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Validation of theoretical footprint models using experimental measurements of turbulent fluxes over maize fields in Po Valley

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Abstract Representative source area of turbulent fluxes measured by eddy covariance stations is an important issue which has not yet been fully investigated. In particular, the validation of the analytical footprint models is generally based on the comparison with Lagrangian model predictions, while experimental results are not largely diffused in literature. In this work, spatial distribution of carbon dioxide, latent and sensible heat fluxes across two different maize fields in Po Valley, is used to validate two theoretical footprint models. Experiments are performed in two totally different scenarios at bare and vegetated soils using two eddy covariance systems: one fixed station which is located about in the middle of the field and a mobile station which is placed at various distances from the field edge to investigate the horizontal variation of the vertical scalar fluxes. The first objective of this work is to provide detailed information about the spatial distribution of turbulent fluxes across Po Valley characteristic fields at bare and vegetated soils, highlighting peculiarities and uniqueness. The second objective consists in the comparison between mobile measurements of carbon dioxide, latent and sensible heat fluxes and the predictions of two analytical footprint models widely used in literature. Contemporaneously, the latter objective will permit to understand what is the best footprint model which, under typical Po Valley atmospheric turbulent conditions, describes a representative source area compatible with the field dimensions and the turbulent flux distributions. The results show that both models are in good agreement with experimental measurements. The results also show that the spatial distribution of turbulent fluxes is strongly influenced by the presence of vegetation in the field. Moreover, the representative source area is different for different scalar fluxes. Another result is about 10:1 fetch-to-height obtained for both field situations.

Keywords Eddy covariance · Footprint · Experimental measurements · Turbulent fluxes

Introduction

Eddy covariance measurements are widely applied to continuously monitor turbulent exchange of mass and energy at the vegetation–atmosphere interface (Aubinet et al. 2000). Moreover, the eddy covariance method is one of the most accurate and direct approaches available in literature to measure turbulent exchanges over field areas with different sizes (Baldocchi et al. 2001). Its field of applicability could include not only agricultural and forest matters (Foken 2008), but also environmental quality for public health (Castaldelli et al. 2013).

The eddy covariance method is a statistical tool which, starting from high-frequency data of wind components and scalar densities, provides estimates of latent, sensible heat and carbon dioxide turbulent fluxes (Baldocchi 2003). The fluxes are calculated as a covariance among turbulent components of vertical wind velocity and scalar concentration (vapor, air temperature or carbon dioxide). The main micrometeorological instruments which give the name to the eddy covariance technique are the tridimensional sonic anemometer and gas analyzer, respectively.

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The reliability of flux measurements depends on certain theoretical assumptions of the eddy covariance technique (Kaimal and Finnigan 1994; Foken and Wichura 1996), the most important of which are horizontal homogeneity, stationarity and mean vertical wind speed equal to zero during the averaging period. Eddy covariance method has been used in micrometeorology for over 30 years, and now, modern instruments and software make this method easily available and widely widespread in different research fields, such as ecology, hydrology, environmental and industrial monitoring (Baldocchi et al. 1988; Papale et al. 2006).

The proliferation of eddy covariance flux systems in a variety of conditions and ecosystems, often violating some of the theoretical requirements of the methodology, has created an increasing interest in footprint analysis (Schmid 1997; Rannik et al. 2000). Schuepp et al. (1990) specify the term 'footprint' as the relative contribution from each element of the upwind source area to the measured concentration or vertical flux. It can be interpreted as the probability that a trace gas, emitted from a given elemental source, reaches the measurement point. As explained in Schmid (2002), the footprint of a measurement is the transfer function between the measured value and the set of forces on the surface–atmosphere interface. Formally, this notion is expressed by Eq. 1 which is referred to the work of Pasquill and Smith (1983).

$$\eta(r) = \int_R Q_\eta(r + r')f(r, r')\mathrm{d}r' \tag{1}$$

where η is the measured value at location r, $Q_\eta(r + r')$ is the distribution of source of sink strength in the surface-vegetation volume, and $f(r, r')$ is the footprint or transfer function, depending on r, and on the separation between measurement and forcing, r'. The integration is performed over a domain R.

As described by Vesala et al. (2008), the determination of the footprint function is not a straightforward task and several theoretical approaches have been derived over the previous decades. They can be classified into four categories: (1) analytical models; (2) Lagrangian stochastic particle dispersion models; (3) large eddy simulations; and (4) ensemble-averaged closure models. Additionally, parameterizations of some of these approaches have been developed, simplifying the original algorithms for use in practical applications (e.g., Horst and Weil 1992; Schmid 1994; Hsieh et al. 2000; Kormann and Meixner 2001).

In this work, Hsieh et al. (2000) and Kormann and Meixner (2001) analytical footprint models are taken into account for the experimental comparison with horizontal spatial distributions of turbulent fluxes. These models have been chosen because they are widely used in literature for their large applicability in different stability conditions of the atmosphere and their simple implementation.

The footprint model validation is an important issue which is scarcely quoted in literature. According to Foken and Leclerc (2004), only a few experimental data set are available for validation proposes. Lagrangian dispersion models are tested against dispersion experiments of artificial tracers for different turbulence regimes (Thomson 1987; Kurbanmuradov and Sabelfeld 2000; Kljun et al. 2002; Leclerc et al. 2003). In Hsieh and Katul (2009), Lagrangian stochastic model predictions are widely investigated over four different experimental campaigns from sagebrush to bare soil. To avoid problems of measurements in complex flow fields, as dispersion inside and above high vegetation canopy, Kljun (2004) suggest the validation under ideally controlled conditions that can be reproduced in wind tunnels. Generally, analytical footprint predictions are often evaluated using results of Lagrangian footprint models. Nowadays, only sites with short vegetation and an accurate selection of measured data, according to the quality check criteria by Foken and Wichura (1996), allow the in situ validation of analytical footprint models in "nearly ideal" conditions (Marcolla and Cescatti 2005; Göckede et al. 2005; Van de Boer et al. 2013).

In this work, Baldocchi and Rao (1995) experimental methodology is repeated investigating the horizontal variation of the vertical turbulent fluxes over a bare and vegetated field with the primary objective to validate Hsieh and Kormann analytical footprint models. The experiments are performed by placing a mobile eddy covariance station at various distances from the upwind field edge versus a fixed eddy covariance station located in the middle of the field. The experimental design described in this work is relatively equal to that of Baldocchi and Rao (1995), but the agro-meteorology context is totally different. While Baldocchi and Rao (1995) experiment has been performed only over a potato field, in this work two opposed situations are explored: when the field is covered by maize with a height of about 2.8 m and after harvesting time when in the field the vegetation is absent. Moreover, the turbulent conditions of atmosphere which occur in the Oregon (US) farms (site where Baldocchi and Rao experiment was performed) are totally different to that characteristic of the Po Valley sites in terms of wind velocity, solar radiation and air temperature. Finally, the field shape and dimensions are completely diversified: while in Oregon farms the fields have a circular shape of about 100 Ha; in the Po Valley the plots have a polygonal shape of about 10 Ha.

These peculiarities make these experiments an interesting footprint model validation increasing the literature experimental data sets and addressing this range of experiments over a completely new context characterized by Padana region agro-meteorology conditions.

Theoretical background

Estimation of flux footprint from experimental data is compared with predictions of two crosses—wind integrated and analytical footprint models proposed by Hsieh et al. (2000) (called Hsieh model) and Kormann and Meixner (2001) (called Kormann model). The choice of these footprint models is a compromise between reliability and simplicity, following the suggestion by Foken and Leclerc (2004) on the necessity of easy-to-use footprint models.

Hsieh et al. (2000) model is constituted by a combination of Lagrangian stochastic model results and dimensional analysis. It analytically relates atmospheric stability, measurement height and surface roughness length to obtain an approximated analytical expression which accurately describes the footprint function. The results are organized in non-dimensional groups and related to the input variables by regression analysis. The advantages of this model are evident: the hybrid model can be expressed by a set of explicit algebraic equations, while some of the complexity and skill of the full model is retained through the regression. However, the pitfall of any approximation or parameterization is that its validity is strictly limited to the range of conditions over which it is developed. The applicability of this model is guaranteed for a measurement height which varies up to 20 m, a roughness length included between 0.01 and 0.2 m and a Monin–Obukhov length range which start from −0.1 to 50 m.

Kormann and Meixner (2001) model belongs to the class of the Eulerian analytic flux footprint models which explore several approaches to approximately resolve the advection–diffusion equation. Schuepp et al. (1990) are the first scientists that have taken a purely analytical approach, based on an approximate solution of the diffusion equation given by Calder (1952) for thermally neutral stratification and a constant wind velocity profile. As stated by the authors, it suffers from the restriction to neutral stratification. Their suggestion, to correct the wind velocity in the footprint calculation based on thermal stability, has no mathematical basis. Instead, Kormann and Meixner (2001) model includes parameterizations of power law for wind velocity and eddy diffusivity extending the applicability of their footprint model to the whole atmospheric stability range. However, some model limitations are present, such as its usage in areas where wind velocity and eddy diffusivity profiles are horizontally homogeneous, and at heights where the effects of a finite mixing depth are negligible. In addition, this model assumes that turbulent diffusion in stream-wise direction is small compared to advection, a form of Taylor's hypothesis, and are thus confined to flow situations with relatively small turbulence intensities. As reported in Neftel et al. (2008), for the application of this model a check for the consistency of meteorological conditions has to be performed. If the inputs of a record results in z_m/L values smaller than −3 or >+3, the record has to be ignored. Similarly, records with a ratio between friction velocity and wind velocity >1 should be considered with caution.

The validation of these models through the use of intra-field spatial distribution of turbulent fluxes permits to understand whether Po Valley atmospheric conditions are compatible with the theoretical assumptions which govern the applicability of these models over different operative contexts, identifying the model which is mainly representative of the source areas of the turbulent fluxes measured by eddy covariance stations.

Hsieh model

Hsieh et al. (2000) develops an approximate analytical model to estimate the flux footprint in thermally stratified flows. This is a hybrid approach combining elements from Calder analytical solution (1952) with the results of Thomson's Lagrangian model (1987). In the analysis of their results, they scaled Gash (1986) effective fetch with the Obukhov length and accounted for the effect of stability introducing two similarity parameters D and P, obtaining the Eq. 2.

$$\frac{x}{|L|} = -\frac{1}{k^2 \ln(F/S_0)} D \left(\frac{z_u}{|L|} \right)^P \tag{2}$$

where z_u is a length scale, function of measurement height and surface roughness. k is the Von Karman constant, L the Obukhov length and D and P depends on stability conditions of the atmosphere. F/S_0 is the ratio between scalar flux and source strength always confined between 0 and 1 (Hsieh et al. 2000).

The footprint function is expressed by Eq. 3.

$$f(x, z_m) = \frac{1}{k^2 x^2} D z_u^P |L|^{1-P} e^{\left(\frac{-1}{k^2 x} D z_u^P |L|^{1-P} \right)} \tag{3}$$

Kormann model

The Kormann model is based on a modification of the analytical solution of the advection–diffusion equation of Van Ulden (1978) and Horst and Weil (1992) for power low profiles of the mean wind velocity and the eddy diffusivity. To allow for the analytical treatment, the model assumes homogenous and stationary flow conditions over homogeneous terrain, it represents the vertical turbulent transport as a gradient diffusion process and it considers only advection in along wind direction. Assuming that vertical and crosswind dispersion are independent, the continuity equation reduces to a two-dimensional advection–diffusion equation.

In the Kormann model the footprint function is expressed by Eq. 4.

$$f(x, z_m) = \frac{1}{x\Gamma\left(\frac{1+m}{r}\right)} \left(\frac{\alpha_u z_m^r}{r^2 \alpha_K x}\right)^{\frac{1+m}{r}} \exp\left(-\frac{\alpha_u z_m^r}{r^2 \alpha_K x}\right) \qquad (4)$$

where Γ is the gamma function, r the shape parameter related to the exponents of the power laws as $r = 2 + m - n$ (Van Ulden 1978) and α_u, α_K are proportionality constants determined by fitting the power laws for u ($u = \alpha_u z^m$) and K ($K = \alpha_K z^n$) to Monin–Obukhov similarity theory (Garratt 1993.

Study site, instruments and data

In this paragraph, filed characteristics, instruments necessary to perform the experiments and data corrections are briefly shown.

Site characteristics

The experiments are carried out in two fields destined for maize cultivations at Landriano (Pavia, Italy) and Livraga (Lodi, Italy), respectively. The fields' geographic coordinates are (45.19N, 9.16E, 87 m a.s.l.) and (45.11N, 9.34E, 61 m a.s.l.) for Landriano (field 1) and Livraga (field 2), respectively. The experiments are performed in two different situations: after harvesting time (field 1) and during maximum phenological development of the homogenous maize canopy (about 2.8 m) (field 2). Both fields have a polygonal shape with a flat area of about 10 Ha large. Field 1 is completely surrounded by tall row plants which generate a strong discontinuity with the neighboring fields, while field 2 is surrounded on three sides by other maize fields and in south–west direction an uncultivated zone is present.

Instruments

In the middle of field 1 and 2, fixed eddy covariance towers A1 (for the field 1) and A2 (for the field 2) are installed, and instruments are briefly summarized in the following.

The stations are equipped with the following sensors: one three-dimensional sonic anemometer (Young 81000), which measures sonic temperature and three components of wind speed at the height of 5 m; one open-path gas analyzer (LICOR 7500) which measures water vapor and carbon dioxide concentrations at the height of 5 m too. Both these instruments have been set with an acquisition frequency of 10 Hz, so that the data can be used to calculate latent, sensible heat and carbon dioxide fluxes through eddy covariance method. One net radiometer (CNR1 by Kipp & Zonen) is located on an arm (2.5 m long) attached on the tower at the height of 4 m. One thermo-hygrometer (HMP45C Campbell Scientific) is

located at the height of 3.5 m to measure air humidity and temperature. In the soil, two thermocouples (by ELSI) and a heat flux plate (HFP01 by Hukseflux) are placed at a depth of about 10 cm. Contemporaneously, soil moisture is detected by three humidity probes (CS616 by Campbell Scientific) at different depths. Finally, one rain gauge (AGR100 by Campbell Scientific) is separately located by the tower and, at the height of about 1.5 m, it measures the precipitation intensity.

Data logger CR5000 (Cambpell Scientific) is used to store all data with an averaged time step of 5 min. This averaged time is designed to ensure that the eddy flux measurement system captures most of the flux-containing eddies. This goal was accomplished by sampling anemometer and gas analyzer sensors rapidly and averaging data over a time step of 5 min. This averaged time is also justified by the results obtained by Masseroni et al. (2012) which, studying surface layer turbulent characteristics over the field 1, show that eddy integral lengths in convective situations tend to be stationary for a time larger than of 300 s (about 5 min).

Data corrections

Energy fluxes have been corrected applying the whole range of correction procedures described in many different literature works (Aubinet et al. 2000; Foken et al. 2004; Mauder and Foken 2004). Before calculating fluxes, two groups of correction have been applied: "instrumental" and "physical" corrections. Axis rotation for tilt corrections, spike removal, time lag compensation and detrending represent preliminary processes which have to be directly applied on high-frequency measurements to prepare the data set for fluxes calculation. Spectral information losses as a consequence of measurement system typologies through transfer function characteristics and sampling errors have to be opportunely corrected to compensate the underestimation of the turbulent fluxes (Moncrieff et al. 2004). Moreover, air density fluctuations and air humidity effects on sonic temperature have to be necessarily corrected through Webb et al. (1980) and Van Dijk et al. (2003) procedures, respectively.

These instrumental and physical corrections are automatically implemented in a PEC (Polimi Eddy Covariance) software which has been opportunely developed for this experiment by Corbari et al. (2012). The core of software is based on four substantial points:

1. Data stored into the data logger are sent on specific computer at the Politecnico of Milan using a GSM modem;
2. Automatically, correction algorithms are activated and turbulent fluxes are calculated;

3. Micrometeorological tests are implemented;
4. Turbulent flux and micrometeorological variable graphics are plotted at the web page http://geoserver.iar.polimi.it.

Micrometeorological tests are checked through Mauder and Foken (2004) criteria. Steady state and integral turbulence characteristic tests are the base of the quality control (Foken and Wichura 1996). The quality of fluxes was successively subdivided in three classes from 0 to 2 for good and bed quality, respectively. For both experimental campaigns about 60 % of fluxes measurements was in class 0 while the remainder was equally distributed in class 1 and 2.

Energy flux measurements are proper to the cultivation if eddy covariance station is correctly positioned inside the field. It has to be opportunely located far from the field edges, so that flux measurements do not belong to the neighboring fields. Moreover, anemometer and gas analyzer have to be compatible with the constant flux layer (Savelyev and Taylor 2005). The constant flux layer represents an area where eddy covariance station measurements are constant with height, and it is defined as 10–15 % of internal boundary layer (Baldocchi and Rao 1995). Considering the whole wind direction ranges and analyzing the bare soil unfavorable conditions where aerodynamic roughness for both fields is about 0.041 m, the constant flux layer depth at the towers A1 and A2, calculated through Elliot (1958)'s formula, is about 6 m ensuring that anemometer and gas analyser are included into the constant flux layer. For data processing and model applications, the effective height of the stations taking into account the displacement height equal to 2/3 of vegetation height (Garratt 1993) has been considered. For the field 1 it can be neglected because it is in bare soil, while for the field 2 it has been opportunely implemented in the theoretical footprint models.

Several conditions should be met before eddy correlation method can be applied to measure the mass fluxes over an experimental field. First, the site should be flat. Second, vertical velocity should be measured normal to the surface streamlines. Third, the crop should be homogeneous and sufficiently extensive. Advective sources or sinks should exist for the scalar under investigation (Baldocchi et al. 1988).

A method which is generally used to confirm the reliability of turbulent flux measurements of an eddy covariance station is the energy balance closure (Foken et al. 2006). However, energy balance issue is still unresolved problem and the closures which are present in literature generally vary from 0.5 to 0.98 (Foken 2008). The slope of the regression line between latent and sensible heat turbulent fluxes and ground heat flux against available energy

(net radiation) is performed over fields 1 and 2 and the results are shown in Table 1.

Experimental execution

Experimental campaigns were carried out in two consecutive years: 2011 and 2012, respectively. For the field 1 the experiment was performed over a range of 9 days, from 15th September to 23rd September in the year 2011, while for the field 2 the experiment was performed over a range of 6 days, from 2nd August to 8th August in the year 2012.

In Tables 2 and 3 daily averaged atmospheric parameters measured by the eddy covariance stations over the experimental periods, are shown. The fields are characterized by similar atmospheric turbulent conditions. Weak wind velocities, which are typical in Po Valley, have a range which vary between 0.7 and 3 m s^{-1} at the measurement height of 5 m. Friction velocities varies between 0.08 and 0.26 m s^{-1}. The atmospheric stability parameters, z/L, are in between -0.124 and -0.021 which are values included in the ranges of applicability of the used footprint models as reported in Hsieh and Katul (2009) and Kormann and Meixner (2001). Air temperatures are greater than 20 °C in accordance with the seasonal mean temperatures. Net radiations are >200 W m^{-2} except for 261 and 262 Julian days of the year 2011 when the sky were particularly covered by clouds. The measured fluxes of latent heat vary between 32 and 132 W m^{-2} during 2011, while during the vegetated experiment between 211 and 246 W m^{-2}. The sensible heat flux has an opposite behavior with values ranging between 40 and 175 W m^{-2} for the bare soil conditions and between 38 and 54 W m^{-2}. The carbon dioxide flux has high values in 2012 between -0.14 and -0.45 mg m^{-2} s^{-1} and lower values between -0.08 and -0.19 mg m^{-2} s^{-1}.

To investigate the horizontal variation of turbulent fluxes across the fields, the experiments are performed by placing a mobile eddy covariance station (B1 for the field 1 and B2 for the field 2) at various distances from the field edge, moving it versus the fixed stations (A1 or A2) placed about in the middle of the fields. The mobile stations (Fig. 1a, b) are equipped with a sonic anemometer (Young 81000) and an open-path gas analyzer (LICOR 7500) which are located at the top of an extensible tripod. To verify if mobile station measurements are equal to those obtained by fixed stations, both stations have been placed

Table 1 Energy balance closure for fixed stations A1 and A2

Station	Slope (−)	R^2 (−)	Intercept (W m^{-2})
A1	0.78	0.87	1.15
A2	0.82	0.80	0.98

Table 2 Meteorological conditions measured by A1 eddy covariance station in the year 2011

Julian day	Mean velocity (m s⁻¹)	St. dev (m s⁻¹)	Friction velocity (m s⁻¹)	St. dev. (m s⁻¹)	Air temperature (°C)	St. dev. (°C)	Wind direction (°)	Net radiation (W m⁻²)	St. dev. (W m⁻²)	LE (W m⁻²)	St. dev. (W m⁻²)	H (W m⁻²)	St. dev. (W m⁻²)	F_{co2} (mg m⁻² s⁻¹)	St. dev. (mg m⁻² s⁻¹)	z_m/L (−)
258	0.71	0.21	0.085	0.055	22.2	3.1	212	269	54	104	35	135	42	−0.13	−0.10	−0.083
259	0.79	0.14	0.090	0.021	22.5	2.5	239	236	34	98	29	120	32	−0.11	−0.06	−0.074
260	1.40	0.24	0.16	0.08	21.3	2.7	251	298	42	114	17	154	26	−0.12	−0.03	−0.044
261	1.59	0.18	0.15	0.02	19.1	1.9	197	93	49	32	16	40	34	−0.17	−0.07	−0.125
262	2.84	0.47	0.26	0.01	15.0	1.7	250	186	41	62	20	107	29	−0.10	−0.08	−0.110
263	1.13	0.23	0.12	0.05	15.3	2.3	202	291	32	83	21	175	24	−0.08	−0.05	−0.021
264	1.02	0.50	0.11	0.03	16.9	3.0	225	284	37	120	36	136	38	−0.10	−0.06	−0.114
265	0.79	0.12	0.10	0.04	18.4	2.7	206	292	45	132	41	140	47	−0.09	−0.02	−0.124
266	1.65	0.34	0.23	0.04	21.9	2.0	122	243	31	98	27	130	19	−0.19	−0.07	−0.097

close together for some days before the experiments. Moreover, the clock among two data loggers (CR5000 for B1 and CR23X for B2) has been set to obtain measurements at the same time.

In the field 1, the mobile system (B1) is placed at nominal distances of 0 m (P1_1), 15 m (P2_1) and 65 m (P3_1) from the field edge along a reference line inclined of about 191° with respect to north. In the field 2, the mobile system (B2) is placed at nominal distances of 0 m (P1_2), 14 m (P2_2) and 50 m (P3_2) from the field edge along a reference line inclined of about 236° with respect to north. The fixed towers (A1 and A2) are placed at a distance of the field edge of about 184 and 188 m, respectively (Fig. 2).

Latent, sensible heat and carbon dioxide flux measurements performed by mobile stations are compared with those which are contemporaneously obtained by the fixed stations. Data are considered only when wind directions are included in a range of 40° with respect to the reference line (Fig. 2) and net radiation is >0 W m⁻² (Baldocchi and Rao 1995). For these reasons, in order to attribute measured fluxes to the analyzed sector, the experimental period covers several days.

The experiment's success is guarantee if the field has at least one border site with a strong discontinuity with respect to the examined field typology, and the reference line has to be orientated with respect to this discontinuity zone (Fig. 2). Moreover, the fluxes which come from the upwind zones with respect to the discontinuity border should be quite constant during the whole experimental period. To verify this condition, the mobile station remained on field border for some days before the experimental campaign and the results have shown that daily averaged fluxes do not drastically change from day to day.

Results

In this paragraph the two objectives of this work are analyzed. Experimental measurements are compared with theoretical footprint models, and thus some considerations about footprint model reliabilities are discussed. Moreover, the differences of the representative source area between sensible, latent heat and carbon dioxide are compared.

Flux measurements across the fields

To investigate latent, sensible heat and carbon dioxide spatial distribution across the fields 1 and 2, eddy covariance measurements performed by B1 and B2 mobile stations have been compared with those obtained by A1 and A2 fixed stations. In practice, mobile station measurements have been normalized with fixed station measurements for

Table 3 Meteorological conditions measured by A2 eddy covariance station in the year 2012

Julian day	Mean velocity (m s⁻¹)	St. dev. (m s⁻¹)	Friction velocity (m s⁻¹)	St. dev. (m s⁻¹)	Air temperature (°C)	St. dev. (°C)	Wind direction (°)	Net radiation (W m⁻²)	St. dev. (W m⁻²)	LE (W m⁻²)	St. dev. (W m⁻²)	H (W m⁻²)	St. dev. (W m⁻²)	F_{CO2} (mg m⁻² s⁻¹)	St. dev. (mg m⁻² s⁻¹)	z_m/L (−)
215	1.01	0.29	0.12	0.05	25.7	2.0	230	310	34	246	30	54	20	−0.23	−0.09	−0.063
216	0.93	0.25	0.10	0.04	25.4	2.4	210	301	32	237	34	44	24	−0.15	−0.11	−0.065
217	1.09	0.12	0.15	0.07	24.7	1.8	250	297	31	225	31	50	21	−0.17	−0.14	−0.052
218	1.11	0.18	0.13	0.08	25.0	2.7	239	285	45	211	37	38	18	−0.34	−0.07	−0.092
219	1.81	0.27	0.17	0.07	26.0	1.4	247	307	40	234	33	52	29	−0.45	−0.08	−0.116
220	1.16	0.17	0.16	0.09	25.0	1.6	290	304	38	237	37	51	28	−0.14	−0.05	−0.067

each point P of the experimental design, so that in each point the slope of the regression line between mobile and fixed station measurements is computed during the sampling period at that point. The slope of this regression defines the ratio F/S_A shown in Fig. 3. F represents the mean latent heat (Fig. 3a) or carbon dioxide (Fig. 3b) flux performed by the mobile system for each measurement point, while S_A is the flux performed by the fixed station for the specific lapse of time of the experimental measurements. The quality of the regression, defined by line regression coefficient, is similar for both sites and it varies between 0.8 and 0.95. F/S_A ratio is a parameter which theoretically varies from zero to one, when the mobile station comes from the field border (P1) to P3 positions, respectively. However, at P1 points (both in the field 1 and 2), the upwind fluxes could not be zero and the F/S_A ratio could start with a value higher than zero. Only in one case (field 1) carbon dioxide experimental measurements lead to a regression line with a slope near to zero.

In the fields 1 and 2 the upwind zones have a sensible heat larger than experimental fields, so that the slope of the regression line is certainly greater than one. Therefore, to obtain the F/S_A ratio point distributions as shown in Fig. 4, the experimental regression line has been reflected over the 1:1 line symmetry, so that F/S_A ratios can vary from zero to one. As shown in Fig. 4, sensible heat at the field border is quite different from field 1–2. In bare soil F/S_A ratio is near to 0.4 as similarly shown for latent and carbon dioxide fluxes in Fig. 3a, b, respectively, while when high vegetation is opposed with an uncultivated zone, at the transition point (P1_2), mobile and fixed station measurements are totally different and the F/S_A ratio is about equal to zero.

The results obtained in these experimental campaigns have shown that flux distributions across the fields are in accordance with the prediction described in Baldocchi and Rao (1995)'s work. In the field 2 latent, sensible heat and carbon dioxide fluxes have a quite standard logarithmic behavior, while in the field 1 this trend is verified only for the latent heat. In the field 1, sensible heat is quite influenced by the boundary conditions, given that F/S_A ratio at P2_1 point is very similar to that in P1_1 position, while for carbon dioxide flux a linear growth trend is shown. When the canopy homogeneously covers the field, boundary condition effects can be neglected if the mobile station is beyond from the field edge of about 50 m where the F/S_A ratio values are already constant and closer to 1. For latent and sensible heat fluxes, a similar behavior is also verified in bare soil while the carbon dioxide flux constantly increases across the field.

The experimental results reveal an intra-field spatial distribution extremely different for each turbulent flux, especially in bare soil. While latent heat appears to have a
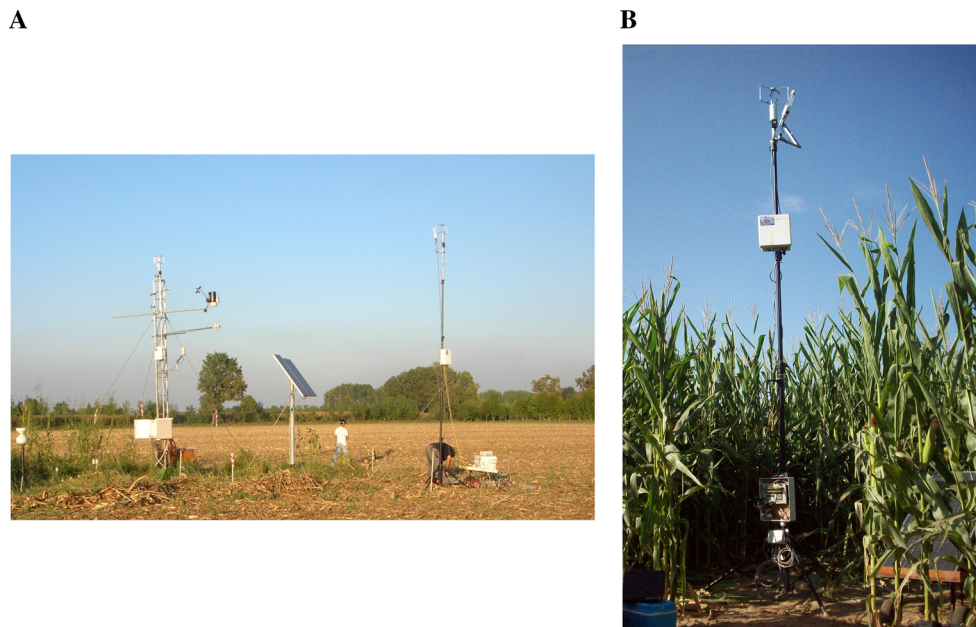
Fig. 1 Mobile stations in the field 1 (**a**) and in Field 2 (**b**). In (**a**) fixed tower A1 is also shown

logarithmic behavior, sensible heat and carbon dioxide fluxes are extremely influenced by the boundary conditions.

In vegetated soil, the boundary condition effects cannot be ignored for distances smaller than 50 m from the field edge. Contrary to the studies of Baldocchi and Rao (1995), Schuepp et al. (1990), Munro and Oke (1975) where the distance at which full flux adjustment occurred corresponds to a 75:1 fetch-to-height, and to the recommendation of 100:1 of Dyer (1963), a new value of fetch-to-height ratio has been found. Considering latent heat flux distributions in fields 1 and 2, and performing the ratio between the length of the transition region (50 m) and the measurement height (5 m for the bare soil and 3.14 m for the vegetated surface), the rule of thumb of about 10 fetch-to-height has been obtained. This value, which is an order of magnitude smaller than those found in the previous studies, could be justified by the different atmospheric turbulent conditions which are present in these various experimental fields. Low wind velocities and solar radiation that characterize Po Valley latitude could homogenize the atmosphere over the field reducing the effect of adjacent zones and increasing the representativeness of the eddy covariance station.

Experimental data compared with footprint model predictions

In this subparagraph footprint model predictions are matched with latent, sensible heat and carbon dioxide flux measurements across the experimental fields. In both sites, the upwind fluxes outside the fields are not zero and the source strength shown in Eq. 1 is simply approximated by the Eq. 5.

$$S(x) = \begin{cases} S_1 & \text{for } x < 0 \\ S_A & \text{for } x \geq 0 \end{cases} \tag{5}$$

where S_1 and S_A are the fluxes measured by eddy stations at 0 m and at the position of the fixed towers, respectively. By superposition, it is possible to calculate the flux ratio using the methodology widely described in Hsieh et al. (2000) and synthetically explained by Eq. 6.

$$\frac{F(x, z_m)}{S_A} = \frac{S_1}{S_A} \int_{-\infty}^{0} f(x, z_m)\,\mathrm{d}x + \int_{0}^{x} f(x, z_m)\,\mathrm{d}x \tag{6}$$

In this way, theoretical footprint models can be compared with experimental measurements, and the results are globally shown in Figs. 5 and 6. Each averaged data of flux is characterized by its own representative source area which is defined by the F/S_A ratio which is calculated through Eq. 6. The data used in Eq. 6 have been measured by the fixed stations over the whole period of time of the two experimental campaigns. The range of F/S_A values obtained by the fixed station experimental measurements is subdivided into groups each of which covers a period of time which corresponds to the time period where the mobile station stays at P1, P2 or P3 positions in the field. Subsequently, the mean of F/S_A values for each group have been calculated, so that F/S_A measured and calculated results can be compared.

Figures 5 and 6 are subdivided in two parts, the first (A, B, C) where the theoretical footprint model results are compared to the experimental measurements, and the second part (D, E, F) where a scatter plot defines if the footprint models are in a good agreement with the experimental results.
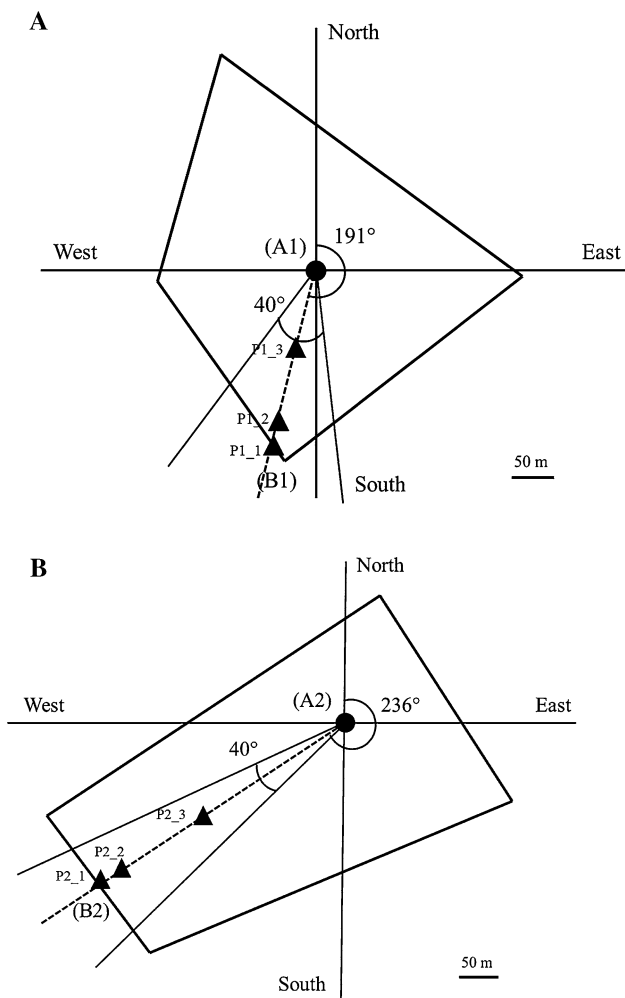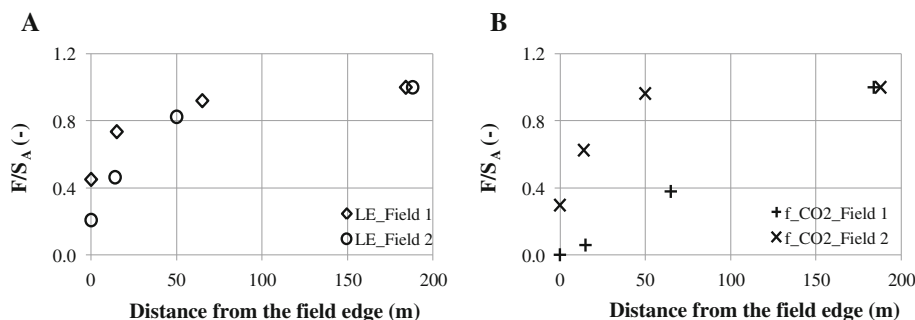
In the field 1, the latent, sensible heat and carbon dioxide variations in spatial distribution, lead to an unsatisfactory definition of a preferred footprint model which can be used to describe the representative source area for the whole range of turbulent fluxes. In fact, while the agreement between Kormann model and experimental data of latent heat flux is good, the same could not be said for sensible heat and carbon dioxide fluxes. Evaluating the errors between model and experimental results through the regression line of the dots in the scatter plots, Kormann model can be considered the best one for latent heat flux with a slope of the regression line equal to 0.98. However, both models are inadequate to describe footprint shape for sensible heat and carbon dioxide fluxes with an estimated error of about 10 and 30 %, respectively.

In the field 2, latent, sensible heat and carbon dioxide spatial distribution are quite similar. F/S_A ratios have rapidly increasing values versus the maximum admissible value of 1 which has been reached in a transition zone of about 50 m. Hsieh model underestimates footprint shape for the whole range of turbulent fluxes with an error which varies from 5 to 27 % for latent and sensible heat fluxes, respectively. Kormann model is in good agreement with latent heat and carbon dioxide experimental data with a slight error of about 2 %, while for sensible heat Kormann model the bias in F/S_A estimates is 20 %.

Discussion

Spatial distribution of turbulent fluxes across the field is particularly influenced by the presence of vegetation which covers the ground surface. In bare soil, the effects of boundary conditions persist for several meters away the field edge while, when the vegetation cover the field, the homogeneity of the canopy produces a rapid change in flux distribution leading to 1 the F/S_A ratio at a distance of about 50 m from the field edge. These results are similar to those obtained by Hsieh and Katul (2009). They compare a Lagrangian stochastic model for estimating footprint over homogeneous and inhomogeneous surface. In spite of

Fig. 2 Maps of the experimental sites. a Field 1 and b field 2. The *circle* indicates the fixed stations (A1 or A2) while the *triangles* the mobile station positions. The *dotted line* indicates the reference line

Fig. 3 Turbulent flux measurements across the fields. a latent heat (LE), b carbon dioxide flux (f_CO$_2$). F/S_A represents the ratio between mobile and fixed station flux measurements

using simplified models for fields 1 and 2, they are in good agreement with the experimental measurements, validating the performance of this approach in different field situations.

The results of this work prove that the rule of thumb strongly recommended by Dyer (1963), where the ratio between fetch-to-height is 100:1, is too high. Despite the 10:1 fetch-to-height ratio suggested in this paper seems to be much less than generally considered appropriate for eddy covariance flux measurements, other scientific works show that the variability of the fetch-to-height ratio is widely confirmed. Horst (1999) and Tsai and Tsuang (2005), in rice, note that the ratio of the fetch to measurement height of a fingerprint area is about 28:1 while Baldocchi and Rao (1995), on potato, find a ratio of 75:1.
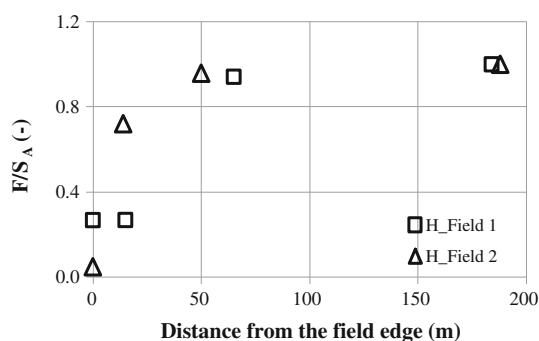
Fig. 4 Sensible heat flux measurement across the fields. F/S_A represents the ratio between mobile and fixed station flux measurements

The results obtained in fields 1 and 2 have shown that representative source area is different for different scalar fluxes. Generally, footprint models describe the representative source area for turbulent flux without specifying if it is latent, sensible heat or carbon dioxide. Experimental results show that, especially in bare soil, intra-field spatial distribution is different for different scalar fluxes, with a logarithmic behavior for latent heat and a linear growth for carbon dioxide. On the other hand, in field 2, the F/S_A logarithmic growth profile is guaranteed for the whole range of turbulent fluxes, but the F/S_A ratio values are not identical. The results are also in accordance with the observations shown in Lee (2002), where, using localized near-field (LNF) Raupach's (1989) theory, the footprint of the elevated and ground-level source fluxes has been compared. He supposes that the mismatch of footprint shapes could be explained by the physics of the turbulence inside and over the canopy.

Kormann model could be considered the best one for the whole range of turbulent fluxes; however, also Hsieh model is in a good agreement with latent heat flux distributions. In the other cases, Hsieh model underestimates the footprint area and this is probably due to the simplified parameterizations which form the model structure. Kormann model approximates footprint area of the turbulent fluxes in a good way also if, in some cases, it result to be underestimated in respect to the experimental measurements. The good agreement of the Kormann model can be due to atmospheric and turbulent conditions which are typical in Po Valley and which are in accordance with the
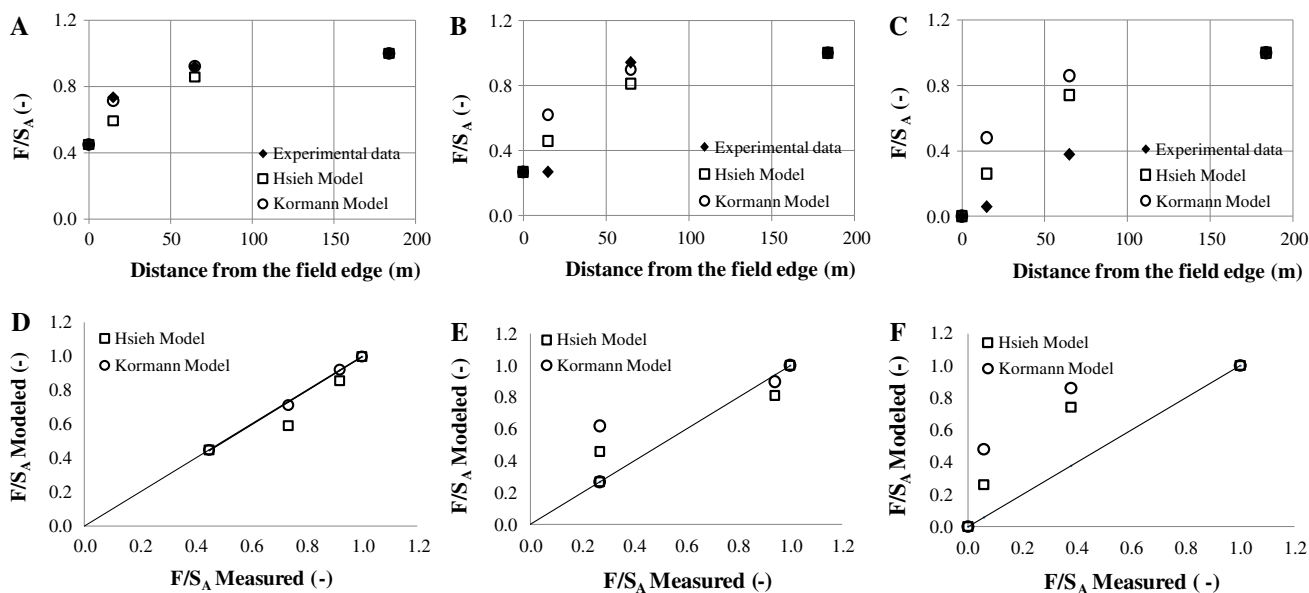

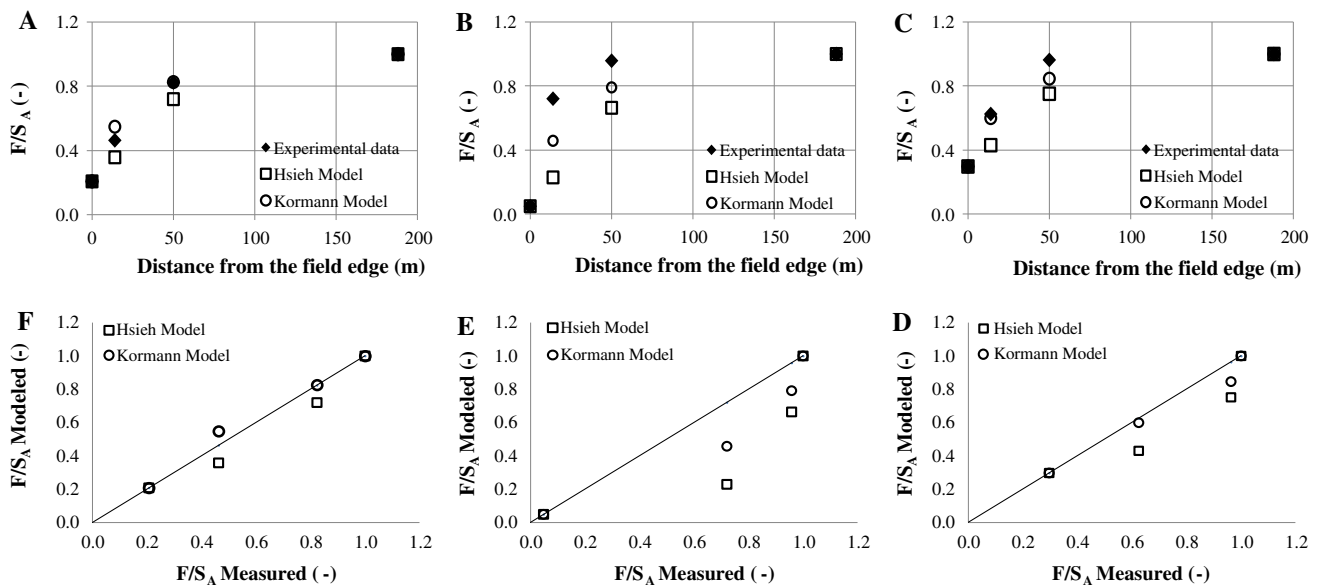**Fig. 5** **a–c** represent the variation of latent, sensible heat and carbon dioxide fluxes in the field 1 with the distance from the field edge. Comparisons with theoretical footprint models are also shown.

d–f represent the *scatter plot* between measured and modeled model predicted F/S_A. The 1:1 *line* is also shown

Fig. 6 **a–c** represent the variation of latent, sensible heat and carbon dioxide fluxes in the field 2 with the distance from the field edge. Comparison with theoretical footprint models are also shown.

d–f represent the *scatter plot* between measured and modeled model predicted F/S_A. The 1:1 *line* is also shown

limitations and basic hypothesis which govern the theoretical model.

Conclusion

In this work, a simple method which is quite different from those recently presented in literature is used to analyze horizontal variability of vertical scalar fluxes across bare and vegetated soils in Po Valley. One mobile eddy covariance station is moved from the field edge to the center of the field where a fixed station is located. Flux measurements from both stations are investigated and two footprint model predictions have been compared. A good agreement of the Kormann model is verified with experimental measurements, while Hsieh model could be used to define footprint shape only for latent heat flux. Variability of scalar fluxes across the fields is particularly influenced by the presence of the vegetation, and in bare soil turbulent flux spatial distributions are highly differenced from flux to flux.

These results have contributed in improving the knowledge of the reliability of analytical footprint model predictions in order to understand the model behaviors over a wide variety of natural situations, where eddy covariance stations could be located. Po valley and its typical cultivations such as maize or rice are still poorly investigated, but the improvement in eddy covariance technique and its applications over a wide range of fields, needs to know more accurately the representative source areas of the

evapotranspiration or carbon dioxide fluxes to improve management practice in water irrigation or plant care.

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