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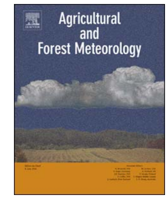

Research paper

Experimental validation of footprint models for eddy covariance CO_2 flux measurements above grassland by means of natural and artificial tracers

Nicola Arriga[a,b,*], Üllar Rannik[c], Marc Aubinet[d], Arnaud Carrara[e], Timo Vesala[c,f], Dario Papale[a,g]

[a] Department for Innovation in Biological, Agro-food and Forest Systems (DIBAF), University of Tuscia, Viterbo, Italy
[b] Research Centre of Excellence Plants and Ecosystems (PLECO), University of Antwerp, Wilrijk, Belgium
[c] Department of Physics, University of Helsinki, Helsinki, Finland
[d] University of Liege, Gembloux Agro-Bio Tech, TERRA Research Centre, Gembloux, Belgium
[e] CEAM, Fundación de la Comunidad Valenciana Centro de Estudios Ambientales del Mediterraneo, Paterna, Spain
[f] Department of Forest Sciences, University of Helsinki, Helsinki, Finland
[g] Euro-Mediterranean Center on Climate Change (CMCC), Lecce, Italy

A R T I C L E I N F O

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A B S T R A C T

Footprint models, which simulate source area for scalar fluxes, are fundamental tools for a correct interpretation of micromoeteorological flux measurements and ecosystem exchange inferred from such data. Over the last two decades models of varying complexity have been developed, but all of them suffer from a significant lack of experimental validation. In this study two different experimental tests have been conducted with the aim of offering validation: a manipulation of the vegetation cover and an artificial tracer emission. In the first case the extension of the flux source has been changed progressively by successive cuts of vegetation, while in the second case by varying the distance of a tracer emission line respect to the measurement point. Results have been used to validate two analytical and a numerical footprint models. The experimental data show a good agreement with footprint models and indicate a limited extension of the flux source area, with approximately 75% of the sources confined within a range of 10–20 times the effective measurement height, i.e. the measurement height above the zero plane displacement. Another interesting result was the strong dependence on the surface roughness of both experimental estimates and numerical simulations of footprint. The effect of surface roughness on experimental results and models outputs was comparable to the effect of atmospheric stability. This indicates that surface roughness and turbulence conditions may play a significant role in source area location, in particular above inhomogeneous surfaces with change in roughness, as in the case of the manipulation experiment. Consequently a careful site specific quantification of these parameters seems to be fundamental to obtain realistic footprint estimates and significantly improve eddy covariance flux interpretation at complex sites.

1. Introduction

The eddy covariance (EC) methodology allows the quantification of mass and energy exchanges between earth surfaces and atmosphere by measurements of wind speed, air temperature and passive tracer concentrations at time scales enabling the capture of a wide range of turbulent motions (Aubinet et al., 1999). The fluxes between ecosystem and atmosphere measured by the EC methodology are originated from an area surrounding, mostly upwind, the measurement point: the source area. The mathematical relation between the spatial distribution of the flux sources and the corresponding magnitude is termed *footprint function* or *source weight function* (Horst and Weil, 1992; Leclerc and Thurtell, 1990; Schmid, 1994; Schmid, 2002) Frequently the evaluation of source area for EC measurements is also referred to as the footprint analysis and both terms are interchangeable (Vesala et al., 2008). The estimation of the source area associated with each single flux measurement is important information that facilitates data interpretation and quality filtering (Göckede et al., 2004; Nicolini et al., 2015; Rebmann et al., 2005). It is of primary importance for analysis integrating both EC and remote sensing data, but also for interpretation of EC data collected in ecosystems that are heterogeneous in terms of land use, vegetation, biophysical characteristics such as leaf area index, biomass, soil type and management. The dimensions of the effective source area are influenced by structural properties of the surface (e.g. roughness), by the measurement height and by micrometeorological conditions (e.g. wind speed and direction, turbulence intensity, atmospheric stability). A footprint function model describes how the factors above influence the spatial distribution of the flux sources. Four categories of

* Corresponding author at: Research Centre of Excellence Plants and Ecosystems (PLECO), Biology Department, University of Antwerp, Universiteitsplein 1B, 2610 Wilrijk, Belgium.
E-mail address: Nicola.Arriga@uantwerpen.be (N. Arriga).

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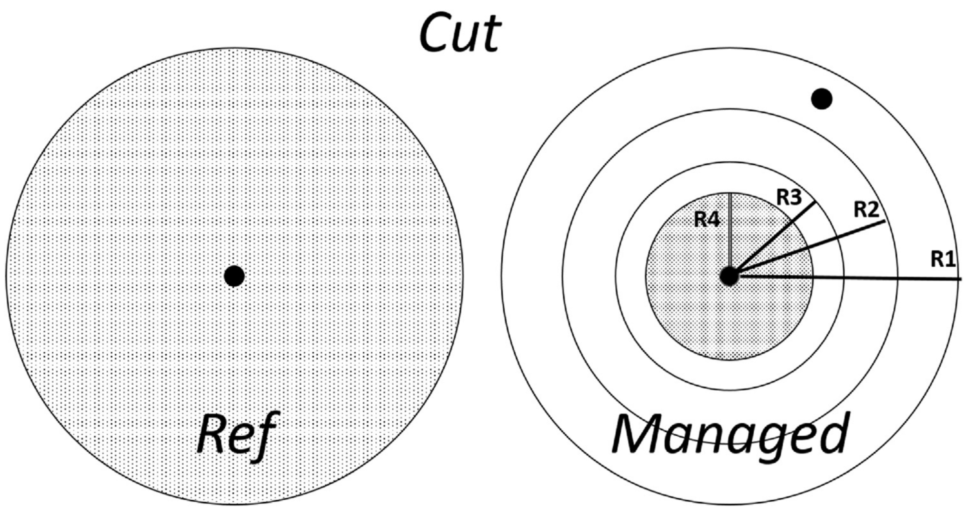

Fig. 1. Sketch of the ME experiment with R*ef* oats disc on the left and *Managed* disc on the right. Dots represent the position of the three EC systems. R1 to R4 are the radii of the successive oats cover after each cut in the *Managed* plot, respectively 30 m, 22 m, 15 m and 11 m.

models of different theoretical and practical complexity have been proposed in the last two decades (Leclerc and Foken, 2014; Rannik et al., 2012): (1) analytical models, (2) Lagrangian stochastic particle dispersion models, (3) large-eddy simulation and (4) ensemble-averaged closure models. As pointed out in past studies (Foken and Leclerc, 2004; Vesala et al., 2008) experimental footprint analyses and simulations are rare, in particular due to the complexity of the technical set-up and to the related costs. Nevertheless a number of experiments have been specifically designed, realized and published. Some authors (Finn et al., 1996; Leclerc et al., 2003) used an artificial emission of tracer gas, SF_6, to validate footprint models, while others (Aubinet et al., 2001; Göckede et al., 2004; Göckede et al., 2005; Marcolla and Cescatti, 2005; Neftel et al., 2008) used spatial heterogeneity of the surface composition for the same scope with different footprint models, mainly analytical. However the experimental validation of the footprint models and the uncertainty in source area evaluation is still a major issue for flux data interpretation. Reducing uncertainties in the estimation of the source area extension would also lead to the development of more accurate footprint models and to pinpointing the optimal location for an EC site. This information would be particularly important to measure fluxes over small vegetation patches, for example in the case of ecosystem manipulation experiments in which ecological or meteorological driving forces such as, e.g., temperature, water or nutrients availability, are modified over grassland and cropland fields generally not larger than few hundred square meters.

In this study two different field experiments have been conducted where the source area has been manipulated with the aim of measuring the effective footprint extension. In the first experiment the surface has been modified altering the vegetation cover while in the second an artificial CO_2 source has been used as a tracer. In both cases the results have been compared with the output of analytical and Lagrangian footprint models. Specifically, the objectives of this paper are: (1) to assess the effect of manipulation of the scalar sources on EC flux measurements and (2) to compare the results of various kind of footprint models with experimental data.

2. Materials and methods

The experimental site was located in Viterbo, Italy, in the area of the University of Tuscia Didactical Farm (42°25′16.10″N, 12°04′37.26″E). The selected area was a flat agricultural field approximately 130 × 95 m in size. This area was planted with oats (*Avena sativa* L.) at the end of 2007 and the measurements were taken between April and October 2008. The following two experiments were conducted:

- A manipulation experiment (**ME**) by means of successive cuts of the vegetation cover in the source area to modify its surface extension and to see the effect on the measured flux compared to a reference plot.
- A controlled emission of CO_2 as an artificial tracer (**AT**) with the aim of estimating the dependence of the footprint function from the distance of the emitting point.

Vegetation species shorter than oats were initially taken into consideration for the ME in order to limit the impact of the roughness step change between cut and uncut areas covered by oats and the consequent formation of internal boundary layer (IBL) (Garratt, 1992). However the footprint management in order to get a clear difference between harvested and not-harvested areas would have been more difficult and uncertain with short vegetation and for this reason this option was excluded. Details of each experiment are described in the following subsections 2.1 and 2.2.

2.1. Source area manipulation experiment (ME)

The first experimental footprint test has been realized with an artificial manipulation of the surface distribution of carbon dioxide sources and sinks in proximity of the EC instrumentation. The covering of oats was cut in order to only keep two discs of intact vegetation of equal dimension, approximately 30 m of radius (*Ref* and *Managed*, see Fig. 1). The mean canopy height (h_c), measured before the beginning of the manipulation in 30 points randomly distributed, was h_c = 1.02m. This experiment took place since day of the year (doy) 132–163 of 2008.

An EC system equipped with a sonic anemometer (model Gill-R3, Gill Instruments Ltd, Lymington, Hampshire, UK) and an infra-red gas analyzer (model LI-7500, LI-COR Inc., Lincoln, NE, USA) was placed in the center of *Managed* disc at 2.35 m above the soil and a second Gill R3 sonic anemometer was placed at 1.4 m. Another identical EC system was placed in the center of the *Ref* disc at the same height. A third EC system of the same type of the other two was placed from doy 151 to doy 162 above the *Cut* surface at a height of 1.5 m to measure the contribution of the external mowed crowns to the flux measured in the center of the *Managed* plot. This measurement height was selected to minimize the source area of the cut plot. Lateral separation between sonics and analyzers was 20 cm, while analyzers were always placed 5 cm below the sonics to minimize spectral loss due to the short distance of the canopy top. In accordance with other studies (Horst and Lenschow, 2009; Kristensen et al., 1997) we did not expect such a small