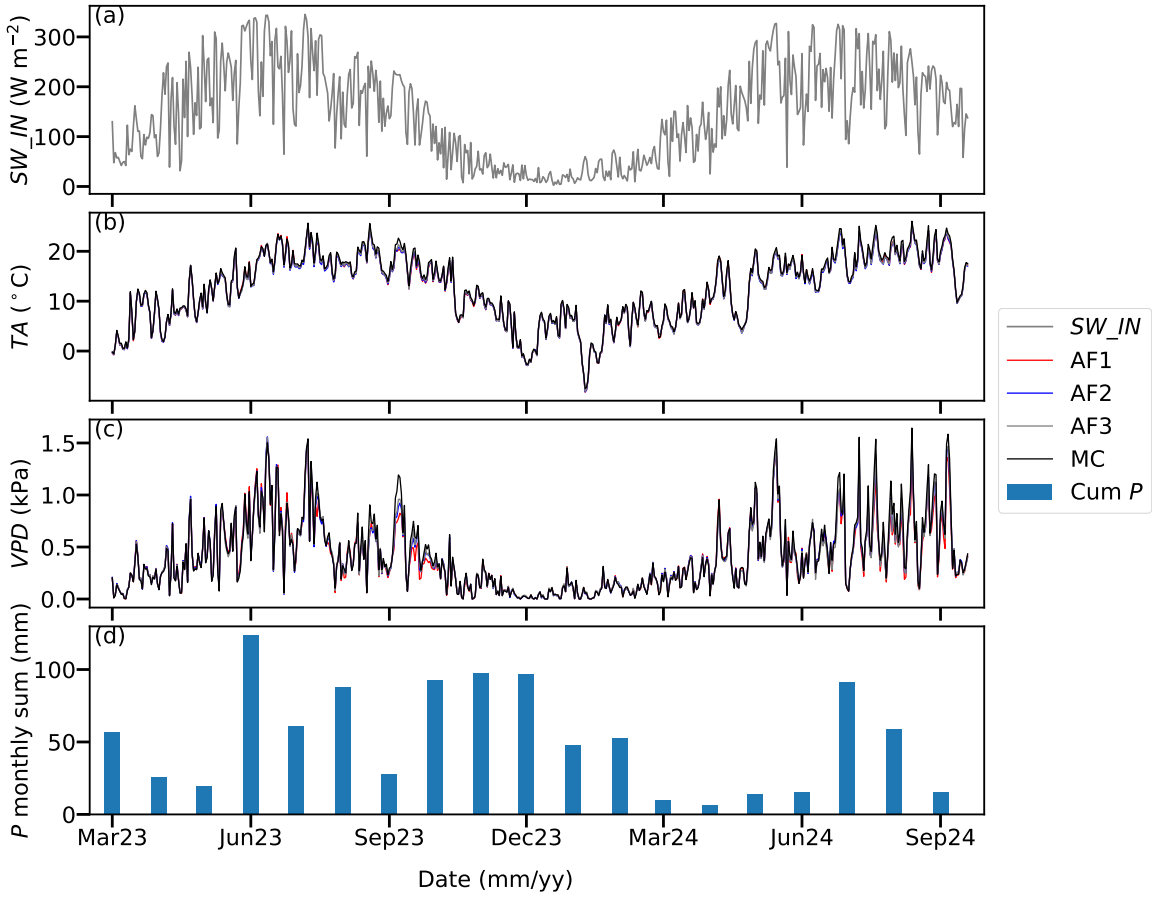

Figure 2. Time series of daily mean meteorological parameter and the cumulative sum of precipitation across the measurement campaign: (a) global radiation (*SW_IN*), (b) air temperature (*VPD*), (c) vapor pressure deficit (*VPD*) and (d) monthly sums of precipitation (*P*). *SW_IN* and *P* were considered as common to all the stations, because the size of the site is small enough to assume homogeneity in these parameters, whereas *TA* and *VPD* were plotted separately for all four stations. Data were filtered for outliers using lower and upper limits, gap-filled as detailed in Section 2.3.3, and then aggregated to daily values by taking the daily mean for *SW_IN*, *TA* and *VPD* and the daily sum for *P*.

VPD values also showed a marked seasonality (Fig. 2c). Values were very low in winter, between 0 and 0.2 kPa, and increased towards summer in both 2023 and 2024, reaching daily means between 1 and 1.5 kPa. *VPD* was still relatively large in autumn of 2023, with values of around 0.5 kPa. Comparing the four stations, the MC site experienced a larger *VPD* from July to October 2023, while during the rest of the campaign no significant differences were observed across the stations. The mean *VPD* was 0.41 kPa at the MC and 0.4 kPa at the AF as an average of the three stations. The differences between the three AF stations were very small.

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3.2 Footprint climatology

The seasonal footprint climatology show the 80 % contributions from the different land uses to the fluxes by all four stations (Fig. 3). All footprints exhibited larger contributions from the western side of the towers in all periods (growing season 2023, harvest period 2023, winter 2023/24, growing season 2024 and harvest period 2024), corresponding to the dominant wind direction at the site. For all periods under consideration, the footprint of the MC tower was smaller than for the three AF towers, due to the lower measurement height. The three stations at the AF exhibited partially overlapping footprints, with different sizes and degrees of similarity depending on the evaluated period. The footprint of the three towers covered approximately four tree rows and four crop rows each. The three towers at the AF presented different footprint sizes, with the largest areas being covered by AF3, followed by AF2 and finally by AF1. The order was the same in all seasons. The footprint from the MC tower covered both the western and eastern fields around the tower, but the contribution was larger from the western part in all seasons. For all stations, there were some contributions to the footprints from the areas beyond the AF or the MC fields. This was especially remarkable in the case of AF3, which had some contributions from the western side of the field in winter 2023/24 (Fig. 3c) and from the northern side of the field in both harvest periods of 2023 and 2024 and the 2024 growing season (Fig. 3b,d,e). However, the contributions of the areas outside the AF were expected to be negligible regarding the interpretation of the results.

The analysis on specific differences between land covers measured by the different stations revealed variations from season to season. In the 2023 growing season, the footprints of AF1, AF2 and AF3 were overlapping the most compared to the other seasons (Fig. 3a). At AF1 predominantly four tree strips, corn, barley and the nettle fiber rows were detected. At AF2, the footprint encompassed a larger area, covering five tree strips, all three crops (rapeseed, corn and barley) plus the nettle fiber was detected. At AF3 the footprint was the most extensive, covering also five tree strips, the three crops and one of the nettle fiber strips, plus some areas beyond the AF site was detected. The overlap of the footprints was more intense between towers AF2 and AF3. The MC tower detected mostly the corn field, with a small contribution of the rapeseed field.

During the harvest period in 2023, the footprint size diminished, partially due to a reduced considered period. The footprint climatology is a weighted average, hence, a longer evaluated period is likely to extend the footprint area. This lead to a reduction in the degree of overlap among the footprints, particularly between AF1 and AF3. AF1 covered three tree strips, corn, barley and nettle fiber; AF2 covered four tree strips, only one row of rapeseed, the whole corn field and a small part of the barley field; AF3 covered also four tree strips, the whole rapeseed field and part of the corn field. The MC tower covered only part of the corn field.

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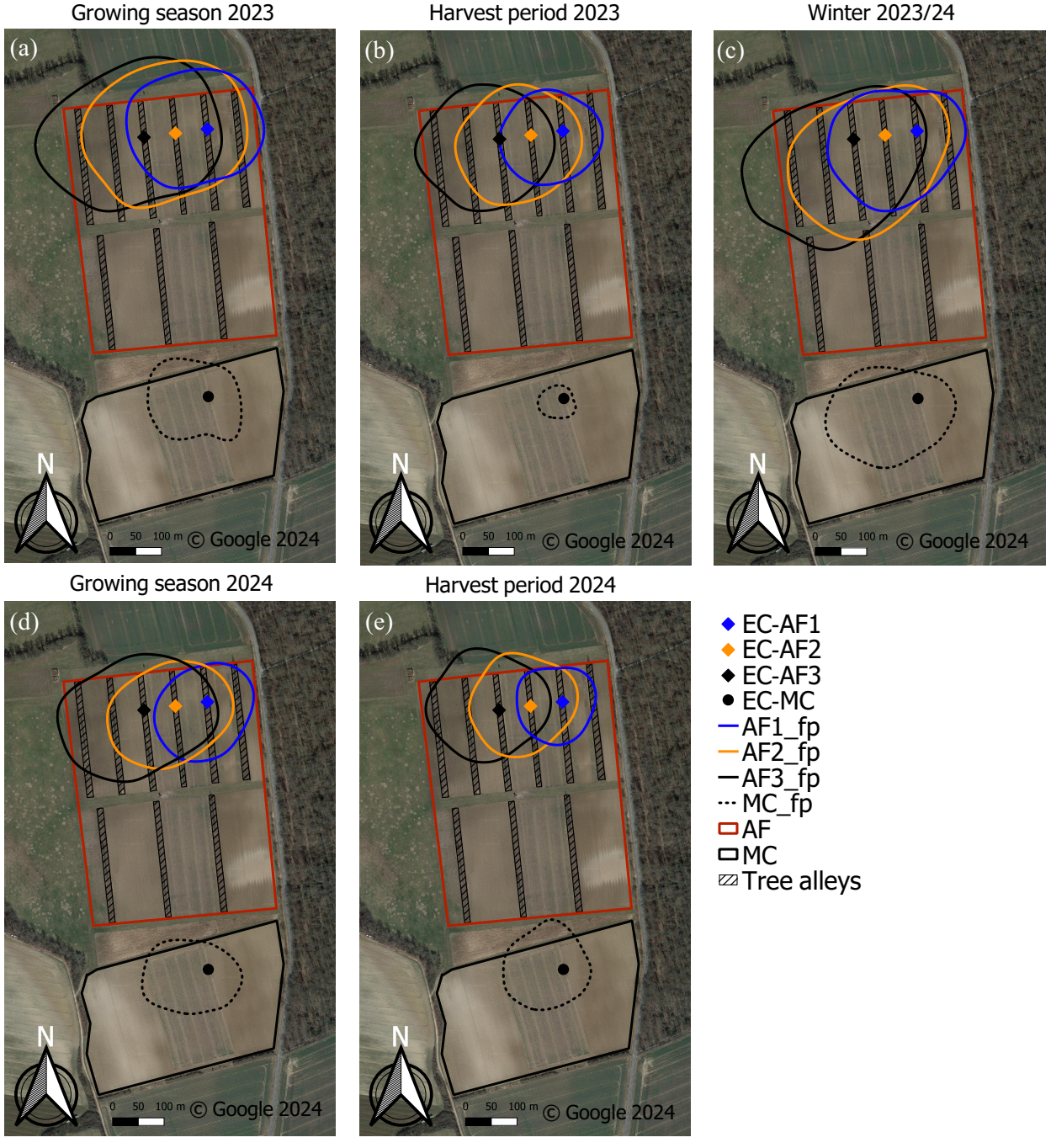

Figure 3. Footprint climatologies, calculated from the model of Kljun et al. (2015), for the three towers at the AF and the tower at the MC (detailed in Section 2.3.4), divided into five different periods: growing season 2023 (a), harvest period 2023 (b), winter period 2023/24 (c), growing season 2024 (d) and harvest period 2024 (e). The lines plotted in the map represent the 80 % contributing areas to the footprint. Figure created with QGIS v. 3.22, aerial map by Google Satellite Maps. © Google 2024.

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In winter 2023/24 (Fig. 3c), the footprint size increased again for all stations, enhancing the overlap. However, this enhancement was not as substantial as the one observed during the 2023 growing season. All crops had been harvested, and only the rapeseed had been sown in the eastern part of the field in September 2023 (Fig. 1b), therefore the remarkable features of this season are that the footprints of both AF1 and AF2 covered one of the rapeseed field rows, together with the nettle fiber, while the footprint of AF3 did not. The other spaces in between tree strips were bare soil during this season. The MC footprint was larger than during the other seasons and covered most of the field in the west of the tower and a small part of the rapeseed field in the east.

During the 2024 growing season, the footprints of AF1 and AF2 exhibited an overlap of approximately 50 % of the footprint area, while the overlap between AF1 and AF3 was significantly less (Fig. 3d). AF1 covered rapeseed, nettle fiber, part of the barley field and only three tree strips; AF2 covered part of the corn field and the barley field, plus four tree strips; AF3 covered the whole corn and barley fields and five tree strips. The MC footprint reduced in size compare to the winter period, and was mostly covering the barley field in the west of the station. Finally, during the 2024 harvest period, the footprint size reduced again for all stations, and so did the overlap (Fig. 3e). AF1 covered only part of the barley field and part of the rapeseed field, together with the nettle fiber and two tree strip; AF2 covered most of the barley field and parts of the rapeseed and the corn fields, plus three tree strips; and AF3 covered the corn field, part of the barley field and almost four tree strips. The footprint of the MC was similar to the 2024 growing season (Fig. 3e) covering mostly the barley field and a minor portion of the rapeseed field.

3.3 Weekly sums of carbon and evapotranspiration

The weekly cumulative sums of *FC* (Fig. 4a) exhibited a marked seasonal behavior and similar variability across the four towers. The seasonal cycle was characterized by the uptake of carbon (negative values) during the growing season and carbon losses (positive values) during winter. The differences were smaller across the three AF towers, with AF1 and AF2 behaving more similar. During the 2023 growing season, there was a strong uptake at all stations of around -30/-40 g C m^{-2} per week, from April to September 2023. This was interrupted by the short dry period of three weeks which occurred at the end of May and first half of June of 2023 (DWD, 2024) with the AF site turning to a carbon source (measured by AF2) or to a weak carbon sink (measured by AF1 and AF3). The uptake was stronger at AF3 until mid June, after which MC showed the strongest uptake (-40 to -60 g C m^{-2} per week) for the rest of the growing season. After the harvest of the rapeseed on 13 July 2023, weekly sums reduced in magnitude but were still large at AF1, AF2 and MC (AF3 was missing during this period), and after the harvest of the barley on 22 August 2023 the sums reduced notably. From October 2023 to March 2024, the values were positive and comparable across all stations, indicating a carbon release from the ecosystems. During the 2024 growing season, the carbon uptake was found to be diminished compared to the 2023 growing season. The strongest uptake of around -25 g C m^{-2} per week occurred in July 2024. AF2 and MC showed the strongest uptake during June and July, however, after the harvest of the rapeseed on 15 July, the uptake reduced and AF2 and MC changed their sign towards a carbon source, while AF1 and AF3 still showed negative values. After the harvest of the barley on 5 August 2024, the uptake of AF1 and AF3 reduced even more, changing in AF1 towards a carbon source. AF3 kept a CO_2 sequestration behavior until the end of the measurement period.

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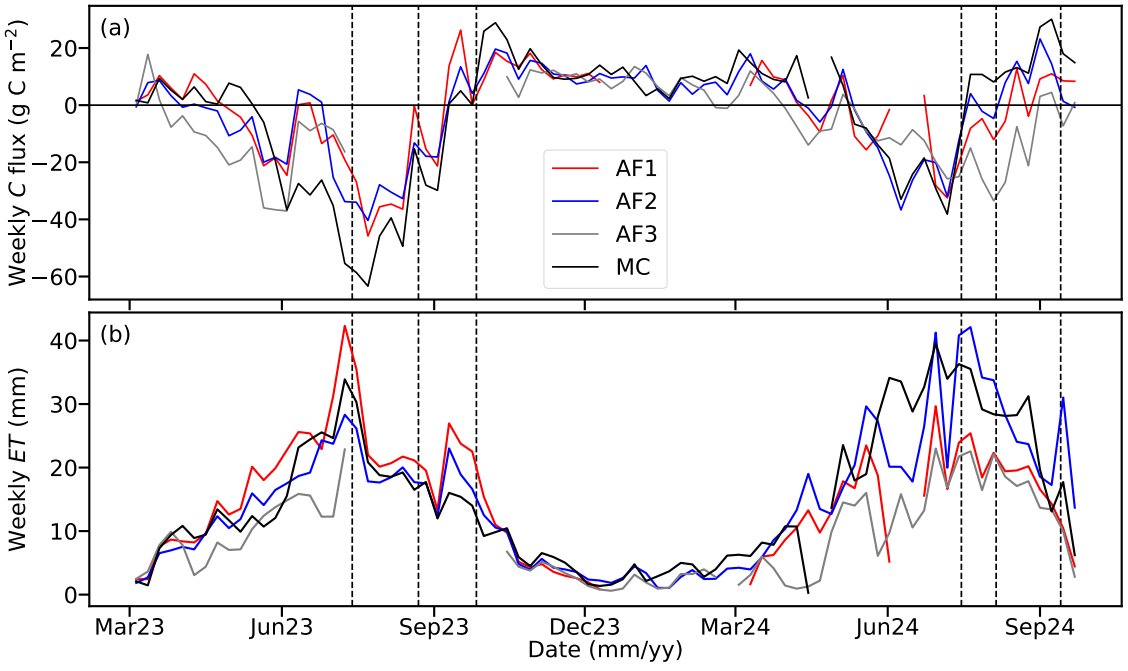

Figure 4. Weekly sums of the net ecosystem carbon exchange as a carbon (*C*) flux (a) and evapotranspiration (b, *ET*) measured at the four stations, across the measurement campaign. Sums were calculated from the gap-filled time series. Missing values correspond to gaps longer than 2 weeks, which were not considered in the analysis. The horizontal line in sub-plot (a) highlights the zero line, separating the uptake (negative fluxes) from the emission (positive fluxes). Vertical dashed lines represent, from left to right, the harvest dates of rapeseed (13 July 2023), barley (22 August 2023) and corn (26 September 2023) in 2023; and rapeseed (15 July 2024), barley (5 August 2024) and corn (13 September 2024). Due to the requirement of taking only gap-filled data for gaps up to two weeks of duration, there were some missing weeks for all stations and two very long gaps, in summer 2023 for AF3 and in winter 2023/24 for AF1.

The weekly cumulative sums of *ET* (Fig. 4b) also exhibited a strong seasonality in all stations and similar variability across them. During the 2023 growing season, there were increasing *ET* weekly sums from April (values around 10 mm per week) until the maximum values attained in July, with a magnitude of 30 mm at AF2, AF3 and MC, and 40 mm at AF1. Afterwards there was a progressive reduction in *ET* especially enhanced after the harvest of the rapeseed on 13 July 2023 and the harvest of the corn on 26 September 2023. AF1 showed the highest values until October 2023. Thereafter, all stations showed low values coinciding with the winter period, of around 5 mm per week, until March 2024. During the 2024 growing season, weekly *ET* was again progressively increasing at all the stations, until they reached the maximum values of 30 and 40 mm. The increase was only interrupted by a reduction in *ET* in June, more marked at the AF towers. After the peak of the growing season, *ET* reduced especially after the harvest of the rapeseed on 15 July 2024 and the barley on 5 August 2024. The highest values during the growing season were found for the MC until July and for AF2 after that, and the reduction in *ET* after the harvest events was more marked in these two stations. AF1 and AF3 kept lower values and exhibited a more similar behavior.

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3.4 Coefficients of variation, spatial and temporal variance

3.4.1 Classification in wind direction bins

The *CVs* calculated at the half-hourly scale (Eq. 1) were the largest for *FC* in most of the wind sectors and the evaluated periods, followed by the *CVs* of *LE* and *H* (Fig. 5). The *CVs* of *WS*, *USTAR* and *W_SIGMA* were low in comparison to the *CVs* of *FC*, *LE* and *H*. The lowest variability across wind sectors in all periods was found for *W_SIGMA*, followed by *USTAR* and *WS*, with *CV* values below 0.15 in most of the cases. Within the 2023 growing season, *FC* showed the largest spatial variability in the eastern and southern wind sectors, with *CVs* above 0.5 and up to 1.2. *LE* and *H* showed similar values of between 0.2 and 0.3, slightly higher for *LE* (close to 0.4) in the northern wind sectors (330-60°). During the 2023 harvest period, no *CVs* of *FC* and *LE* could be calculated due to the absence of data from AF3, therefore only the variability of *H* and turbulence parameters could be addressed. *H* showed the largest variability in the northeastern wind sectors (0-150°), with values of *CVs* of above 0.2. In winter 2023/24, the *CVs* of *FC* were the largest in the eastern half (0-180°), with values between 0.2 and 0.8, while *LE* and *H* showed similar values between them; in the sectors 180-270° the *CVs* of *LE* were the largest, with values up to 0.6, followed by *CVs* of *FC*. For the sectors 270-360° the *CVs* of all variables were smaller than 0.3 and very similar across them. During the 2024 growing season, *FC* showed the largest variability in the eastern (30-180°) and northeastern sectors (330-30°), with values between 0.4 and 1.7, while the *CVs* of *LE* were similar to the *CVs* of *H* with a magnitude between 0.2 and 0.4. In the western sector (180-330°), however, the *CVs* of *LE* were the largest, with values between 0.4 and 0.5, and *CVs* of *FC* were similar to the *CVs* of *H*. Finally, during the 2024 harvest period, in the eastern sector (0-180°) the *CVs* of *FC*, *LE* and *H* were very similar, with values between 0.2 and 0.4, and in the western sector (180-360°) the *CVs* of *LE* were slightly larger, between 0.4 and 0.5, and *CVs* of *FC* and *H* remained similar. Both for *FC* and *LE*, both variance values were larger during the growing season and the harvest period in both years than during winter, due to the larger magnitude of fluxes. As an overall picture, σ_s was larger than σ_t in the western and northeastern wind sectors. Due to the scope of this analysis, it is important to remark in which wind sectors σ_s was larger than σ_t. Looking first at *LE* (Fig. 5, mid row) σ_t dominated the variance in all wind sectors during the 2023 growing season. During winter 2023/24, σ_t of *LE* was larger than σ_s in all sectors except in the bin 210-240°, when σ_s was much larger than σ_t. During the 2024 growing season, σ_s was larger than σ_t in the wind sectors of 60-90° and 300-330°. Finally, during the harvest period in 2024, the spatial component was larger than the temporal one only in the sector 60-90°.

Regarding *FC* (Fig. 5, bottom row), the picture was different compared to *LE*, with a higher relevance of the spatial component of the variance. During the 2023 growing season σ_t dominated all wind sectors except for the bins 60-90° and 150-180°, but the values of σ_s were close to the values of σ_t in all the eastern sectors. During winter 2023/24, σ_s was larger than σ_t in all wind sectors except 0-30°, with the largest difference in the eastern (90-120°) and southwestern (210-240°) sectors, and with relatively large values in the sectors 120-210°. During the 2024 growing season, σ_s was larger than σ_t in all sectors except in the northwestern ones (300-360°), reaching very large values in comparison to other periods (up to 80 $\mu mol^2\ m^{-4}\ s^{-2}$) in the eastern half. Finally, during the 2024 harvest period, σ_s was larger than σ_t in the sectors 0-60° and 150-240°, while σ_t dominated in the northwestern sectors.

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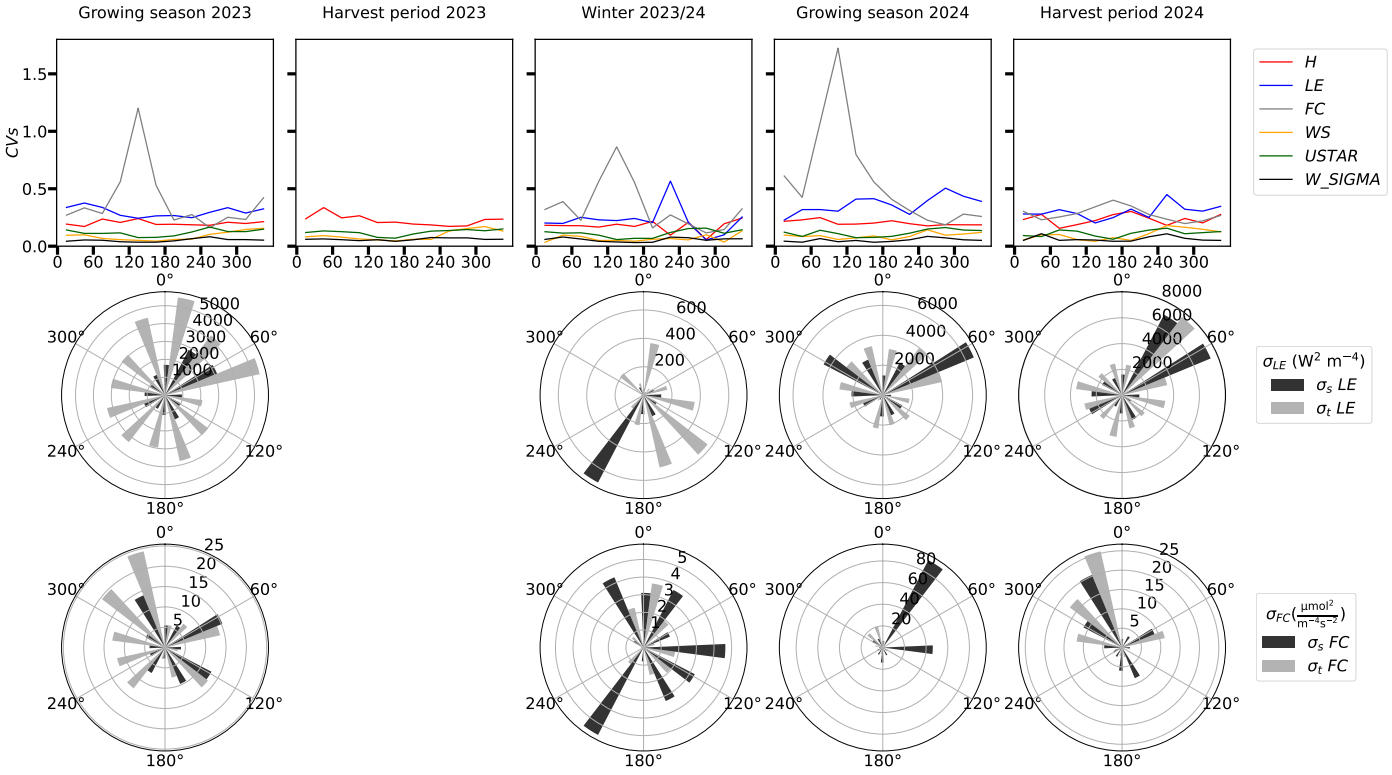

Figure 5. (Top row) Coefficients of variation (CVs), calculated after Oren et al. (2006), for *FC*, *LE* and *H*, *WS*, *USTAR*, and *W_SIGMA*; (mid row) spatial (σ_s *LE*) and temporal (σ_t *LE*) variance for *LE*; (bottom row) spatial (σ_s *FC*) and temporal (σ_t *FC*) variance for *FC*. Data were grouped in all cases by wind direction bins of 30° each and separated into the five analysis periods (growing season 2023, harvest period 2023, winter 2023/24, growing season 2024 and harvest period 2024) detailed in Section 2.3.4. Due to the two very long gaps in AF1 and AF3 (see Fig. 4), plus some shorter gaps, there were no data corresponding to the harvest period in 2023 for *FC* or *LE*, therefore the sectorial plots for the variance partition are missing. Note that in the first row, due to the large magnitude of some of the *CVs* of *FC*, the variability in the lines corresponding to the other variables is more difficult to visualize. Note that the scale is different in the circular plots, depending on the magnitude of what is represented in each season.

3.4.2 Classification in weekly intervals

The weekly *CVs* across the measurement campaign were largest for *FC*, with a large difference to the rest of the variables being evaluated (Fig. 6a). The difference was especially remarkable during winter and from March to May 2024. At the beginning of the 2023 growing season, in March and April, the *CVs* of *FC* were between 0.3 and 2, much larger than the *CVs* of *LE*, while in May, June and until mid July (when the large gap in AF3 started), *CVs* of *FC* and *LE* were similar, with values between 0.2 and 0.5, except for a very large value of 10 the first week of June. In the short evaluated winter period, *CVs* of *FC* were very large in comparison to the other variables, with values up to 3.9, and one very large value of 48. However this value could be classified as an outlier because of the larger noise and uncertainty in the winter data. The *CVs* of *LE* showed a small variability

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and were close to *H*, with values between 0.1 and 0.3. During the 2024 growing season, in March and April the *CVs* of *FC* were large, with values up to 17 in March, while *CVs* of *LE* were between 0.3 and 0.5, and *CVs* of *H* between 0.2 and 0.3. From May 2024, the *CVs* of *FC* were similar to the *CVs* of *LE*, with values around 0.5 and slightly lower during the 2024 harvest period, and followed closely by the *CVs* of *H*. During the whole campaign, the *CVs* of *USTAR*, and *W_SIGMA* were much lower than for *H*, *LE* and the *FC*, similar as shown in Figure 5, with values below 0.2 across the whole period. However, the *CVs* of $\bar{u}$ were similar to the ones of *H* during the growing season as well as the 2023 harvest period. After summer 2023 the *CVs* of $\bar{u}$ reduced their magnitude. The *CVs* of *USTAR*, and *W_SIGMA* were the lowest and did not change much during the campaign. In general, there was no clear effect of the harvest event on the variation of *CVs* for all variables.

With regards to partitioning the variance into its temporal and spatial components, σ_t was higher than σ_s for both *LE* and *FC* (Fig. 6b and 6c) during all the evaluated periods. The highest variance was observed during the end of the growing season in both years and during the harvest period in 2024, while the lowest occurred in winter time. During winter, σ_s and σ_t were very similar for both *LE* and *FC*. The spatial variance of *LE* and *FC* was largest in the summer months of both years. However, the difference between σ_t and σ_s changed from *LE* to *FC*. In the case of *LE*, σ_s was very close to σ_t from March to August 2024, being even higher in some weeks, and decreased largely in the harvest period. In the case of *FC*, σ_s stayed at very low values in comparison to σ_t during the whole period. The effect of harvest events in 2024 was shown by a lower variance in both temporal and spatial components, especially visible in the case of *LE* for which σ_s reduced sharply after the harvest of the rapeseed in 2024 (Fig. 6b).

3.5 Effect size and statistical representativeness of the three-towers network

Figure 7 shows the effect size time series, based on the daily sums, for the comparison of *FC* and *LE* across the AF and between AF and MC. In the case of the AF evaluation for *FC*, $d_{\text{AF-Fc}}$ values were mostly in the range -0.7 to -1.0 in most periods. After May in both years, values started to reduce progressively, reaching -1.3. The values were lowest (more negative) of around -1.4 in July 2024. With respect to the comparison between AF and MC for *FC*, the dynamics of $d_{\text{AF-MC-Fc}}$ were similar to the behavior of $d_{\text{AF-Fc}}$, with slight differences. The values were always between 0.5 and 1.5, being especially concentrated in the range 0.8-1.0 in the periods of February to May 2023, winter 2023/24, and March, August and September of 2024. In both summers of 2023 and 2024, $d_{\text{AF-MC-Fc}}$ was larger with values between 1.0 and 1.5. The maximum values were reached in July 2023.

The comparison of *LE* showed different dynamics (Fig. 7). Regarding the evaluation of $d_{\text{AF-LE}}$, the values were very constant at around -1.0 during 2023 and winter 2023/24. In 2024, a higher variability was observed, but reduced magnitudes (less negative) as compared to $d_{\text{AF-Fc}}$. The magnitudes decreased slightly to -0.7 to -0.8 at the end of the campaign, during the months of June, July and September 2024, while August showed again values close to -1.0. With respect to $d_{\text{AF-MC-LE}}$, values were in the range 0.7-1.1 most of the time, with a slightly higher variation from March to July 2023. During the 2024 growing season, the variability was lower. In general, $d_{\text{AF-MC-LE}}$ varied less than $d_{\text{AF-MC-Fc}}$ during the whole campaign.

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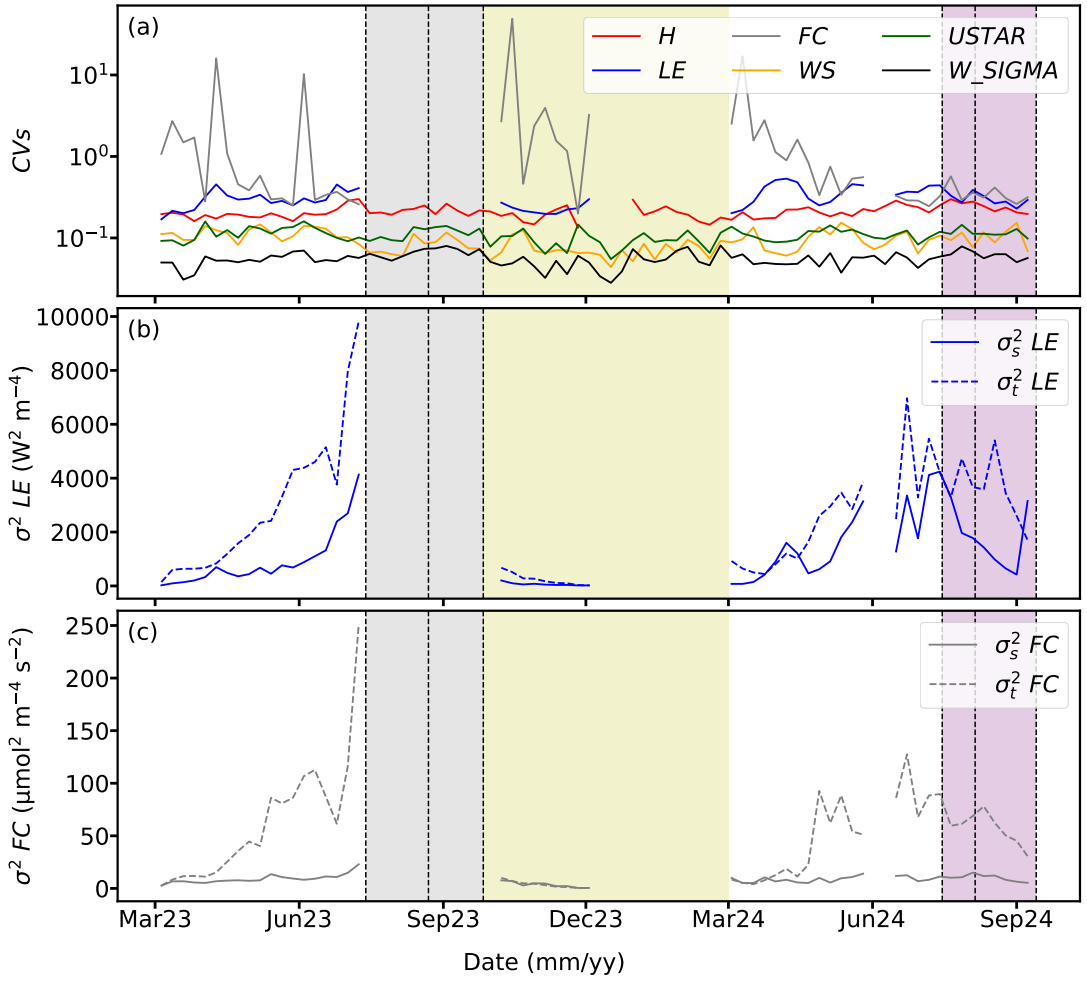

Figure 6. (a) Coefficients of variation (CVs), calculated after Oren et al. (2006), for *FC*, *LE* and *H*, $\bar{u}$, *USTAR*, and *W_SIGMA* (logarithmic scale); (b) spatial (σ_s *LE*) and temporal (σ_t *LE*) variance for *LE*; (c) spatial (σ_s *FC*) and temporal (σ_t *FC*) variance for *FC*. The plotted values are weekly means calculated at 30-min temporal resolution from the flux time series.Vertical dashed lines represent, from left to right, the harvest dates of the crops in 2023, for rapeseed (13 July 2023), barley (22 August 2023) and corn (26 September 2023); and in 2024, for rapeseed (15 July 2024), barley (5 August 2024) and corn (13 September 2024). Dashed areas correspond to the 2023 harvest period (grey), the winter period (yellow) and the 2024 harvest period (purple), for a better comparison with Figure 5. Due to the two very long gaps in AF1 and AF3 (see Fig. 4), plus some shorter gaps, there were no data corresponding to the harvest period in 2023 for *FC* or *LE* and only few weeks of data in the winter period. Note the logarithmic scale in panel (a), introduced due to the large magnitude of some of the *CVs* of *FC* for visualization purposes.

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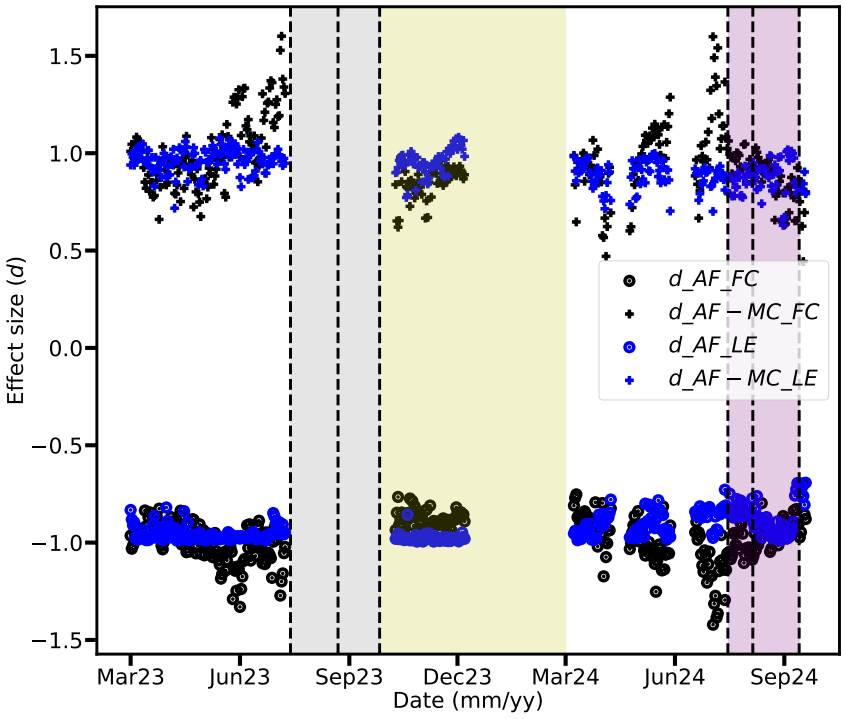

Figure 7. Time series of the effect size (*d*) for *FC* and *LE*. *d* was calculated according to Eq. 3, based on the daily sums of *FC* and *LE*. Black filled circles represent the comparison between AF1 and the average of the three stations at the AF (AF1, AF2 and AF3) for the *FC*. Black crosses represent the comparison between the average of the three stations at the AF (AF1, AF2 and AF3) and the MC station for *FC*. Blue filled circles represent the comparison between AF1 and the average of the three stations at the AF (AF1, AF2 and AF3) for *LE*. Blue crosses represent the comparison between the average of the three stations at the AF (AF1, AF2 and AF3) and the MC station for *LE*. Vertical dashed lines represent, from left to right, the harvest dates of the crops in 2023, for rapeseed (13 July 2023), barley (22 August 2023) and corn (26 September 2023); and in 2024, for rapeseed (15 July 2024), barley (5 August 2024) and corn (13 September 2024). Dashed areas correspond to the 2023 harvest period (grey), the winter period (yellow) and the 2024 harvest period (purple), as in Figure 6.

4 Discussion

4.1 Spatial and temporal variability of *FC* and *LE* above the AF system

Using three distributed EC stations over the same AF system, a small spatial variability in meteorological parameters was found, but the spatial variability in CO_2 and energy fluxes was larger. The AF site is not very large (19.1 ha) compared to the median farm size of 29.4 ha in Lower Saxony (Jänicke et al., 2022). The effect of several rows of trees perpendicular to the wind can significantly influence the microclimatic conditions of different areas in the agricultural field, compared to open croplands (Kanzler et al., 2019). However, the meteorological conditions measured at the three towers were very similar, probably due to the fact that all stations were located within the tree strips, and not in between or outside them and due to the small size

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of the AF field. The observed variability in *FC* and *LE* should therefore not be attributed to the meteorological drivers, but to the differences in the footprint areas of the three stations. The footprint climatology of the stations partially overlapped (Fig. 3), but the most intense flux contributions originated from an area around the towers. Differences in crop development and management practices could explain most of the spatial variability of the observed fluxes across the three towers throughout the campaign, because of the different crops that were sown in between the tree strips (spatial variability) and the different crop distribution from 2023 to 2024 (temporal variability) (Fig. 1).

The higher spatial variability in turbulent fluxes compared to other turbulence and wind parameters (Fig. 5), especially for *FC* and *LE*, was found also in the studies of Katul et al. (1999) and Oren et al. (2006). This can be explained by the control of stomatal and boundary layer conductances, as well as the more complex nature of sources and sinks for CO_2 and H_2O fluxes (Katul et al., 1999). The larger *CVs* of *FC* at the eastern wind sectors (Fig. 5) during all evaluated periods relate directly to the footprint climatology differences, because the footprints were the most different at the eastern side of the three AF stations (Section 3.2). There was still a relatively large variability in *LE* and *FC*, due to the much smaller size of the footprint climatology area, which led to less overlapping footprints from the three stations (Fig. 5 and 3), therefore higher. The harvest events in 2024 did not seem to affect the *CVs* (Figs. 5 and 6a) compared to the 2024 growing season.

The larger temporal variance, compared to spatial variance, for both *FC* and *LE*, could be explained by the dominance of seasonal and diel patterns of these variables. Spatial variability was important (Sections 3.4.1 and 3.4.2), but it had less relevance than the larger seasonal and diurnal variability. Nonetheless, σ_t was similar to σ_s in winter for both *LE* and *FC*, which can be attributed to the dormant state of the ecosystem, leading to small diel variations and therefore small temporal variations. In summer 2024, for *LE*, σ_s was similar to σ_t, due to the less overlapping areas caused by a reduction in the footprints (Fig. 3) compared to the 2023 growing season, but also to the absence of a fully developed crop in the eastern part of the field, because of the bad growth of rapeseed during this season. This caused weaker *LE* measured especially at tower AF1 and led to a lower spatial variation.

Compared to similar approaches in the literature, Peltola et al. (2015) found a paired temporal and spatial variability in CH_4 fluxes measured at three different heights at a tall EC tower and two additional EC stations over an agricultural landscape. Hollinger et al. (2004) measured fluxes using two towers with non-overlapping footprints in a forest and found that the temporal variability was larger, but the spatial disagreement in *FC* was not negligible, despite the apparent homogeneity of the ecosystem studied. Rannik et al. (2006) also compared *FC* measured from two nearby towers over the same ecosystem, with partially overlapping footprints, and found relevant systematic errors in the daytime fluxes attributed to the variability in the turbulent flow field caused by the complexity of the terrain. These systematic differences were important to attribute long-term uncertainties in the ecosystem C uptake, such as it would happen in the complex AF site of the present study. Davis et al. (2010) investigated heterogeneity in *FC* above an arable land and demonstrated the large imprint of spatial heterogeneity in annual balances of C. Moreover, Soegaard (2003) quantified the annual carbon budget of an agricultural landscape by combining footprint-weighted fluxes and spatial variability in different crops, demonstrating the large potential of spatial heterogeneity to bias annual estimates of fluxes. In the present study, the influence of the different land covers around the towers was detectable, except during the winter period, both for *FC* and *LE*, but the differences were smaller than expected for different crops with

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clearly different seasonality. This could be explained by the partially overlapping footprints, as already mentioned, but also to the buffering effect caused by the presence of the trees. Trees were assumed to behave similarly across the AF, so their similar CO_2 and water fluxes attenuated the potentially largest differences in turbulent fluxes that would be expected among the crops without trees.

The weekly cumulative sums of *FC* and *ET*across the campaign (Fig. 4) can be explained by the differences in the phenological state of the crops and the management around the towers. These differences can be directly connected to the previously explained behavior of the *CVs* and partitioning of the variance. Spatially replicated experiments demonstrated the potential to more accurately estimate the uncertainty in turbulent fluxes, such as applied in Hollinger and Richardson (2005). However, the footprint areas of the three stations at the AF in the present study were not homogeneous and they only partially overlap, which means that in practice it is difficult to assess the uncertainty for paired observations as in Hollinger and Richardson (2005). Conversely, the deployment of three towers provided a more comprehensive dataset compared to the single tower approach, and the uncertainty of the AF as a whole could be estimated by calculating the standard deviation of the measured fluxes across the three towers. However, the selection of the exact site of the towers in the present study might not have been optimal (Chen et al., 2011), since footprints were partially overlapping (Fig. 1 and 3). This was due to logistic constraints that precluded the selection of any other location within the AF site, such as in the southernmost part of the field. On the other hand, the purpose of the study was to investigate small scale variability in the highly heterogeneous AF, a goal that was generally accomplished.

Assuming that the trees were growing in a similar way across the whole AF site, the observed variations in weekly sums of carbon and *ET* (Fig. 4) can be attributed to the developmental differences among the crops cultivated around the stations. Specifically, the earlier development of rapeseed in 2023 led to an initial carbon uptake at AF3, because the main footprint covered rapeseed (Fig. 3a). This aligned with the larger *CVs* of *FC* in the eastern side of the field (Fig. 5), and during March and April 2023 (Fig. 6a). However, the earlier growth of rapeseed did not result in increased *ET* in AF3 (Fig. 4b), leading to comparable *CVs* of *LE* for all wind sectors (Fig. 5). This is because rapeseed can maintain a relatively large carbon uptake while using limited water resources (Najibnia et al., 2014). The subsequent development of corn and barley led to similar weekly uptakes of carbon at AF1 and AF2, but a larger *ET* at AF1, leading to a decrease in the *CVs* of *FC* and a modest increase in the *CVs* of *LE*. Besides the partially overlapping footprint (Fig. 3), the reason behind is the different water use efficiency among barley and corn, being lower for barley and therefore explaining similar carbon uptake as corn at a higher *ET* (see e.g. Pohanková et al., 2018). After the short drought in May-June, which affected all three stations by reducing both carbon uptake and *ET* due to water stress, weekly carbon uptakes of AF1 and AF2 and weekly *ET* sums were larger than for AF3 until the harvest period. This can be attributed to corn and barley being less present in the footprint area of AF3 (Fig. 3a). Corn and barley exhibited a more intense physiological activity, immersed in the growing season, while rapeseed was likely at its maturity stage.

The harvest of rapeseed in 2023 had a negligible effect on the carbon uptake of AF1 and AF2 much, but seemed to have an effect on *ET*, which reduced for both stations. This can be attributed to a period of several precipitation events, low *TA* and *VPD* (Fig. 2) which reduced both physiological activity and atmospheric water demand. The harvest of barley and corn reduced the carbon uptake and *ET*. Especially the corn harvest had a large impact because it was the main crop in the footprints of AF1 and

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AF2 (Fig. 3b). After the harvest period, the slightly larger difference between the three stations may be an effect of the larger gap-filling uncertainty due to the longer gaps and agrees with an enhanced spatial variance compared to the temporal one (Fig. 6b and c).

In 2024, the very dry spring (Table 2) did not affect weekly sums of *ET* since they were similar to the previous year, but affected weekly sums of *FC*, visible by lower fluxes compared to 2023. In 2024, there was no earlier development of the rapeseed as it occurred in 2023, due to the very wet winter conditions. The variability in *ET* was larger than in 2023 due to less overlapping footprints and due to the difference in rapeseed growth (Fig. 3d). The larger carbon uptake at AF2 as well as larger *ET* (Fig. 4) during all the 2024 growing season was due to the influence of barley and partially corn, while AF1 detected only part of the barley field and the non-well developed rapeseed (Fig. 3c). Carbon uptake and *ET* were smaller at AF3 because corn developed later, but reached similar values as AF1 once corn started to grow. After the harvest of the rapeseed, AF1 and AF2 reduced both their carbon uptake and *ET*, with AF2 turning into a carbon source. The effect was more intense for AF2, explained not by the footprint of AF2 in the rapeseed field (Fig. 3e), but rather by the fact that barley had reached the maturity already and there was a strong ecosystem respiration enhanced due to the rainy and wet conditions, as well as a reduced ET. Carbon uptake and *ET* release at AF3, on the other hand, did not detect the effect of the rapeseed harvest, because AF3 was not measuring the corresponding portion of the field (Fig. 3e). AF3 kept a large weekly carbon uptake and similar *ET* due to the presence of the corn in its footprint area (Fig. 3). Afterwards, the harvest of barley reduced the uptake of AF1, turning it onto a carbon source, and of AF3 as well as *ET* due to the footprint covered by both stations (Fig. 3e). *FC* was progressively more positive at all three towers until it reached carbon emissions also for AF1 and AF3 around the harvest of the corn, which was the main crop in the footprint area of AF3.

4.2 Differences in *FC* and *ET* between AF and MC systems

The AF site had typically lower air temperature and higher *RH* than the MC (Fig. 2), because the trees at the AF act as a buffer to keep cooler air temperatures and cooler soil resulting in a larger RH. This is pointed out in a review by Quandt et al. (2023). The authors stated that during drought events and under drier and warmer climatic conditions, as projected in future climate scenarios, the buffer effect of the trees in keeping cooler temperatures and more humid air could potentially be enhanced.

C uptake and *ET* release were enhanced at the AF at the beginning of the 2023 growing season, because of the earlier development of the trees and the rapeseed, both present in the footprint of all three AF stations (Fig. 1 and 3a). The MC station was measuring mostly the corn field (Fig. 3a). Corn is a crop with a later development compared to barley or rapeseed (Lokupitiya et al., 2009; Soegaard, 2003), but typically very productive (Hollinger et al., 2005; Lokupitiya et al., 2016). Therefore, carbon uptake was larger at the MC during most of the 2023 growing season after corn started its stronger development phase, later than rapeseed and barley. *ET*, on the other hand, was similar to AF2, indicating a larger water use efficiency. In our study, the short dry period in May/June 2023 occurred when the corn was at its highest development stage. Therefore the corn was not affected as strongly as the rapeseed and barley, which was in a more advanced development stage. In general the whole campaign took place during very wet conditions, which potentially enhanced the ecosystem respiration due to the fostered soil organic matter decomposition, with larger litter amounts at the AF. This, together with a larger respiration from the trees, can

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explain why AF2, although being surrounded by corn, did not show similar carbon uptake, as the other tower within the AF system.

During the 2023 harvest period, the footprint of the MC station covered only corn, not rapeseed (Fig. 3b). Corn was still growing during July and August of 2023 at the MC, which explains why at the MC tower very large carbon uptake and *ET* release was retained, while AF2 and AF1 showed reduced fluxes. In winter carbon and *ET* weekly sums were very similar, due to the dormant state of the ecosystems as mentioned in the previous section. However, fluxes were very small in magnitude and it is difficult to attribute clear differences between sites.

During the 2024 growing season, carbon uptake at the AF was similar to the MC, which is different to 2023. The magnitude of the carbon uptake at all stations was lower than in 2023. In 2024, barley was grown in the main footprint area of the MC (Fig. 3d), as well as a portion of the rapeseed field, which did not grow well this year. In general, barley is a crop with less intense physiological activity than corn (Pohanková et al., 2018), which explains the smaller differences to the AF stations. Also, the meteorological conditions were very wet in winter with a dry spring. During the harvest period in 2024 the carbon uptake and *ET* reduced more sharply at the MC than at the AF, after the harvest of the rapeseed, because of its partially contributing footprint (Fig. 3e). The reduction was more pronounced after the harvest of the barley, which contributed the most to the main footprint covered by the station.

Trees within the AF buffer all the effects of management practices of the crops in between tree strips, since their eco-physiological activity follows a clear seasonality, similar to forests in comparable climates (Anthoni et al., 2004), and might partially mask the effect of management in certain portions of the field. Since all three towers at the AF cover similar footprint areas and the western side of the stations was always predominant in the footprint climatology, only large changes in the source/sink behavior of the field around them can be detected. During the 2023 growing season the footprint area contributing to the fluxes (Fig. 3) covered corn, which was harvested at the end of September, so just a small effect on the fluxes was observed after the harvest of the barley at the end of August (Fig. 4). In 2024, on the other hand, the effect of harvest on a reduction in carbon and *ET* was more pronounced, because of the earlier development of barley compared to corn.

By contrast, in the paper by Callejas-Rodelas et al. (2024), the authors compared 4 months of measurements and both carbon uptake and *ET* were enhanced at the AF during a measurement campaign from April to August 2022, conducted at the same site. Similar results were obtained by van Ramshorst et al. (2024), who showed an enhanced carbon uptake and *ET* release at a grassland AF system compared to a MC grassland. However, they only measured in summer, with enhanced physiological activity of grasses and trees. The dominant species in the footprint area of the MC stations were rapeseed in Callejas-Rodelas et al. (2024) and grass in van Ramshorst et al. (2024). These species are known to have a lower physiological activity as compared to corn (Lokupitiya et al., 2009; Zhang et al., 2014).

4.3 Effect size and spatial representativeness of the distributed network

The effect size *d* was in most cases between 0.7 and 1.3 (Fig. 7), indicating differences between the evaluated daily sums of *FC* and *ET* on the order of the pooled standard deviation, therefore leading to a relatively large effect size (Abdaki et al., 2024). The lower variability of *d* for *LE* than for *FC* across the whole measurement campaign relates directly to the findings discussed

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in previous sections, e.g. the *FC* had the largest spatial variability most of the time. Larger spatial variation in *FC* influences daily sums which were later on used to calculate *d*. The increase in spatial variability of *FC*, which was more pronounced than the change in spatial variability of *LE*, explained the increase in *d* during the growing seasons of 2023 and 2024, for both the comparison of AF vs. MC and the comparison of the three stations at the AF.

The larger *d* values calculated for the comparison between AF and MC than for the comparison between multiple towers at the AF (Fig. 7) can be interpreted as an effect of the larger ecosystem differences between AF and MC than within the AF. The differences within the AF system were a result of the small scale heterogeneity of the AF system. Because differences in means were larger than differences in the standard deviation, *d* can be interpreted such that a network of three EC towers above the AF allowed a better understanding of the effect of management and smaller scale disturbances inside the AF system. However, at the ecosystem scale comparison, AF vs. MC, the traditional approach with only one EC tower could still be sufficient to detect differences between the two ecosystems.

Low values of *d* were typically attained during winter months. Then fluxes were small (Fig. 4), which lead to a decrease of both the temporal and spatial variability (Fig. 5 and 6). The small effect of heterogeneity across the sites was likely masked by the larger noise in the data, the longer and more frequent gaps and the larger uncertainty in the gap-filled fluxes (Section 2.3.3).

Several studies addressed spatial representativeness of fluxes and the footprint climatology. These studies focused either in studying RE (Hollinger and Richardson, 2005), in separating ecosystem structure and sampling errors in the spatial variability of fluxes (Oren et al., 2006), in disentangling temporal and spatial variability of fluxes using a single tower approach and footprint modeling (Levy et al., 2020; Soegaard, 2003), in the representativeness of single point measurements at the pixel scale for regional to global scale models (Chasmer et al., 2009; Chen et al., 2009; Wang et al., 2016; Ran et al., 2016), or in studying the effect of diverse meteorological conditions in the footprint climatology and canopy structure (Abdaki et al., 2024). To the best of our knowledge, the study of Cunliffe et al. (2022) was the only one deploying several LC-EC setups, similar to the ones used in our study, and one additional conventional EC setup, to quantify the impact of landscape heterogeneity on turbulent fluxes. They studied a dryland site with very low flux magnitudes, different from our site, and obtained a useful agreement between different LC-EC and the conventional EC setups. The differences between setups were attributed to the heterogeneity of the ecosystem, covered by different bushes and grass species, but a less detailed analysis on spatial and temporal variability of fluxes was performed.

In the EC community, EC replicates are not common (Hill et al., 2017; Stoy et al., 2023). Therefore the effect size of either means or sums of fluxes is typically not estimated. Hill et al. (2017), as the first paper showing the potential of LC-EC setups in increasing spatial replication in EC studies, estimated the effect size through the comparison of the average carbon sequestration and the standard deviation of the cumulative sums, for ideal and non-ideal FLUXNET sites (Baldocchi, 2014). In the present study, the effect size was calculated in a similar way, but based on daily sums and pooled standard deviations (errors) of the 30-min time series. The concept in Hill et al. (2017), therefore, was different, since the measurement errors tend to decrease relative to the aggregation period when cumulative sums are calculated (Moncrieff et al., 1996). Their calculated standard deviation was based on the uncertainty in cumulative sums of half-hourly carbon fluxes and not on time series of higher temporal resolution, e.g. 30 minutes. These time series are commonly characterised by higher variability. Due to this

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difference in the time scale used in the analysis, their findings on how many towers are needed to properly sample an ecosystem cannot be compared to ours.

In general, there is still an ongoing discussion on how much the landscape heterogeneity affect balances of CO_2 and H_2O measured by single EC towers. The LC-EC setups could help to bridge the gap of low spatial replication across such heterogeneous sites by allowing the installation of multiple setups due to their reduced cost. This could be complementary to other methodologies developed, to understand the effect of spatial heterogeneity on fluxes measured from single towers, such as in Levy et al. (2020) or Griebel et al. (2016), or measured with several conventional EC setups (Soegaard, 2003; Hollinger et al., 2004; Katul et al., 1999; Oren et al., 2006).

4.4 Footprint modeling and turbulence dynamics at the AF site

The footprint model employed in the present study (Kljun et al., 2015) allowed to understand where the source/sink areas of CO_2 and H_2O were located, at a basic level. The implementation of the aerodynamic canopy height after Chu et al. (2018) helped to increase the accuracy of the footprint model to cope with the heterogeneity of the AF site. The three towers at the AF shared a similar footprint climatology (Fig. 3), if the 80 or 90 % area of the contributions to the footprint were considered. However, the most intense footprint values, which indicate the largest contribution to the measured fluxes, concentrated in smaller areas around the towers (Kljun et al., 2002). Therefore, most of the observed variability in the development of *FC* and *LE* can be attributed to the heterogeneity in the land cover around the stations, with different crops at different phenological stages during the campaign. The smaller variability of fluxes in winter can be attributed to the absence of crops and the latency state of the trees. One of the key features of the three towers network is that it allowed to disentangle the effect of management activities, e.g. crop harvest, therefore providing interesting insights in the smaller scale features caused by the alternating structure of the AF. The division of data in wind direction bins, as done in e.g. Kutsch et al. (2005), to address the spatial variability of fluxes, turbulence parameters and both spatial and temporal components of the variance, complemented the information provided by the footprint maps.

Canopy height influences the wind speed and the dynamics of turbulence within the AF (Markwitz, 2021), and therefore the footprint covered by the towers (Kljun et al., 2015). The footprint area, therefore, is very sensitive to a steep change in the canopy elements. The increase in tree height from 2023 to 2024 led to a reduction of the footprint size and less overlap between them (Fig. 3). This, together with differences in crop development and meteorological conditions, contributed to an increase in the *CVs* of *FC* and *LE*, and showed the relevance of the spatial components of the variance for both flux variables.

The parameterization implemented in the model of Kljun et al. (2015) does not allow to consider the effect of spatial heterogeneity as represented by roughness length and *USTAR*, which are the basic parameters for an accurate footprint estimation. This is the main source of uncertainty for the footprint modeling in this study. Due to the structure of the AF, it is likely that the footprint model overestimates the footprint area, attributing the sources and sinks to areas further beyond what really contributes to the flux. In addition, footprint estimates are sensitive to the vertical distribution of sources and sinks along the canopy and to the time air parcels expend within it (Launiainen et al., 2007; Prabha et al., 2008). This is likely happening at this AF site, due to the structure of the tree rows. A more advanced modeling approach combining, firstly, information on flow

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dynamics and spatial structure, with e.g. Large Eddy Simulations, similar as performed in Markwitz (2021) and van Ramshorst et al. (2022), and secondly, footprint modeling by applying the procedure described in Göckede et al. (2006) to account for the spatial heterogeneity in roughness length and friction velocity, would provide more accurate footprint estimates. In addition, if the footprint climatology were aggregated based on weighted footprints, as in Chen et al. (2009), the sources and sinks of carbon and water vapour across the site would be characterized in more detail.

The structure of the AF system influences the flow dynamics and therefore affects the turbulence measurements. An Internal Boundary Layer develops across the field, due to the obstacle represented by the edge of the tree rows (Markwitz, 2021). In the roughness sublayer, tree rows induce persistent waves behind them, thereby enhancing the differences in the turbulence-related parameters *WS*, *USTAR*, and *W_SIGMA*. However, the dissimilarities were not larger than for the *LE* or *FC* (Fig. 5 and 6), because these were controlled by the very irregular distribution of carbon and water sources/sinks, which had a larger impact than the variability in turbulence statistics. In addition, the canopy structure and the spatial heterogeneity at the AF could potentially lead to a large storage of carbon and energy. The storage terms were not accounted for, although they might be relevant at the edges between crops and trees and within the tree rows, which are very dense and therefore less coupled with the atmosphere. All of it might influence advection in horizontal and vertical directions (Mammarella et al., 2007; Aubinet et al., 2010; Feigenwinter et al., 2008), however, it was not possible to account for those terms with the current datasets.

Furthermore, the sensor location bias, defined as the uncertainty caused by measuring only at one point above a heterogeneous site, also depends on the stability conditions (Chen et al., 2011). Under more unstable conditions, the footprint size would decrease and the location bias of each of the towers would increase, better justifying the use of several EC towers to better sample the whole ecosystem. A more detailed study on stability regimes, footprint size and spatial variability of fluxes would inform on this feature, but it was not performed in this study due to the limited data availability and the difficulty in gap-filling turbulence parameters needed to classify stability regimes, such as Obukhov length. With longer time series and more complete turbulence and footprint information, some of the previously detailed shortness of this study could be addressed.

4.4.1 Errors in *FC*, *LE* and *H*

The errors that affect the flux calculation are difficult to disentangle as they propagate through the whole processing routine, from the raw data measurements until the final flux corrections. Therefore, the uncertainty in the use of LC-EC was assigned, for the measured fluxes, based on the previous inter-comparison studies of Callejas-Rodelas et al. (2024) and van Ramshorst et al. (2024), as detailed in Section 2.5. This procedure is similar to the approach applied in Peltola et al. (2015), where they used a previous instrument cross-comparison campaign (Peltola et al., 2014) to assign instrumental uncertainty to the setups they deployed. However, the uncertainty in the use of LC-EC, defined in relation to conventional EC, was obtained during a specific campaign and under specific site conditions, hence there might be a bias in the LC-EC error attribution. Additionally, the uncertainty in the gap-filled fluxes was calculated as explained in Section 2.5, by assigning individual errors to the 30-min fluxes, which can then be propagated when performing the daily cumulative sums. This was detailed as a first attempt on how to easily evaluate errors and propagate them through cumulative sums whenever a new EC setup has been compared to conventional EC setups and balances of carbon or *ET* are calculated using gap-filled data.

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Focusing on the uncertainty in the gap-filling procedure, the presence of very long gaps, especially affecting tower 3 at the AF, would have had largely increased the uncertainty in the data (Lucas-Moffat et al., 2022) if all the time series were filled. Therefore, only measured data and gaps shorter than two weeks were used, which did not allow for a complete spatial heterogeneity study, mainly because of the missing data for AF3 during the harvest period 2023. Using the combination of both REddyProc for very short gaps and the XGBoost model for long gaps was the optimal solution found for this study, similar as done in Winck et al. (2023), and it allowed to assign individual errors to each 30-min flux, as explained in Section 2.5. Additionally, using more strict filtering criteria, such as a higher *USTAR*-threshold or a lower quality flag, would on the one hand provide data of better quality, but would on the other hand increase the uncertainty due to gap-filling of a higher number of gaps.

We used *TA*, *SW_IN* and *VPD* as predictors for gap-filling, which are generally recognized as the main drivers of CO_2 and H_2O fluxes (Vekuri et al., 2023; Wutzler et al., 2018). *WS* was used because of its influence on the development of turbulence and on the spatial information carried by eddies, especially above a very rough surface such as the AF and wind direction was selected to account for the spatial heterogeneity across the different measurement locations of the towers (Richardson et al., 2006). Other meteorological variables were either less relevant for the analysis, such as atmospheric pressure, or more complex to gap-fill, such as net radiation.

Random error (RE) was not considered directly in this analysis, however, it was partially accounted for indirectly when calculating standard deviations of the time series. In addition, RE decreases with increasing length of the datasets (Moncrieff et al., 1996), therefore it becomes less relevant for longer term assessment of carbon and *ET* balances. Also, the approach implemented in e.g. Richardson et al. (2006) and Hollinger and Richardson (2005) treated RE either with similar conditions in consecutive days, or with the approach of two independent towers, but in the present study the towers had partially overlapping footprints and different land covers around them, hence, cannot be considered as independent.

5 Conclusions

This study shows for the first time 1.5 years of measurements from a distributed network of three EC towers above a temperate heterogeneous agroforestry system and a comparison to an adjacent monocropping agricultural system. The use of three EC stations allowed to capture the spatial and temporal variability across the site, which especially affected *FC*. The main differences were attributed to the different developmental stages of the crops across seasons, with larger disturbances of *FC* and *LE* after harvest events. Because of the high degree of spatial heterogeneity, it was important to have a broader footprint coverage to capture small scale differences at the AF. Furthermore, binning the data in wind direction sectors and weeks allowed us to have a detailed picture on the temporal and spatial components of the variance and the coefficients of spatial variation, given that the differences between the different stations were small enough to be masked if a less resolved analysis had been performed.

Secondly, this study included a complex gap-filling procedure which complemented previously published recommendations on how to work with lower-cost EC data. The datasets gathered during the campaign and the processing scheme added value

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to the data collection of the project, from previous years of measurements, above several agroforestry and monocropping sites. Future research will address in more detail the contrast between different agroforestry and monocropping sites, with more years of data and under a broader range of meteorological conditions.

Finally, the footprint coverage required to capture the spatial heterogeneity across the AF, and within the AF and MC, was improved thanks to the use of lower-cost EC setups. We proved satisfactorily the hypothesis that the degree of uncertainty introduced by the use of slower-response gas analyzers for CO_2 and H_2O was counteracted by the better representation of all processes occurring within the AF system. Therefore, we recommend the installation of multiple EC setups, including lower-cost setups, anytime when the degree of heterogeneity of an ecosystem is large. An added value in future studies would be to compare overlapping and non-overlapping measurements in terms of footprint.

Code and data availability. Data corresponding to this publication, as well as the codes to analyze results and prepare the figures for this publication are available at Zenodo, https://doi.org/10.5281/zenodo.14855288 (Callejas-Rodelas et al., 2025).

Author contributions. JACR performed the measurements, data analysis and manuscript writing. AK and CM wrote the project proposal, contributed to data analysis and manuscript editing. IM, TV and OP contributed to data analysis and manuscript editing.

Competing interests. 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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