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Drivers of spatio-temporal variability of carbon dioxide and energy fluxes in a Mediterranean savanna ecosystem

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A B S T R A C T

To understand what is driving spatial flux variability within a savanna type ecosystem in central Spain, data of three co-located eddy covariance (EC) towers in combination with hyperspectral airborne measurements and footprint analysis were used. The three EC systems show consistent, and unbiased mass and energy fluxes. Nevertheless, instantaneous between-tower flux differences i.e. paired half hourly fluxes, showed large variability. A period of 13 days around an airborne hyperspectral campaign was analyzed and proved that between-tower differences can be associated to biophysical properties of the sampled footprint areas. At high photosynthetically active radiation (PAR) net ecosystem exchange (NEE) was mainly controlled by chlorophyll content of the vegetation (estimated through MERIS Terrestrial Chlorophyll Index (MTCI)), while sensible heat flux (H) was driven by surface temperature. The spatial variability of biophysical properties translates into flux variability depending on the location and size of footprints. For H, negative correlations were found with surface temperature for between-tower differences, and for individual towers in time, meaning that higher H was observed at lower surface temperatures. High aerodynamic conductance of tree canopies reduces the canopy surface temperature and the excess energy is relieved as H. Therefore, higher tree canopy fractions yielded to lower surface temperatures and at the same time to higher H. For NEE, flux differences between towers were correlated to differences in MTCI of the respective footprints, showing that higher chlorophyll content of the vegetation translates into more photosynthetic CO_2 uptake, which controls NEE variability. Between-tower differences of latent heat fluxes (LE) showed no consistent correlation to any vegetation index (VI), or structural parameter e.g. tree-grass-fraction. This missing correlation is most likely caused by the large contribution of soil evaporation to ecosystem LE, which is not captured by any of the biophysical and structural properties.

To analyze if spatial heterogeneity influences the uncertainty of measured fluxes three different measures of uncertainty were compared: the standard deviation of the marginal distribution sampling (MDS), the two-tower-approach (TTA), and the variance of the covariance (RE). All three uncertainty estimates had similar means and distributions at the individual towers while the methods were significantly different to each other. The uncertainty estimates increased from RE over TTA to MDS, indicating that different components like space, time, meteorology, and phenology are factors, which affect the uncertainty estimates. Differences between uncertainty estimates from the RE and TTA indicate that spatial heterogeneity contributes significantly to the ecosystem-flux uncertainty.

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1. Introduction

Savanna type ecosystems play an important role in global carbon stocks and their productivity (Ahlstrom et al., 2015; Grace et al., 2006), they are highly variable in seasonal carbon and water vapor fluxes (Eamus et al., 2013; Paço et al., 2009; Tagesson et al., 2015; Unger et al., 2012) and inter-annual (Chen et al., 2016; Costa-e-Silva et al., 2015; Dubbert et al., 2014; Ma et al., 2007; Nagler et al., 2007; Pereira et al., 2007) time scales. Savannas are complex ecosystems which consist of scattered trees and a coexisting continuous grass layer/understory (Scholes and Archer, 1997). The relative contribution of trees and the understory to overall ecosystem fluxes experience strong seasonal variations, and can vary substantially depending on the savanna type and its characteristics (e.g. Dubbert et al., 2014; Moore et al., 2016; Otieno et al., 2015; Paço et al., 2009). Within a savanna ecosystem, the spatial distribution of trees and the composition of the understory can result in spatial heterogeneity of biophysical properties and ultimately fluxes. To determine spatial flux heterogeneity on the ecosystem scale, flux footprint models offer a great possibility as they allow relating flux measurements and therefore flux variability, to surface properties. When detailed spatial information on surface characteristics are available for the footprint area, they can be utilized to explain spatial flux variability. Due to the intrinsic uncertainties associated with the eddy covariance (EC) technique, the observed variability in flux measurements is not entirely related to spatial heterogeneity. Rannik et al. (2016) reviewed different flux error estimates for EC measurements and compared their values for different ecosystems. They suggested to use the method proposed by Finkelstein and Sims (2001) or Wienhold et al. (1995) to estimate the random uncertainty of turbulent flux measurements. Both methods can be used to associate uncertainties to each individual flux averaging period. These uncertainty estimates account for the properties of the measured time series (vertical wind speed and scalar of interest), but do not integrate information about the observed variability in flux measurements observed under similar meteorological conditions and phenological stages. Two widely used methods to quantify this uncertainty are the standard deviation of the marginal distribution sampling (MDS; Reichstein et al., 2005) and the two-tower-approach (TTA; Hollinger and Richardson, 2005; Kessomkiat et al., 2013). The MDS is based on the assumption that, for a short time window and under the same meteorological conditions, fluxes should be similar. The TTA uses two co-located towers (i.e. a few hundred meters apart), which are sampling independent areas of the same homogeneous ecosystem and compares the differences of the simultaneous flux measurements. For the TTA differences in meteorological conditions are (nearly) completely eliminated and differences in phenological stage and biophysical properties should be minimized. Nevertheless, biophysical properties within the footprint area (Schmid, 2002) can change spatially and, therefore, influence flux measurements and increase the uncertainty estimate. High spatial resolution remote/proximal sensing provides means to better characterize and quantify spatial heterogeneity. For example, Balzarolo et al. (2015) and Perez-Priego et al. (2015) showed for grasslands, that variability in measured CO_2-fluxes can be related to changes in vegetation indices (VIs), which were derived from hyperspectral measurements. The best agreement was found between CO_2-fluxes and VIs associated to chlorophyll and water-content of the canopy, as well as sun-induced chlorophyll fluorescence. For savanna type ecosystems, where a multispecies herbaceous layer (annual grasses, forbs, and legumes) coexists with sparsely distributed trees, spatial heterogeneity of e.g. chlorophyll content of the vegetation and leaf area index (LAI) introduce a new dimension to account for. Variations of biophysical properties can occur at the herbaceous- and tree layer, or as a consequence of changes in the tree density and canopy fraction within the footprint area. From this point of view, it is not clear how representative flux measurements can be in such a complex ecosystem to represent ecosystem scale fluxes correctly. To be precise, this is not a special problem of savanna type ecosystems but to all EC-sites presenting significant variability in biophysical properties at EC footprint scale.

This work focuses on the analysis of data collected with three co-located EC flux towers within the framework of a fertilization experiment (Migliavacca et al., 2017). Here, only the data acquired before the fertilization are analyzed. The main objective is to evaluate the causes of differences between the simultaneous, half hourly flux measurements collected by the three co-located EC towers and to identify the main factors, (especially random errors vs. variability in biophysical surface properties), controlling the variability of measured carbon-, water-, and energy fluxes. For this purpose we (i) conduct a thorough uncertainty analysis including three different methods and (ii) make use of a combination of EC measurements, high resolution airborne hyperspectral information, and footprint analysis to identify spatial heterogeneity of mass and energy fluxes, and to correlate spatial flux differences with VIs derived from hyperspectral data and surface properties.

2. Methods

2.1. Site description

The study was carried out in the Majadas de Tietar site (Casals et al., 2009) located in western Spain (39°56′25″N 5°46′29″W). The ecosystem is a typical "Iberic Dehesa", with an herbaceous stratum of native pasture and a tree layer of scattered oak trees, with 98% of the trees being *Quercus ilex*. The tree density is about 20–25 trees ha^{-1} with a mean DBH of 46 cm and a canopy height of about 8 m. The canopy fraction of the trees is about 20%. The herbaceous layer consists mostly of various annual native species such as *Vulpia bromoides* (L.), *Vulpia geniculate* (L.), *Trifolium subterraneum* (L.), *Ornithopus compressus* (L.) with often more than 20 species within 4 m^2. The fractional cover of the three main functional plant forms within the pasture (grasses, forbs, and legumes), varies spatially but also seasonally according to their phenological status (Perez-Priego et al., 2015). The LAI of the trees is around 0.35 m^2 m^{-2} (1.5–2.0 m^2m^{-2} on a tree basis) while the spring peak green LAI of the herbaceous layer ranges between 0.5–2.5 m^2m^{-2} due to spatial heterogeneity (Migliavacca et al., 2017).

For clarity, we emphasize that the analyzed ecosystem is very heterogeneous on spatial scales of centimeters to few tens of meters with large variability in plant species and their distribution within the herbaceous layer. Trees on average are equally distributed within the ecosystem with locally more clustered and open areas. On scales of few hundreds of meters the ecosystem becomes homogeneous. This scale, at which the ecosystem is becoming homogeneous corresponds to the size of daytime flux footprints which are the basis for the analysis of this study.

The savanna is managed and used for continuous grazing of livestock with a low density of 0.3 cows ha^{-1} which is similar at all the sites. During the driest summer months (July–September) the cattle is usually moved to nearby mountain grasslands.

Mean annual temperature is 16.7 °C and annual precipitation is ca. 650 mm with large inter-annual variability. The prevailing wind directions are West-Southwest and East-Northeast (Fig. 1).

Three EC towers were operated simultaneously at the site to monitor ecosystem fluxes. The Control-Tower (CT) is the long-term eddy covariance FLUXNET site Majadas de Tietar (ES-LMa in FLUXNET, since 2003), while the other two towers (Nitrogen added Tower (NT), ES-LM1 in FLUXNET; and Nitrogen and Phosphorous added Tower (NPT), ES-LM2 in FLUXNET) were set up in March 2014 at a distance of 450 and 630 m from the CT in northwestern and southern direction, respectively (Fig. 1). The locations have been selected such that the footprints do not overlap under most frequent meteorological conditions, and that the tree cover and management around the towers are similar.