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Dynamics in carbon exchange fluxes for a grazed semi-arid savanna ecosystem in West Africa

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ABSTRACT

The main aim of this paper is to study land–atmosphere exchange of carbon dioxide (CO_2) for semi-arid savanna ecosystems of the Sahel region and its response to climatic and environmental change. A subsidiary aim is to study and quantify the seasonal dynamics in light use efficiency (ε) being a key variable in scaling carbon fluxes from ground observations using earth observation data. The net ecosystem exchange of carbon dioxide (NEE) 2010–2013 was measured using the eddy covariance technique at a grazed semi-arid savanna site in Senegal, West Africa. Night-time NEE was not related to temperature, confirming that care should be taken before applying temperature response curves for hot dry semi-arid regions when partitioning NEE into gross primary productivity (GPP) and ecosystem respiration (R_{eco}). Partitioning was instead done using light response curves. The values of ε ranged between 0.02 g carbon (C) MJ^{-1} for the dry season and 2.27 g C MJ^{-1} for the peak of the rainy season, and its seasonal dynamics was governed by vegetation phenology, photosynthetically active radiation, soil moisture and vapor pressure deficit (VPD). The CO_2 exchange fluxes were very high in comparison to other semi-arid savanna sites; half-hourly GPP and R_{eco} peaked at -43 μmol CO_2 m^{-2} s^{-1} and 20 μmol CO_2 m^{-2} s^{-1}, and daily GPP and R_{eco} peaked at -15 g C m^{-2} and 12 g C m^{-2}, respectively. Possible explanations for the high CO_2 fluxes are a high fraction of C4 species, alleviated water stress conditions, and a strong grazing pressure that results in compensatory growth and fertilization effects. We also conclude that vegetation phenology, soil moisture, radiation, VPD and temperature were major components in determining the seasonal dynamics of CO_2 fluxes. Despite the height of the peak of the growing season CO_2 fluxes, the annual C budget (average NEE: -271 g C m^{-2}) were similar to that in other semi-arid ecosystems because the short rainy season resulted in a short growing season. Global circulation models project a decrease in rainfall, an increase in temperature and a shorter growing season for the western Sahel region, and the productivity and the sink function of this semi-arid ecosystem may thus be lower in the future.

1. Introduction

The African Sahel region is located south of the Sahara desert and the area is dominated by semi-arid grassland with shrubs and low tree coverage. The region is strongly dependent on rain-fed agriculture and pastoral livelihood, and drought and famine frequently impact the people living in the region (OECD, 2009). The semi-arid ecosystems in the Sahel are vulnerable to the effects of climate change, because of this rainfall dependency (e.g. Hickler et al., 2005). Climate thereby strongly affects the land-atmosphere carbon dioxide (CO_2) exchange processes which can have strong positive or negative feedbacks on the climate system. Recently, it has been shown that semi-arid ecosystems has an increasingly important function as a sink of the global carbon cycle, because of increased rainfall and CO_2 fertilization effects (Donohue et al., 2013). In the future, semi-arid regions can even overrule tropical forests in dominance affecting the inter-annual variability in the global carbon cycle (Poulter et al., 2014).

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It is thereby important to study variability in the land atmosphere CO_2 exchange processes for semi-arid savanna regions. The net ecosystem exchange of CO_2 (NEE) is the balance between the CO_2 assimilated through gross primary production (GPP) by the vegetation and the carbon (C) decomposed and released as CO_2 by ecosystem respiration (R_{eco}). There have only been a few studies investigating temporal dynamics of the CO_2 exchange processes using the eddy covariance technique in the Sahel region, and most of them only cover a few weeks of data (e.g. Verhoef et al., 1996; Friborg et al., 1997; Moncrieff et al., 1997b; Hanan et al., 1998; Ardö et al., 2008). To our knowledge there are only three previous studies of land atmosphere exchange of CO_2 based on EC data from the Sahel region which covered an inter-annual period (Boulain et al., 2009; Merbold et al., 2009; Tagesson et al., 2015). However, none of these studies has focused on the temporal dynamics in the CO_2 exchange processes and their budgets. The CO_2 exchange processes are known to vary considerably and many controlling factors for these variations have been suggested: temperature, radiation regime, species composition, and moisture and nutrient availability (Lloyd and Taylor, 1994; Semmartin and Oesterheld, 1996; Rockström and de Rouw, 1997; Chapin et al., 2002; Hanan et al., 2011).

Due to the lack of in situ measurements, earth observation has proved an important tool in studying the ecosystem properties of the Sahel. Within earth observation, it is common to estimate GPP using a light use efficiency (LUE) model (Monteith, 1972, 1977). The LUE-model calculates GPP from the photosynthetically active radiation absorbed by the vegetation (APAR), using a simple conversion efficiency coefficient (the light use efficiency, ε). Initially, ε was considered to be relatively constant, but substantial differences have been found between plant communities, and also due to species composition, development stage, and stress level (Goetz and Prince, 1996; Gower et al., 1999; Drolet et al., 2008). Values of ε and its constraining factors therefore need to be investigated for various plant communities when GPP is to be estimated over larger areas. The main aim of this paper is to make a detailed study of the CO_2 exchange processes of a semi-arid savanna ecosystem in the Sahel region, and their response to climatic and environmental change. Our long time series of CO_2 fluxes allowed us to study the seasonal and diurnal variation in CO_2 fluxes and the influence of hydro-climatic variables (air and soil temperature, relative air humidity, photosynthetically active radiation (PAR), vapor pressure deficit (VPD), rainfall and soil moisture) and vegetation phenology. In addition, our CO_2 flux measurements allow us to estimate annual C budgets for the land-atmosphere exchange processes, and to study inter-annual variation of these budgets. A final objective was to quantify and study the seasonal dynamics of ε to better understand the temporal variability in ε to be implemented in improved earth observation based productivity models.

2. Material and methods

2.1. Site description

The measurements were conducted north-east of the town of Dahra in the Ferlo region of Senegal, West Africa (15.40 °N, 15.43 °W, elevation 40 m). The Dahra measurement site is located in the Sahelian ecoclimatic zone. Annual mean rainfall is 416 mm (for the period 1951–2003) of which more than 95% of the rain falls during the rainy season (July–October), with August being the wettest month (Agence Nationale de l'Aviation Civile et de la Météorologie, Senegal). Annual air temperature (period 1951–2003) is 29 °C; May has the highest mean monthly temperature (32 °C) and January the lowest (25 °C). South-westerly winds dominate during the rainy season, whereas north-easterly winds dominate during the dry season. The leaf area index (LAI) generally ranges between 0 and 2 (Fensholt et al., 2004). The growing season closely follows the rainy season and is short (2–3 months). The site is a typical low tree and shrub savanna environment with ~3% tree cover (Rasmussen et al., 2011). The most abundant tree species are *Balanites aegyptiaca*, *Acacia tortilis* and *Acacia Senegal.* The species composition of the ground vegetation for the years 2010–2013 is given in Table 1 (Mbow et al., 2013; Tagesson et al., 2015). The study area is homogenous and flat, and the dominant plant communities extend for several kilometers in all directions surrounding the study site. The soil is sandy luvic arenosol with low amounts of organic material and low clay content (clay = 0.35%, silt = 4.61%, and sand = 95.04%). The land is grazed and located within the Centre de Recherches Zootechniques de Dahra of the Institut Sénégalais de Recherche Agricole (ISRA). For a complete description of the site and the measurements conducted at Dahra, see Tagesson et al., 2015.

2.2. Eddy covariance measurements

The NEE (μmol $CO_2\,m^{-2}\,s^{-1}$) measurements were done between 8 August 2010 and 31 December 2013 using an EC system which had a 3-axis Gill R3 Ultrasonic Anemometer (GILL instruments UK) and an open-path CO_2/H_2O infrared gas analyzer (LI-7500, LI-COR Inc. Lincoln, Nebraska, USA) installed at 9 m height. The open-path analyzer was tilted 29° from vertical with 20 cm northward separation and −24 cm vertical separation from the anemometer. The anemometer and infrared gas analyzer data were sampled at 20 Hz. Every 4 weeks, the span and the offset of the gas analyzer were measured and the gas analyzer was calibrated. We processed the raw EC data using EddyPro 4.2.1 software (LI-COR Biosciences, 2012), and the fluxes were calculated for 30 min periods. The processing includes despiking (Vickers and Mahrt, 1997) (plausibility range: window average ±3.5 standard deviations), 2-D coordinate rotation (Wilczak et al., 2001), time lag removal between anemometer and gas analyzer by covariance maximization

Table 1
Dominant species of the herbaceous vegetation at the Dahra field site in 2010–2013. For a complete list of species composition, see Supplementary material of Tagesson et al., 2015

	2010	2011	2012	2013
Dominant species	Aristida adscensionis	Aristida adscensionis	Aristida adscensionis	Aristida mutabilis
	Zornia latifolia	Dactyloctenium aegypticum	Cenchrus biflorus	Eragrostis tremula
	Cenchrus biflorus	Zornia latifolia	Dactyloctenium aegypticum	Zornia glochidiata
	Dactyloctenium aegypticum	Eragrostis tremula	Zornia latifolia	Dactylotenium aegyptium
	Eragrostis tremula	Cenchrus biflorus	Eragrostis tremula	Alysicarpus ovalifolius