

## Final Authors Response

We thank the anonymous reviewer #2 for helpful comments.

### Anonymous Reviewer #2

I would like to congratulate the authors to a truly improved manuscript. It is very much better than the previous version; the text is better structured and the message is much clearer. I am also happy that an uncertainty analysis has been conducted; this is far too often overseen in papers presenting annual CO<sub>2</sub> flux budgets. Well done. However, I still have some questions and comments remaining.

#### Comments:

**L81** What do you mean by low zero displacement height? Please give a value and explain why it was set to this.

**Authors' response:** The zero displacement height was set to zero because the grass is heavily grazed and thus it is usually not taller than about 5cm. The text was changed accordingly.

**L163-L164.** Please include an explanation to why E<sub>0</sub> was estimated on an annual basis whereas R<sub>b</sub> was estimated on an 6 day basis. Does it really make physical sense that E<sub>0</sub> is not changed over the growing season?

**Authors' response:** The E<sub>0</sub> parameter was tested to vary freely together with R<sub>b</sub> parameter in which case most of the E<sub>0</sub> values were below zero. On the other hand, in the two step fitting the R<sub>b</sub> parameter had clear seasonal cycle. A similar approach was used in a flux partition comparison study by (Lasslop et al., 2010).

**L189** How do you know that ustar 0.2 is the optimal ustar threshold? It is quite high in relation to most studies. For a method to determine the optimal threshold see Lund et al. (2007).

**Authors' response:** The ustar threshold was determined using the same approach as in Lund et al. (2007). Added sentence describing the method at line 140.

**L186.** Are you certain that your ustar filtering is a random error? More data is usually filtered during morning and during night time, indicating that it is a systematic error rather than a random error. Please see Moncrieff et al. (1996). You do not have to do the full analysis of investigating which errors are random and systematic as in Moncrieff; it is a quite big job. But if you want to keep ustar filtering as a random error, please explain why.

It is very good that you did an uncertainty analysis, however we all know that a true quantification of all uncertainties related to the eddy covariance method is very hard to do. What about all instrumentation errors, uncertainties related to all different kind of preprocessing choices, errors related to the WPL correction, etc. I would just like you to put in an humble sentence describing that this is an estimate including some important uncertainties, but not all, affecting the annual CO<sub>2</sub> flux budgets.

**Authors' response:** It is true that the ustar filtering is selectively systematic error. This was corrected to the text. The beginning of the Section 2.5 now reads as follows “*The uncertainty in the annual CO2 budget was estimated by considering the most significant, albeit admittedly not all possible error sources, for both random and systematic errors.*”

**L199** the systematic errors should be summed without being taken in quadrature; it is only the random errors that should be taken in quadrature. Please see Moncrieff et al. (1996).

**Authors' response:** We disagree with this point because both systematic and random errors should be added in quadrature. This is also demonstrated in the discussion section of the Moncrieff et al. (1996) paper. All errors regardless of their type should be added in quadrature if they are independent errors i.e. uncorrelated.

**L201** I am trully sorry, I was slightly sloppy in my previous review. MCD43A2 is not a BRDF product, it is a NBAR (nadir BRDF adjusted reflectance) product.

**Authors' response:** Corrected.

**Fig S1** Please also include an explanation to what the NDVI comparison point is in the Figure caption. When only looking at the figure I thought this was where you took your NDVI value from. Later when reading the text I realised, that it was the point without grazing.

**Authors' response:** Corrected.

**Fig S2** Please do like in Fig 3, include all data as well as the binned data.

**Authors' response:** Corrected.

**L217.** I still do not understand why you did not use the light response function instead of the Lloyd Talyor equation when partitioning NEE into GPP and Reco. You did not see any clear relationship between night time respiration and temperature, would it then not be better to use a relationship where you see a strong correlation?

**Authors' response:** The light response functions were tested extensively by our own implementation of Lasslop et al., (2010) (Lasslop et al., 2010) and by the Dynamic INtegrated Gapfilling and partitioning for Ozfluz (DINGO) implementation (Beringer, (2014)). The majority of the fit parameters were not in sensible range and forcing them to certain range as was done in Lasslop et al., (2010) left very few fitted parameter values. Partitioning was also tested without forcing the parameters to any range which resulted in negative daytime respiration for the dry season months June, July and August. The light response functions are challenging to fit as pointed out by Aubinet et al., (2012) and with our data it was not possible to get sensible results using this approach.

**L240-L243** Why don't you combine Fig 6, Fig S3 and Fig S4, it would make it easier to see the relationship between VPD and the fluxes. Why is the Fig S3 and Fig S4 in the supplementary material, they seem to be quite important for the results?

**Authors' response:** The combination of carbon flux and VPD plots was tested but there was too much overlap with the plot lines. The Figures S3 and S4 were combined with Fig 6 and the VPD figure was added to the article.

**Section 3.3** Should probably be called intra-annual, since it is investigating seasonal dynamics.

**Authors' response:** Corrected.

**L255,** I still do not understand why you using monthly data in your analysis. Your dailys sums are beautiful and not too noisy (Fig S5). The variability seen in S5 is the variability you want to explain, but that variability disappears when taking the monthly averages. If you necessarily want to keep the monthly averages you should give an explanation for this in the manuscript.

**Authors' response:** It is true that the monthly values did hide the early wet season transition point after which the ecosystem is mostly taking up carbon. These dates were added to the analysis. An explanation for the monthly scale analysis was added to the beginning of Sec. 3.3. *“This analysis was based on monthly data in order to facilitate comparison between the years, which would not be possible with daily data due to the large scatter in carbon fluxes and environmental variables.”*

**L321-L324** Please rephrase this sentence. It was really hard to understand what you meant.

**Authors' response:** Rephrased. The sentence now reads as follows *“Within our three year flux data period, the peak NDVI was related to the peak GPP in year 2010-2011 and in year 2011-2012 but it did not capture the rainy season peak in GPP in 2012-2013.”*

**L364** Which previous studies? I think that it is mainly in humid savanna ecosystems where there is a clear relationship between ecosystem respiration and temperature, whereas dry savanna ecosystems generally have not seen a clear relationship.

**Authors' response:** There was a mistake in this sentence. The sentence now reads as follows *“Similar results were observed at a West-African dry savanna, where none of the environmental variables could explain the half-hourly night-time respiration measurements (Tagesson et al., 2015).”*

**Table 1.** I am sorry, I still do not understand what the publishing author is? Is it the first person finding this species? Please clarify this and the acronyms used in the table.

**Authors' response:** The species names in the table are taken from the website [www.theplantlist.org](http://www.theplantlist.org) which is an effort provide standard accepted names for all plant species. The figure caption now reads as follows *“Dominant plant species within the flux footprint. The plant species name is written in italics whereas the roman text refers to the author. Some author names are abbreviated.”*

**Fig 3 and Fig S2.** Please explain in the figure caption how the bins were defined, between 0-150 PAR, 150-450 PAR etc. Or? They are not defined to have 100 values per bin, then there would be 28 points.

**Authors' response:** The figures were made again with equal sized bins. The captions now read the exact amount of data in each bin.

**Fig 7, legend 4.** What is yearly sum?

**Authors' response:** Yearly precipitation sum. Corrected the legend.

## References

Aubinet, M., Vesala, T. and Papale, D., Eds.: Eddy Covariance, Springer Netherlands, Dordrecht., 2012.

Beringer, J., Dynamic INtegrated Gapfilling and partitioning for Ozfluz, (2014), GitHub repository, <https://github.com/jberinge/DINGO12>

Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneeth, A., Barr, A., Stoy, P. and Wohlfahrt, G.: Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation, *Glob. Change Biol.*, 16(1), 187–208, doi:10.1111/j.1365-2486.2009.02041.x, 2010.

# Carbon balance of a grazed savanna grassland ecosystem in South Africa

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**Abstract.** Tropical savannas and grasslands are estimated to contribute significantly to the total primary production of all terrestrial vegetation. Large parts of African savannas and grasslands are used for agriculture and cattle grazing, but the  
15 carbon flux data available from these areas is limited. This study explores carbon dioxide fluxes measured with the eddy covariance method for three years at a grazed savanna grassland in Welgegend, South Africa. The tree cover around the measurement site, grazed by cattle and sheep, was around 15 %. The night-time respiration was not significantly dependent on either soil moisture or soil temperature on a weekly temporal scale, whereas on an annual time scale higher respiration rates were observed when soil temperatures were higher. The carbon dioxide balances of the years 2010–11, 2011–12 and  
20 2012–13 were  $-85 \pm 16$ ,  $67 \pm 20$  and  $139 \pm 13$  g C m<sup>-2</sup> yr<sup>-1</sup>, respectively. The yearly variation was largely determined by the changes in the early wet season fluxes (September to November) and in the mid-growing season fluxes (December to January). Early rainfall enhanced the respiratory capacity of the ecosystem throughout the year, whereas during the mid-growing season high rainfall resulted in high carbon uptake.

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## 1 Introduction

Savannas are highly dynamic ecosystems which cover about 40 % of Africa and 20 % of the global land area (Scholes and Walker, 1993). The savanna ecosystems are generally characterized by alternating wet and dry seasons, during the latter of which wildfires can occur. There can also be transitional seasons between the wet and dry seasons. There are large differences between savannas in terms of their tree cover, species composition and soil type. Furthermore, large parts of African savannas have been inhabited by humans throughout the evolution of our species and thus are modified by activities such as grazing and logging.

Overall, the African continent is estimated to be a small sink of atmospheric carbon, although the uncertainty of this estimate is high due to the lack of long-term measurements in many key ecosystems of the continent (Valentini et al., 2014). The tropical savannas and grasslands are estimated to account for 30 % of the global primary production of all terrestrial vegetation (Grace et al., 2006). In addition, it has recently been shown that the inter-annual variability of the terrestrial carbon cycle is dominated by semi-arid ecosystems (Ahlström, 2015).

The main meteorological drivers of the carbon fluxes between the atmosphere and African savannas are precipitation, soil moisture and soil temperature (Merbold et al., 2009). The maximum carbon assimilation rates in a range of different African ecosystems have been shown to be an exponential function of the mean annual rainfall (Merbold et al., 2009). While the total ecosystem respiration was observed to be exponentially dependent on the soil temperature at seasonal time scales in South African savanna (Kutsch et al., 2008). Archibald et al. (2009) did not consider the conventional exponential function an appropriate representation of the temperature response. Instead, they found that a generalized Poisson function was a better descriptor of the effect of temperature on respiration, as it describes both the exponential increase of respiration with the temperature and its decrease at higher temperatures.

Net Ecosystem Exchange (NEE) has been determined by eddy covariance at various savanna sites (Ago et al., 2014; Archibald et al., 2009; Brümmer et al., 2008; Quansah et al., 2015; Tagesson et al., 2015; Tagesson et al., 2016; Veenendaal et al., 2004). Many of the Sahelian measurement sites are affected by grazing or agriculture, whereas all the Southern African sites are located inside national parks or nature reserves. However, large parts of Southern African savannas are used for agriculture and grazing; for example in South Africa 80 % of the land surface is taken up by farmlands (Kotze and Rose, 2015).

The yearly sum of NEE has been observed to range between -429 (sink) and +155 (source)  $\text{g C m}^{-2} \text{yr}^{-1}$  across eight sites in semi-arid African savannas (Archibald et al., 2009; Brümmer et al., 2008). Archibald et al. (2009) found that the main drivers of inter-annual variation in NEE are the amount of absorbed Photosynthetically Active Radiation (PAR), length of the growing season and the number of days in the year when moisture was available in the soil. Tagesson et al. (2016) synthesized data from six different sites across the Sahel and found the yearly NEE sum to range between -373 and -10  $\text{g C m}^{-2} \text{yr}^{-1}$ . The variability of NEE was strongly linked to changes in Gross Primary Production (GPP) which was regulated by

vegetation phenology and soil moisture dynamics. However, the environmental drivers for the inter-annual variation in NEE are poorly understood.

65 To understand these human-influenced savanna ecosystems, we analysed three years of eddy covariance CO<sub>2</sub> flux data from a grazed semi-arid savanna in central southern Africa. The carbon balance of this ecosystem was determined for three yearly periods and its response to the environmental drivers was analysed at diurnal, monthly and inter-annual time scales. The longer-term productivity at the measurement site was assessed using a remotely sensed Normalised Differential Vegetation Index (NDVI) as proxy for GPP. The main objective of this study is to quantify the carbon balance and its inter-annual  
70 variation in a grazed semi-arid savanna ecosystem and to find possible climatic drivers for this variation.

## 2 Materials and methods

### 2.1 Site description

The Welgegend atmospheric measurement station (26°34'10"S, 26°56'21"E, 1480 m a.s.l.; www.welgegend.org) in South Africa has been measuring atmospheric aerosols and trace gases since May 2010. This site is located on a flat savanna  
75 grassland plain which is grazed by cattle and sheep. The monthly mean temperature and precipitation at a nearby weather station during 1998–2014 are shown in Fig. 1. In general, the rainy season lasts from October to April, coinciding with the highest temperatures, but there can be substantial amount of rain as early as in September. This is followed by the dry and cooler season from May to September. The mean annual rainfall was 540 mm with a standard deviation of 112 mm between 1998 and 2014. During this period, on average, 93 % of the yearly rainfall occurred between October and April. The main  
80 wind direction was from the north-west during daytime and the north-east during night-time. The aerodynamic roughness length was estimated to be 0.42 m assuming ~~a low~~ zero-plane displacement height.

The measurement site is located at a commercial farm which has about 1300 head of cattle which varies ± 300 depending on the year. During a wet year there are more animals than during a dry year. The cattle are grazing on an area of approximately 6000 ha, which consists of natural grazing (e.g. at the measurement site), planted grazing and maize/sunflower fields that are  
85 grazed after harvesting. This form of farming is considered large-scale commercial farming. Due to the semi-arid climate, the carrying capacity of the grazing fields tends to be low and thus the grazing area is large. The farmers cannot keep track of the grazing patterns, but they do move the cattle around to optimize grazing and protect the field against overgrazing.

The area around the eddy covariance measurement tower is dominated by perennial C<sub>4</sub> grass species (Table 1). The dominant grass species are *Eragrostis trichophora*, *Panicum maximum* and *Setaria sphacelata*. There is also a considerable amount of  
90 forbs, of which the dominant species are *Dicoma tomentosa*, *Hermannia depressa*, *Pentzia globosa* and *Walafrida densiflora*. This grassland type is referred to as a thornveld. It has a tree cover above 15 % and an average tree height of 2.5 m. The common tree species are *Vachellia erioloba*, *Searsia pyroides* and *Celtis africana*.

The soil organic carbon content was 0.93 % and the pH was 5.69. Detailed descriptions of the soil texture and chemical composition around the measurement site are given in Table S1. The soil around the site is loamy sand.

95 Based on the vegetation sampling described in Sect. S1, the LAI within the flux footprint had a maximum value of 2.32 m<sup>2</sup> m<sup>-2</sup> in April and a minimum of 0.37 m<sup>2</sup> m<sup>-2</sup> in July (Table 2). The leaf biomass followed the same trend, with a maximum value of 644 g m<sup>-2</sup> and a minimum of 233 g m<sup>-2</sup> (Table 2).

## 2.2 Instrumentation

100 At the measurement site there are continuous measurements of atmospheric aerosols, trace gases and meteorology (Booyens et al., 2015; Jaars et al., 2014; Laakso et al., 2013; Vakkari et al., 2014, 2015). In this paper, we present the data directly relevant to carbon cycle dynamics from September 2010 to August 2013.

The meteorological measurements included air temperature (Rotronic MP 101A) and pressure (Vaisala PTB100B), wind speed (Vector A101ML) and direction (Vector A200P/L), relative humidity and temperature gradient (Vaisala PT-100) between two points (2 m and 8 m height). The meteorological measurements were sampled every minute and the 15 min  
105 averages were recorded. Precipitation was measured at a 1.5 m height by two tipping buckets (Vaisala and Casella) working in parallel. Radiation measurements were placed at a 3 m height and included incoming and outgoing PAR by Kipp & Zonen PAR-lite sensors, direct and reflected global radiation by Kipp & Zonen CMP-3 pyranometers and net radiation by Kipp & Zonen NR-lite2 net radiometer.

110 Soil moisture and temperature were measured in one soil profile, having sensors at depths of 5, 20 and 50 cm. There was also a separate soil moisture sensor approximately 10 m away from the soil profile. Soil temperatures were measured with PT100 platinum thermometers, soil moisture with Delta-T sensors, and soil surface energy flux with Hukseflux HFP01 heat flux plate at a 5 cm depth.

115 Carbon dioxide, water vapour, sensible heat and momentum fluxes were measured using an eddy covariance setup similar to the one described by Aurela et al. (2009). The sonic anemometer was a METEK USA-1, and the CO<sub>2</sub> concentrations were measured using a Li-Cor LI-7000 closedpath gas analyzer. The sampling frequency of these instruments was 10 Hz. The anemometer and the gas sampling tube were installed at a 9 m height, which was well above the average tree height of 2.5 m. The separation distance between the gas sampling tube and the centre of the anemometer was 20 cm. The flow rate of the sampling system was 6 L min<sup>-1</sup>. The length of the inlet tube for the LI-7000 gas analyzer was about 20 m. The material of the inlet tube (ID 4 mm, OD 6 mm) was PTFE, and the pump was Dürr A-062 E1. The gas analyzer was calibrated every month  
120 with a high-accuracy CO<sub>2</sub> span gas (378 ppm verified by the Cape Point GAW station), and Afrox instrument grade synthetic air with CO<sub>2</sub> < 0.5 ppm was continuously used as a reference gas.

The state of the measurement system was continuously monitored by visiting the measurement site once or twice a week. During each visit, the state of the measurements was logged and corrective actions taken as required. During the data analysis the log file was used to check erroneous measurement periods.



### 125 2.3 Processing of eddy covariance data

The turbulent fluxes were calculated as 30 min block averages from the 10 Hz raw data after a double rotation of the wind coordinates (McMillen, 1988) and calculation of the CO<sub>2</sub> mixing ratios with respect to dry air by accounting for water vapour fluctuations (Webb et al., 1980). For each averaging period, the time lag between the anemometer and gas analyzer signals was determined using a maximum covariance method. The fluxes were corrected for systematic losses using the transfer function method of Moore (1986). This included a compensation for the low-frequency losses due to block averaging. For the more significant high-frequency losses, an empirical first-order transfer function representing the overall system performance was determined from the field data using the sensible heat flux as a reference. A spectral half-power frequency of 1.6 Hz was determined for CO<sub>2</sub>. Generic cospectral distributions (Kaimal and Finnigan, 1994) were assumed for estimating the flux underestimation in different conditions, providing correction factors as a function of wind speed and atmospheric stability. The correction for CO<sub>2</sub> flux loss was 5 % on average.

The storage flux was calculated by assuming a uniform distribution of CO<sub>2</sub> between the soil surface and the measurement height. During the last measurement year, the CO<sub>2</sub> concentration was also measured at a 1.5 m height, which enabled us to calculate a two-point estimate of the storage flux for comparison.

The corrected fluxes of CO<sub>2</sub> were filtered by discarding the data with a friction velocity lower than 0.2 m s<sup>-1</sup> (18 % of data excluded). Below this limit, the CO<sub>2</sub> flux was observed to increase with increasing friction velocity. In addition, CO<sub>2</sub> fluxes were filtered by setting an acceptable range for average CO<sub>2</sub> concentration (300–500 ppm), gas analyzer sample cell pressure (50–120 kPa) and CO<sub>2</sub> concentration variance (0–10 ppm<sup>2</sup>), which resulted in a 3 % loss of flux data in total.

There was only one longer period of malfunction of the gas analyzer, which lasted for 15 days in November 2010. In total, 33 % of the CO<sub>2</sub> flux values in the final time series were missing or discarded, which is similar to the 19-site average of 35 % reported by Falge et al. (2001).

The flux “footprint” area was estimated using the analytical model introduced by Kljun et al. (2004). According to this model, 90 % of the flux originated within a distance of 324 m upwind from the measurement tower. Figure S1 shows the distance of the mean 80 % cumulative flux footprint as a function of wind direction. This footprint area is predominantly located within homogeneous thornveld (Fig. S1).

### 150 2.4 Partitioning and gap filling of the CO<sub>2</sub> flux data

The measured net CO<sub>2</sub> flux was partitioned into GPP and ecosystem respiration,  $R_{\text{eco}}$ , by fitting a respiration function to the night-time data and calculating GPP as the difference between NEE and  $R_{\text{eco}}$ . Night-time and daytime periods were separated by a threshold PAR value of 20  $\mu\text{mol m}^{-2} \text{s}^{-1}$ . The fit parameters were calculated in a moving data window which was defined for each day with an initial length of 6 days. As the data set did not have gaps longer than 15 days, the moving window was expanded up to 20 days if necessary, to cover at least 50 measurement points.

The night-time respiration was calculated using the exponential temperature function:

$$R_{eco} = R_b \exp\left(E_0 \left(\frac{1}{T_0} - \frac{1}{T_{soil} - T_1}\right)\right) \quad (1)$$

where  $R_b$  is the base respiration,  $E_0$  is the temperature sensitivity,  $T_0 = 56.02$  K,  $T_{soil}$  is the soil temperature at 5 cm depth and  $T_1 = 227.13$  K (Lloyd and Taylor, 1994). This function was fitted in two steps by first determining the  $E_0$  parameter  
 160 | individually for each year and then fitting the  $R_b$  parameter for each data window separately (Lasslop et al., 2010).

The GPP values derived from the NEE observations and  $R_{eco}$  estimates were used to fit the hyperbolic tangent function of PAR for every day using data from the 6 to 20 days moving window:

$$GPP = F_{p,max} \cdot \tanh\left(\frac{d \cdot PAR}{F_{p,max}}\right) \quad (2)$$

where  $F_{p,max}$  is the canopy assimilation at light saturation and  $d$  is the initial slope of light response (von Stamm, 1994). The  
 165 | model parameters were determined using the “lsqnonlin” command of MATLAB Release 2015b, which uses a trusted region  
 least squares algorithm. The missing values in the GPP time series were filled with the GPP values calculated using Eq. (2).  
 Finally, the NEE time series was gap filled using the sum of  $R_{eco}$  and GPP.

The eddy covariance measurement data used in this study covered the period from September 2010 to August 2013. We  
 analysed the data as one-year periods from 1 September to 31 August, as a growing season at this southern hemispheric site  
 spreads to two consecutive years.

## 170 | 2.5 Uncertainty estimation

The uncertainty in the annual  $CO_2$  budget was estimated by considering the most significant, albeit admittedly not all  
possible error sources, for both random and systematic errors. For the former, we included the stochastic measurement error  
 inherent in eddy covariance measurements and; the error resulting from the gap filling of the  $CO_2$  flux time series for  
 missing data ~~and the uncertainty due to data filtering by a minimum friction velocity limit~~. The random error related to both  
 175 | the stochastic variability and the gap-filling procedure was calculated as a root mean square error by comparing half-hourly  
 values of measured ( $NEE_{obs}$ ) and modelled ( $NEE_{mod}$ )  $CO_2$  fluxes

$$E_{RMS} = \sqrt{\sum \frac{(NEE_{obs} - NEE_{mod})^2}{n}} \quad (3)$$

Where  $NEE_{mod}$  was calculated with Eqs. (1) and (2). This procedure assumes that the agreement is not affected by systematic  
 measurement or model errors. It provides a conservative error estimate for the random measurement error (Aurela et al.,  
 2002), and for the gap-filling error also includes the effect of this random variability on the model fit. The annual  
 180 | measurement error,  $E_{meas}$ , and gap-filling error,  $E_{gaps}$ , were calculated by multiplying  $E_{RMS}$  by the square root of the number  
 of accepted measurements and missing data, respectively.

In addition to the random error, the annual ~~systematic~~ random error due to friction velocity filtering,  $E_{ustar}$ , was estimated based on a sensitivity test in which the full calculation procedure for the annual balance was repeated with modified data sets; these data sets resulted from screening with two additional values of friction velocity (0.15 and 0.25 m s<sup>-1</sup>) (Aurela et al., 2002).  $E_{ustar}$  was estimated as an average deviation from the annual carbon balance calculated using the optimal friction velocity limit (0.20 m s<sup>-1</sup>).

~~In addition to the random error, w~~We estimated the systematic error due to the correction for flux losses described in Sect. 2.3,  $E_{loss}$ , and assumed that other systematic errors have been sufficiently compensated for in the post-processing of the eddy covariance data. We calculated the annual error from the mean daytime and night-time fluxes that were determined separately for dry and wet seasons. The uncertainty estimate for our correction coefficients was adopted from Mamadou et al. (2016), who observed that the cospectral functions determined for their grassland site differed from the commonly used generic cospectra (Kaimal and Finnigan, 1994), also used in the present study, which difference has an influence on the correction factors. By using the mean differences in the correction factors (daytime 4 %, night-time 14 %) reported by Mamadou et al. (2016), we could modify the degree of our flux loss correction and estimate the resulting uncertainty in the annual CO<sub>2</sub> balance.

The total uncertainty of the annual carbon balance was calculated by adding the different annual errors in quadrature:

$$E_{tot} = \sqrt{E_{meas}^2 + E_{gaps}^2 + E_{ustar}^2 + E_{loss}^2} \quad (4)$$

## 2.6 Satellite data

In order to study long-term productivity, monthly averages of NDVI were calculated from the MODIS ~~NBAR (nadir BRDF adjusted reflectance)~~ BRDF-product MCD43A4 (one 500 m pixel) at the flux footprint of the eddy covariance measurement (Figure S1). This product uses the reflectance data which is adjusted using a bidirectional reflectance distribution function for view angle effects. The NDVI signal is a simple transformation of spectral bands without any bias from ground-based parameters (Huete et al., 2002).

## 3 Results and discussion

### 3.1 CO<sub>2</sub> exchange dynamics

Figure 2 shows a time series of incoming PAR, air temperature, precipitation and CO<sub>2</sub> flux for the full measurement period. The incoming PAR and air temperature were highest in January and lowest in July. Precipitation was highest during the growing season 2010–2011 with a yearly sum of 721 mm. The highest inter-annual variation in CO<sub>2</sub> flux occurred during the wet season, whereas during the dry season CO<sub>2</sub> fluxes were rather similar in magnitude.

The daytime canopy carbon assimilation in the middle of the wet season (DJF) followed the common pattern where the daytime CO<sub>2</sub> uptake increased with increasing incoming PAR until it reached a saturated value (Fig. 3). The dry season

(JJA) CO<sub>2</sub> flux rates were an order of magnitude lower than the wet season rates and canopy assimilation was rarely saturated with respect to PAR. On average, the mean daytime NEE decreased with increasing VPD when VPD exceeded a limit of 1 kPa (Fig. S2).

The night-time respiration did not show a clear exponential relationship with either soil moisture or soil temperature in any of the respiration fitting windows, which ranged from 6 to 20 days (data not shown). The highest ranges of soil moisture in individual fitting data sets were from 1 to 7 % during the dry season and from 8 to 21 % during the wet season, but there was no significant relationship with respiration. A clear linear increase in respiration with increasing soil moisture was only observed once, after the first intense rainfall event in early November 2010. Similarly, the night-time respiration did not increase strongly with soil temperature in any of the respiration fitting windows. Instead, the respiration rate remained rather constant with a  $\sim 2 \mu\text{mol m}^{-2} \text{s}^{-1}$  reduction at the highest temperatures during the middle part of the wet season in 2010–2011. However, on an annual time scale, higher respiration rates were observed when soil temperatures were higher (Fig. 4). There is little correlation with soil water content during either dry or wet season, or on an annual time scale. Therefore, it seems that the ecosystem respiration is driven by plant phenology, being higher during the rainy seasons and on average unaffected by short-term variations in soil water content and soil temperature. Our respiration relations are similar to those reported by Tagesson et al. (2015), who observed no relationship between the night-time NEE and the environmental drivers for 7-day periods in grazed savanna in Senegal.

Even though the temperature dependency was weak, the respiration rates modelled with Eq. (1) correlated well with the measured respiration ( $R^2=0.56, p < 0.01$ ).

### 230 3.2 Diurnal CO<sub>2</sub> cycle

The mean monthly diurnal variation of NEE reveals a change in the ecosystem dynamics during the transition from the dry to wet season (Figs. 5 and 6). The highest values of carbon uptake occurred every year in December or January from 10 am to 12 am (the darkest pixels in Fig. 5), whereas the incoming PAR had its peak between 11 am and 1 pm (data not shown). This phase difference is most likely caused by the stomata closure before the radiation peak, as plants avoid water loss.

235 To understand the controlling drivers of the diurnal NEE cycle, we analysed the mean monthly diurnal cycle of GPP, respiration and VPD. The diurnal cycles of GPP and respiration show that the monthly diurnal variation of GPP between the years is larger than the variation in respiration (Fig. [6S3](#)). The mean monthly diurnal cycle of the VPD values above a 1 kPa threshold, VPD<sub>1</sub>, shows marked differences from September to November between different years (Fig. [7S4](#)).

In September the mean diurnal NEE cycle can be depicted by a smooth curve, with a nearly levelled maximal uptake period from 10 am to 3 pm. The diurnal cycle of NEE is positive in September 2012 due to higher respiration rates. In October 2010, the daily peak GPP is about  $2 \mu\text{mol m}^{-2}$  lower than during the other years, which could be due to VPD as VPD<sub>1</sub> was 1 kPa higher than during the other years. In November 2010, the diurnal pattern of NEE showed a sharp dip after the maximal uptake was reached. The peak NEE value in November 2012 was reached already at 9 am, whereas in the other years the

November peak NEE value was reached at 11 am. This is explained by the different diurnal cycles of GPP during the other  
245 | years (Fig. [6S3c](#)). From December to February, the differences in the diurnal cycle of NEE are explained by the differences  
in the GPP cycle. From March to August, the differences in  $VPD_1$  were not large and the largest variation between the years  
are seen in the diurnal cycle of GPP.

### 3.3 ~~Intraer~~-annual variation in $CO_2$ fluxes

In this section, we analyse the differences in carbon fluxes and their environmental drivers at a monthly scale during the  
250 | three measurement years. [This analysis was based on monthly data in order to facilitate comparison between the years,  
which would not be possible with daily data due to the large scatter in carbon fluxes and environmental variables.](#)

The highest carbon uptake was observed during the growing season 2010–2011 (Figs. [87](#) and [S5S3](#)). Heavy rainfall occurred  
from November to January, and soil temperature was relatively low. This contributed to the strong growth of vegetation and  
large net carbon uptake. Furthermore, VPD was low from January to April, which resulted in continued uptake of carbon.  
255 | Due to the relatively low soil temperatures throughout the growing season, the yearly respiration in 2010–2011 was lower  
than during the year 2012–2013.

During the year 2011–2012 the annual rainfall was lower than during the other years; especially the December–January  
precipitation was low. Moreover, VPD was relatively high during this period and thus the growth of vegetation was weak. In  
February and March, the carbon balance was positive possibly due to enhanced heterotrophic respiration and a relatively  
260 | small LAI.

During the year 2012–2013, the total respiration was relatively high already in September. The early rainfall may have led to  
an early growth of soil microbial populations that enhance the soil respiration capacity during the whole season.  
Furthermore, respiration was high throughout the growing season due to the consistently higher air and soil temperatures.  
From December to February, the monthly GPP was relatively high but the net carbon uptake was less than during the year  
265 | 2010–2011 due to the much higher respiration rates. From February to April, soil moisture was relatively low and VPD was  
high, and thus the carbon uptake by photosynthesis was limited. This led to the most positive carbon balance of all years. On  
the other hand, the monthly values of NEE and any of the environmental variables were not linearly correlated ( $R^2 < 0.05$ ,  $p$   
> 0.1). The lack of significant correlations may indicate that also at monthly scale the relation between NEE and the  
environmental drivers are non-linear and thus it would not be straightforward to separate the effects of the different drivers.  
270 | Furthermore, confounding effects by phenological variations are likely during the transitions from wet to dry season.

There was roughly a ten-fold difference in the monthly GPP sums between the wet and dry seasons. During the dry season,  
the grasses are dormant and only trees are contributing to GPP. During the dry season, this contribution did not vary between  
the years, even though soil moisture varied significantly. Therefore, the inter-annual variation in GPP was largely due to the  
variation during the wet season.

275 | At a monthly time scale there were two periods which largely determined the inter-annual variation of NEE. Firstly, at the  
beginning of the rainy season (September to November) NEE showed a large variation which was due to variation in both

the respiration and GPP components. Secondly, from December to January the ecosystem was taking up carbon during each year. During this period the monthly respiration and GPP were highest and the monthly respiration followed precipitation patterns. The primary carbon uptake period spanned from December to January, whereas the total carbon uptake period varied in magnitude and in length from 3 to 6 months. There was some variation in the date of the transition to carbon uptake period, which took place on 20 November in the year 2010–2011 and on 25 November in 2011–2012 whereas in year 2012–2013 this transition took place on 10 December (Fig. S3).

In conclusion, the high precipitation in December and January led to large carbon uptake rates during the growing season. On the other hand, early rainfall in September and the relatively high air and soil temperatures throughout the year resulted in a significantly higher yearly respiration sum and thus in a more positive carbon balance.

### 3.4 Annual carbon balances

The carbon balances ( $\pm$  uncertainty) from 1 September to 31 August for the years 2010–2011, 2011–2012 and 2012–2013 were  $-85 \pm 16$ ,  $67 \pm 20$  and  $139 \pm 13$  g C m<sup>-2</sup> yr<sup>-1</sup>, respectively (Table 3). The total uncertainty for these years was 19 %, 30 % and 9 % of the corresponding annual balance. The mean annual random measurement error was 6 %, the gap-filling error was 4 %, and the friction velocity filtering error was 18 %. The uncertainty due to the systematic flux loss correction error was about 1 % of the annual carbon balances.

While the uncertainty derived for the eddy covariance measurements can be considered moderate, it should be noted that the estimates of the ecosystem carbon balance are also affected by the calculation of storage fluxes. The 2012–2013 CO<sub>2</sub> balance calculated using the two-point estimate for the storage flux was 88 g C m<sup>-2</sup> yr<sup>-1</sup>, which was 51 g C m<sup>-2</sup> yr<sup>-1</sup> less than the balance based on a single CO<sub>2</sub> concentration measurement level. The one-point storage flux was used for the whole measurement period because the two-point concentration data covered only the last year of measurements. Assuming a similar influence on the annual balance of the other years, the CO<sub>2</sub> balance of the growing season 2011–2012 remains slightly positive, while that of 2010–2011 becomes even more negative.

The changes in the yearly NEE sum cannot be explained by the changes in annual precipitation, temperature, length of rainy season or peak NDVI. However, the number of days when soil moisture was higher than 7 % is related to the annual NEE sum. The soil moisture of 7 % is thought to be a critical limit below which plants become water stressed (Archibald et al., 2009). Given that our data only covered three years, it is not possible to generalize the relation between the annual carbon balance and the number of wet soil days. Moreover, at monthly and weekly scales the carbon balance and wet soil days were not correlated (Table 3).

The annual GPP variation followed the variation in precipitation and peak NDVI, whereas the relation between the annual respiration and environmental drivers was not clear. As shown in Sect. 3.3, the environmental drivers such as soil moisture and soil temperature do partly control the wet season carbon fluxes, while the carbon balance of a dry season is less sensitive to the changes in these variables. Therefore, the environmental drivers can have a different kind of effect on carbon balance during different seasons. Furthermore, as the annual sum of NEE is a small difference of two large components, i.e. carbon

310 uptake by photosynthesis and carbon release to the atmosphere by respiration, the NEE sum is sensitive to small changes in its components.

### 3.5 NDVI as proxy for GPP

315 There was a strong positive correlation between the monthly sum of GPP and the monthly mean NDVI ( $R^2=0.83$ ,  $p<0.001$ ) (Fig. 98). Sjöström et al. (2009) also found a high correlation between the 8-day NDVI mean and GPP sum in Sudanian savanna with a tree cover of 7 %.

320 Figure 109 shows a 12-year time series of monthly NDVI and precipitation data for Welgegund. The peak value and the shape of the annual cycle of both variables vary significantly between the years. The peak NDVI occurred each year between December and March and it lagged the peak rainfall by 1 or 2 months with the exception of the year 2007. ~~Within our flux data period, the peak NDVI was similar in 2011–2012 and 2012–2013, because it did not capture the rainy season peak in GPP in 2012–2013. On the other hand, it did highlight the year 2010–2011, which had a significantly higher GPP. Within our three year flux data period, the peak NDVI was related to the peak GPP in year 2010–2011 and in year 2011–2012 but it did not capture the rainy season peak in GPP in 2012–2013.~~ Based on the NDVI data, it can be concluded that the year 2010–2011 represents a common pattern at this site, whereas in 2011–2012 and 2012–2013 the NDVI peak values were lower than the long-term average.

325 Scanlon et al. (2002) demonstrated with a 16-year NDVI time series from the Advanced Very High Resolution Radiometer across a rainfall gradient that grassy areas contributed most to the inter-annual variation in NDVI. In addition, trees have been shown to have more consistent phenological cycles in savannas (Archibald and Scholes, 2007). Therefore, according to NDVI dynamics, the Welgegund site shows characteristics of a grassland.

330 From September 2001 to August 2013, the yearly maximum values of the measurement site NDVI were on average 0.02 units smaller than those of a nearby moist sandy grassland area which is not grazed (land-use class 6 in Fig. S1). This difference is most probably due to heavy grazing at the measurement site.

### 3.6 Comparison to other sites

335 The annual NEE sum and its inter-annual variation at our site differ significantly from the results reported by a previous study at a grazed savanna grassland in Dahra, Senegal (Tagesson et al., 2015, 2016b). The Dahra site had a peak MODIS LAI (MOD15A2) between 1.4 to 2.1 and a mean annual precipitation of 524 mm, which are similar to the Welgegund site. However, the yearly carbon balance at Dahra, which varied from -336 to -227 g C m<sup>-2</sup> during three years, showed that this site is a strong sink. The major difference between these two sites is that the dominant grass species change yearly at Dahra, whereas Welgegund has a perennial grass layer. The large difference in the carbon balance is due to the much larger carbon uptake at Dahra during the rainy seasons, which may be explained by the moderately dense C<sub>4</sub> ground vegetation and high soil nutrient availability.

340

On the other hand, the carbon balance at our site is similar to the balance measured at the Skukuza site in Kruger National Park, South Africa, which has yearly precipitation similar to Welgegund but a significantly higher tree cover of 30 % (Archibald et al., 2009). The reason for this agreement in carbon balance is probably the large mammalian herbivore population and fires at the Skukuza site, which make the carbon balance more positive.

- 345 At the savanna sites of Nalohou, Benin and Bontioli, Burkina Faso, which have significantly higher annual precipitation (852 and 1190 mm, respectively) and LAI, the carbon balance varied from  $-429$  to  $-136$  g C m<sup>-2</sup> yr<sup>-1</sup> (Ago et al., 2014; Brümmer et al., 2008). These sites were not grazed but the grasses were burned annually. During the dry season at the Nalohou site, higher soil moisture resulted in higher soil respiration rates and thus a more positive total carbon balance. In contrast, at the Bontioli site higher precipitation during the transition period from wet to dry season resulted in a higher uptake of carbon.
- 350 However, at Welgegund the dry season fluxes were an order of magnitude smaller than the wet season fluxes and the dry season carbon balance did not significantly vary between the years. Similarly, the dry season carbon balance did not show significant differences at grassland, cropland and nature reserve sites in the Sudanian Savanna which receives a similar amount of precipitation to the Welgegund site (Quansah et al., 2015).

#### 4 Conclusion

- 355 The results of this study indicate that the inter-annual variation of NEE is high at the Welgegund savanna grassland site, as compared with a grazed savanna grassland in Senegal. The carbon balances for the years 2010–2011, 2011–2012 and 2012–2013 were  $-85 \pm 16$ ,  $67 \pm 20$  and  $139 \pm 13$  g C m<sup>-2</sup> yr<sup>-1</sup>, respectively. This is similar to the variation at the Kruger National Park where the annual NEE ranged from  $-138$  to  $155$  g C m<sup>-2</sup> yr<sup>-1</sup> during a 5-year measurement period (Archibald et al., 2009).
- 360 The night-time respiration was not significantly dependent on either soil moisture or soil temperature on a weekly temporal scale, whereas on an annual time scale higher respiration rates were observed when soil temperatures were higher. ~~The lack of functional dependence on soil moisture and temperature differs from the findings of previous studies. Similar results were observed at a West African dry savanna, where none of the environmental variables could explain the half-hourly night-time respiration measurements (Tagesson et al., 2015).~~
- 365 The beginning of the rainy season (September to November) and the mid-growing season (December to January) largely determined the inter-annual variation of carbon balance. An early rainfall in September 2012 and the higher soil temperature resulted in higher respiration rates and thus a more positive carbon balance. During the mid-growing season both the ecosystem respiration and GPP were highest and the monthly respiration rates followed the precipitation patterns.
- 370 Future work should focus on the respiration variations during the daytime. With more direct soil respiration measurements and cattle respiratory flux measurements the overall uncertainty of the total ecosystem respiration estimates could be reduced. In addition, these measurements would provide much needed information about the environmental drivers of respiration specific to savanna ecosystems.



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## Tables

**Table 1. Dominant plant species within the flux footprint. ~~The species names include the name of the publishing author. The plant species name is written in italics whereas the roman text refers to the author. Some author names are abbreviated.~~**

Species	Growth form	Mean leaf area (cm <sup>2</sup> )	Mean height (m)	Mean canopy (m)	Number of individuals
<i>Vachellia erioloba</i> (E.Mey.) P.J.H.Hurter	Tree	5.9	3.2	1.8	16
<i>Searsia pyroides</i> (Burch.) Moffett	Tree	8.2	2.9	1.2	9
<i>Celtis africana</i> Burm.f.	Tree	18	3.4	1.4	6
<i>Ehretia rigida</i> (Thunb.) Druce	Tree	4.1	2.5	1.8	5
<i>Vachellia karroo</i> (Hayne) Banfi & Galasso	Tree	9.4	2.4	1.6	3
<i>Diospyros lycioides</i> Desf.	Shrub	7.9	1.8	0.8	7
<i>Asparagus larycinus</i> Burch.	Shrub	0.7	1.5	1.1	6
<i>Asparagus suaveolens</i> Burch.	Shrub	0.5	1.3	0.9	4
<i>Grewia flava</i> DC.	Shrub	6.7	2.2	1.8	3

<i>Pentzia globosa</i> Less.	Forb		< 0.5		18
<i>Walafriada densiflora</i> Rolfe	Forb		< 0.5		11
<i>Hermannia depressa</i> N.E. Br.	Forb		< 0.5		8
<i>Dicoma tomentosa</i> Cass.	Forb		< 0.5		6
<i>Euphorbia inaequilatera</i> Sond.	Forb		< 0.5		4
<i>Panicum maximum</i> Jacq.	Graminoid		< 1.5		18
<i>Setaria sphacelata</i> (Schumach.) Stapf & C.E.Hubb. ex Moss	Graminoid		< 1.5		14
<i>Eragrostis trichophora</i> Coss. & Durieu	Graminoid		< 1.5		11
<i>Themeda triandra</i> Forssk.	Graminoid		< 1.5		10
<i>Eragrostis curvula</i> (Schrad.) Nees	Graminoid		< 1.5		9

485 **Table 2. One-sided leaf area index and leaf biomass within the flux footprint area in 2011-2012.**

Sampling date	Herbaceous LAI	Woody LAI	Total LAI [m <sup>2</sup> m <sup>-2</sup> ]	Herbaceous LAI/ Total LAI [%]	Herbaceous [g m <sup>-2</sup> ]	Woody [g m <sup>-2</sup> ]	Total [g m <sup>-2</sup> ]
15.4.2011	1.20	1.12	2.32	51.7	383	261	644
16.7.2011	0.12	0.25	0.37	32.4	147	86	233
16.10.2011	0.30	0.47	0.77	39.0	108	169	277
16.1.2012	0.53	0.79	1.32	40.2	157	224	381

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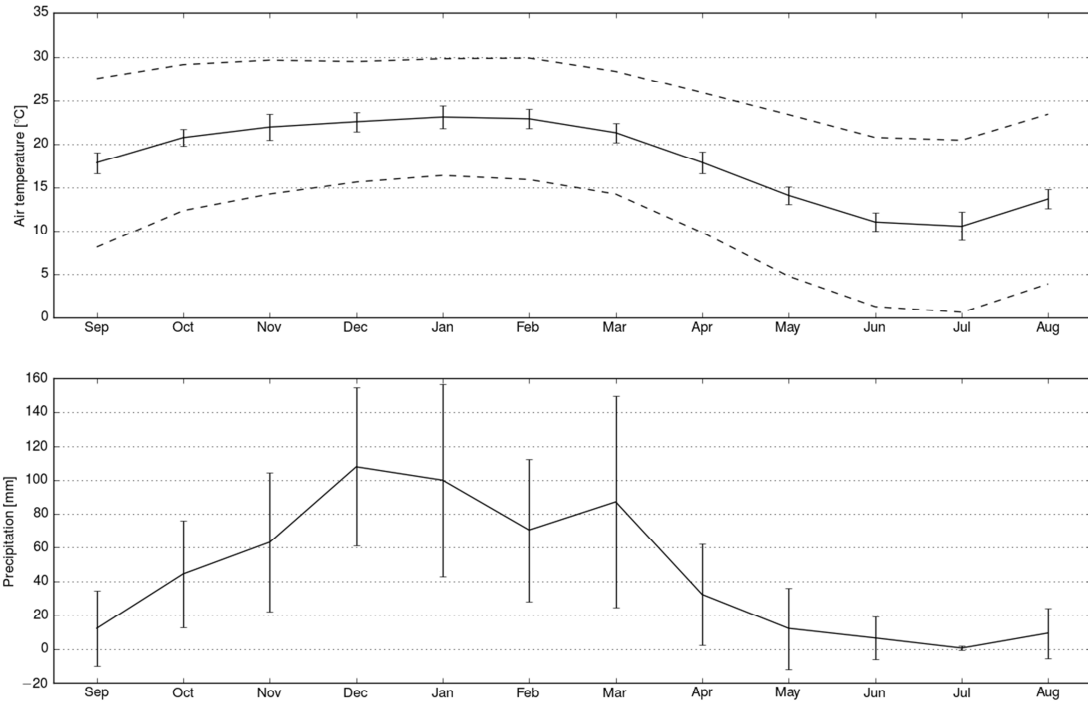
**Table 3. Annual carbon balance and key environmental drivers calculated for each year from September to the August of the following year.**

	NEE [gC m <sup>-2</sup> yr <sup>-1</sup> ]	GPP [gC m <sup>-2</sup> yr <sup>-1</sup> ]	Respiration [gC m <sup>-2</sup> yr <sup>-1</sup> ]	Annual precipitation[mm]	Rainy season length [days]	Peak NDVI	Number of days when soil moisture was higher than 7 %	Annual total PAR [mol m <sup>-2</sup> ]
2010	-85 ± 16	-1360	1275	721	207	0.53	232	15500
2011	67 ± 20	-1014	1080	422	178	0.43	101	15300
2012	139 ± 13	-1179	1318	615	228	0.44	79	15500

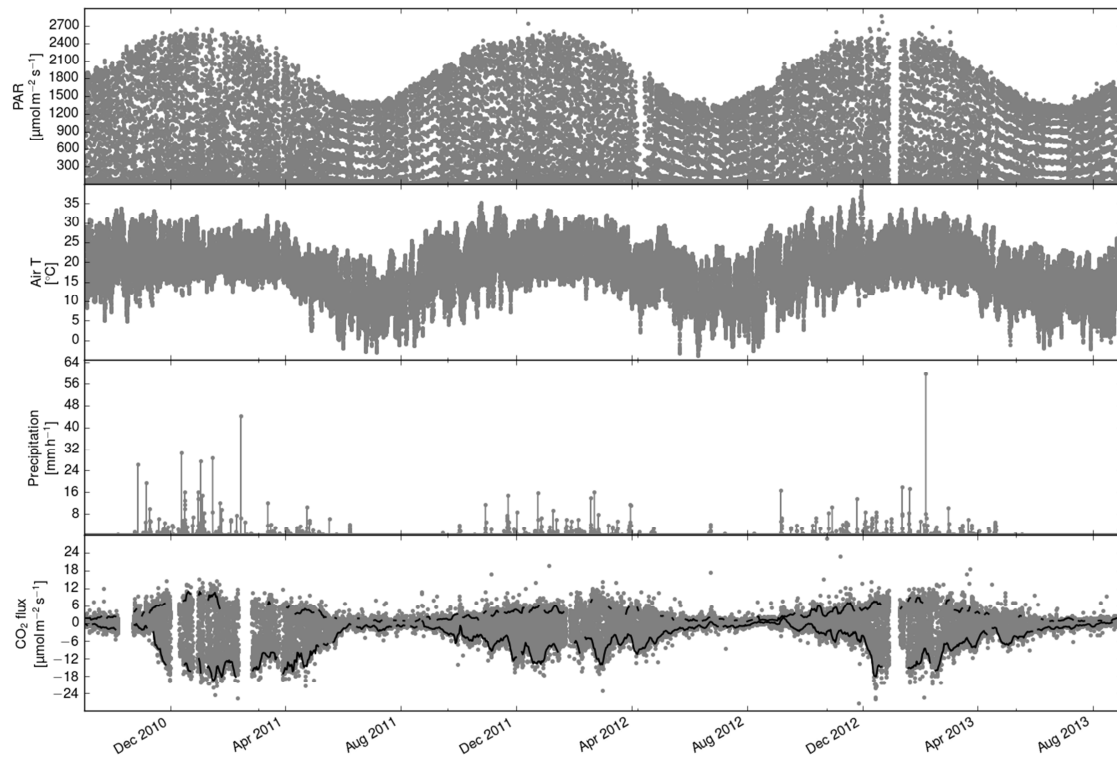
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## Figures



**Figure 1. Monthly mean meteorological data from a nearby weather station in Potchefstroom during 1998-2014. The upper figure shows the mean (solid line) and minimum and maximum (dashed lines) air temperatures. The lower figure shows the mean precipitation. Error bars indicate  $\pm 1$  standard deviation.**



**Figure 2.** Time series of incoming PAR, air temperature, precipitation and CO<sub>2</sub> flux for the measurement period from September 2010 to August 2013. The solid lines within the CO<sub>2</sub> flux data show the five day centered mean of minimum daytime and maximum night-time CO<sub>2</sub> flux. Incoming PAR, air temperature and CO<sub>2</sub> flux data are 30 minute averages.



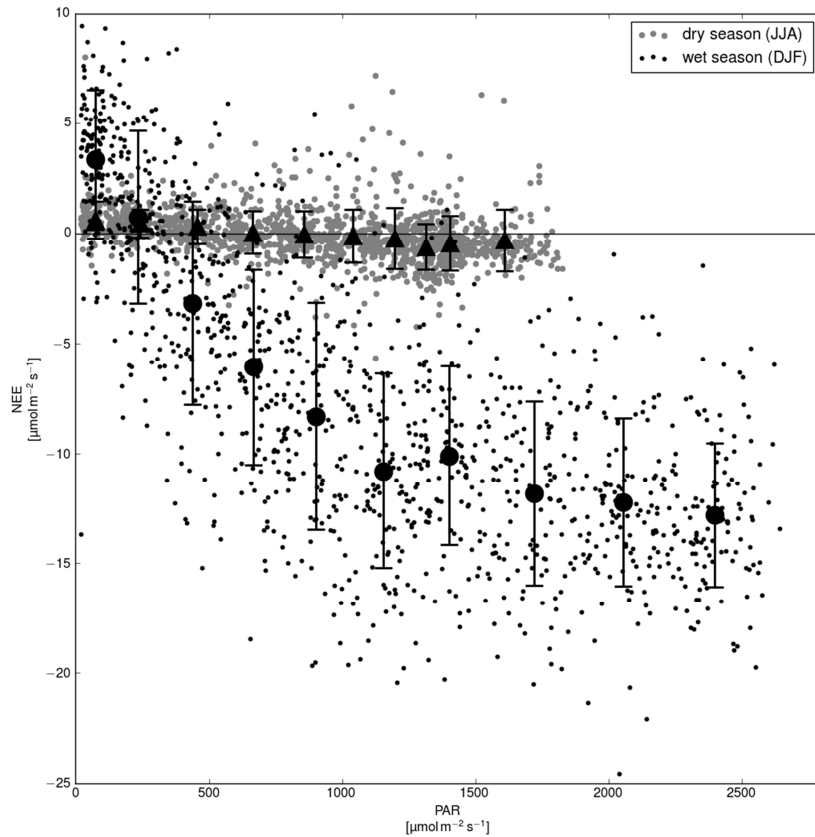
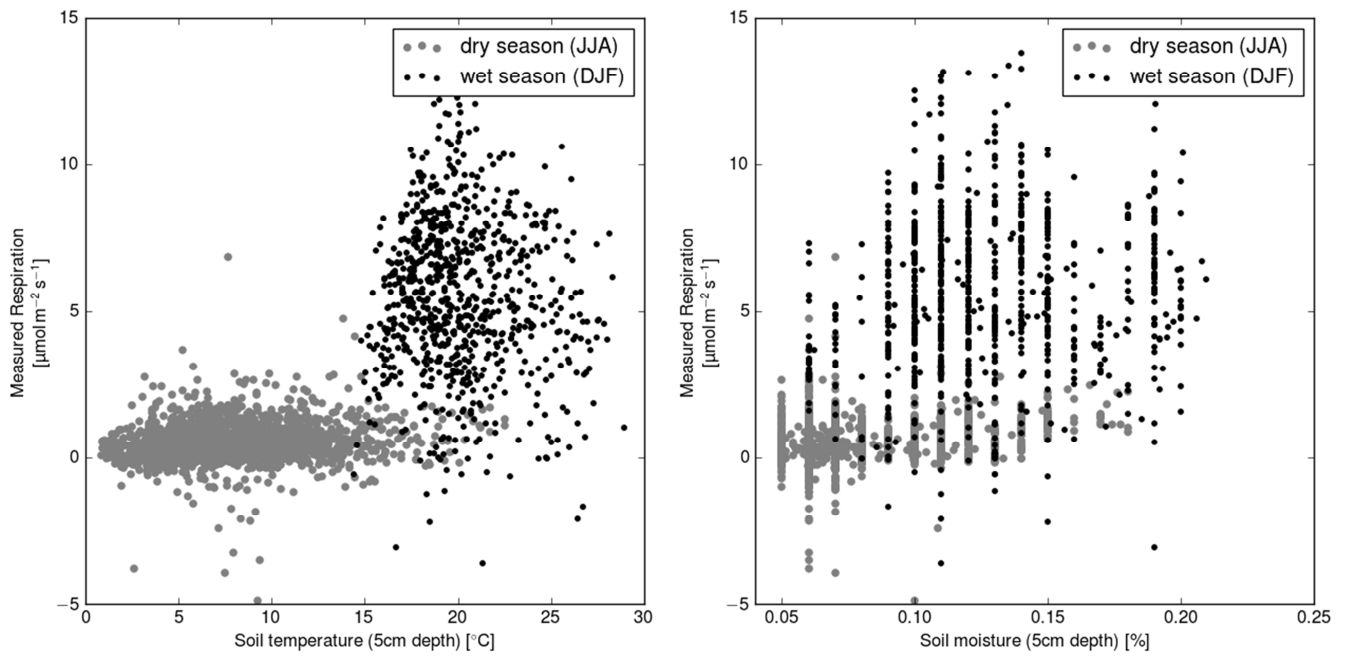


Figure 3. Relationship between PAR and daytime NEE for wet (DJF) and dry (JJA) seasons from September 2010 to August 2011. The triangles (dry season) and circles (wet season) indicate bin averaged values and error bars indicate  $\pm 1$  standard deviation. Daytime was defined as periods when PAR is higher than  $20 \mu\text{mol m}^{-2} \text{s}^{-1}$ . ~~The figure shows 2814 values and each bin contains at least 100 values~~ Each bin in dry season contained 157 values whereas the wet season bins contained 125 values.

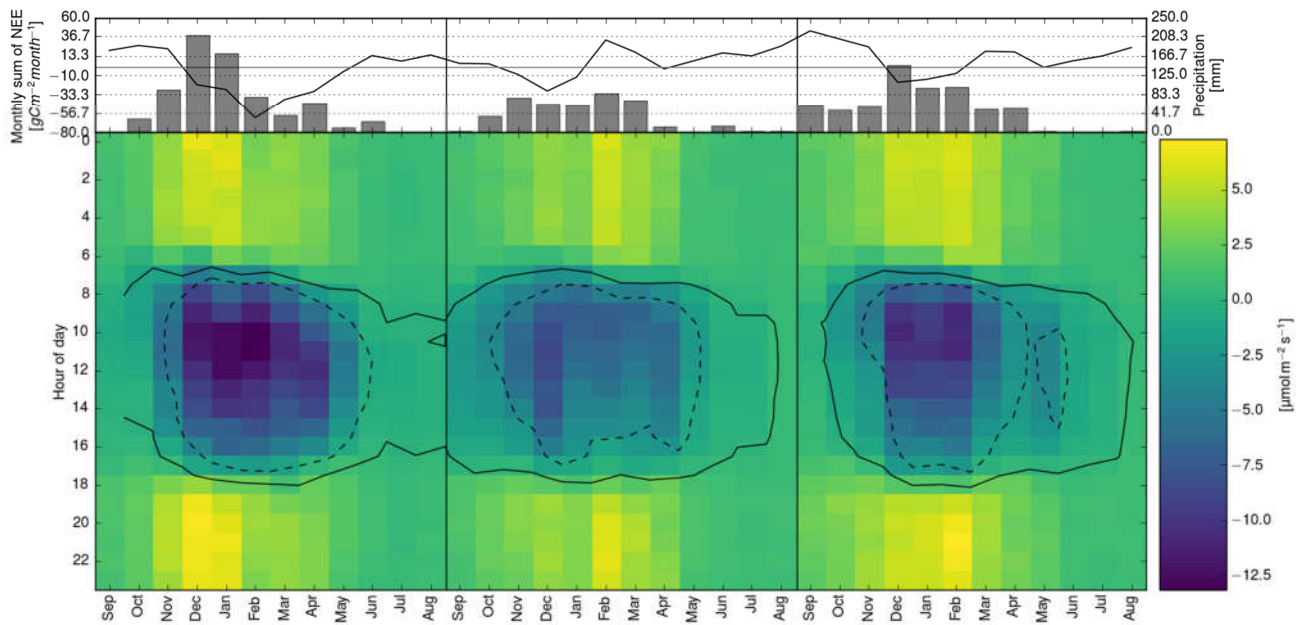




**Figure 4. Relationship between night-time respiration and soil temperature (left) and soil moisture (right) for wet (DJF) and dry (JJA) seasons from September 2010 to August 2011. Night-time was defined as periods when PAR is less than  $20 \mu\text{mol m}^{-2} \text{s}^{-1}$ .**

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**Figure 5.** Contour plot of monthly mean NEE for each hour of day. The solid line shows the zero isoline and the dashed line shows the NEE values less than  $-0.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ . The upper panel shows the monthly NEE as a solid line and the monthly precipitation as bars.

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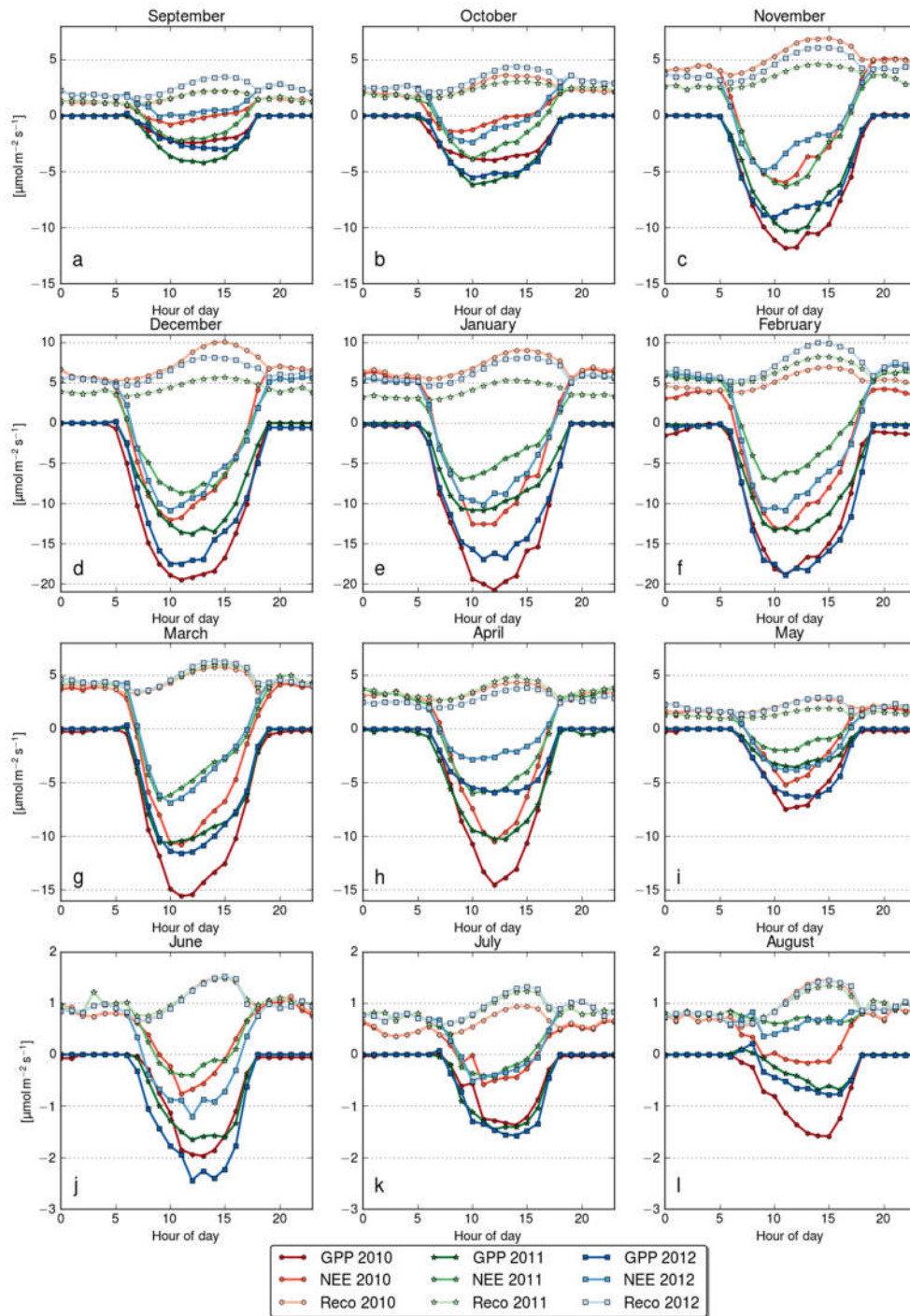
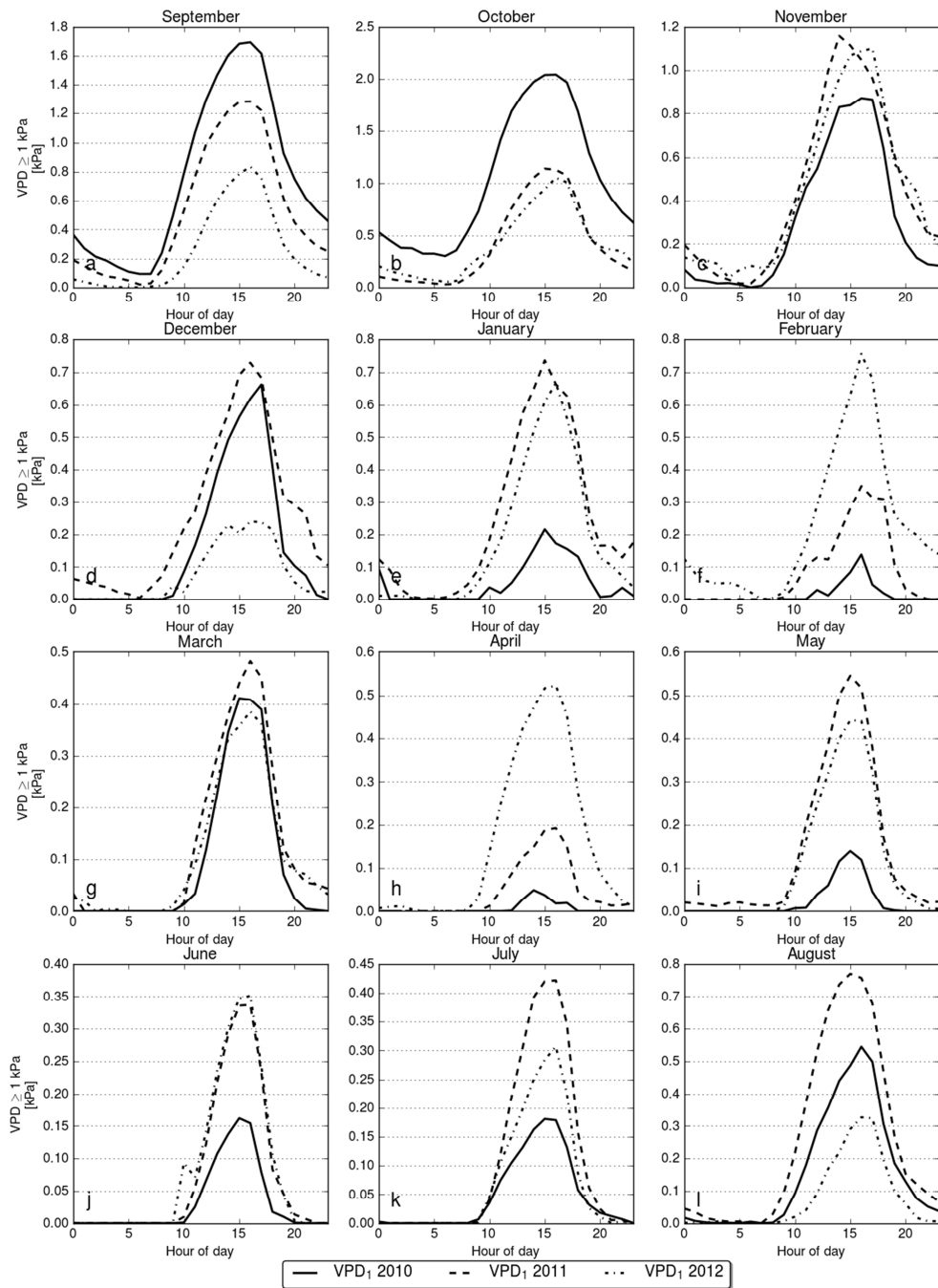
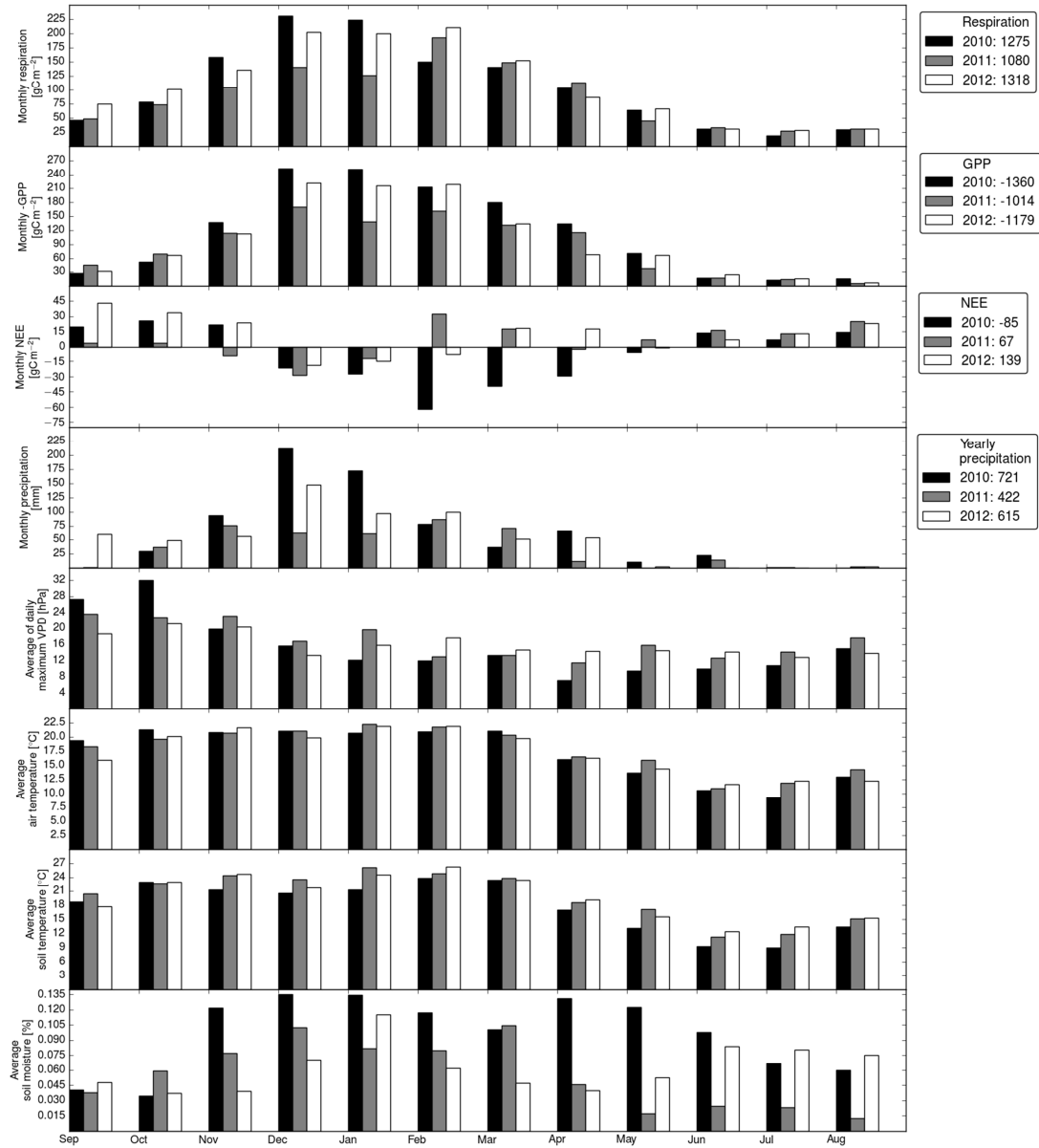


Figure 6. Monthly mean diurnal cycle of GPP, respiration and NEE for each month of the years 2010, 2011 and 2012.



**Figure 7. Monthly mean diurnal cycle of the VPD values above 1 kPa,  $VPD_1$ , for yearly periods between 1st of September and 31 of August years 2010, 2011 and 2012.**



**Figure 87.** Monthly sums of respiration, GPP, NEE, precipitation and the monthly average of air temperature, soil temperature, soil moisture and daily maximum VPD. The panels on the right side show the yearly sums for the years 2010-2011, 2011-2012 and 2012-2013.

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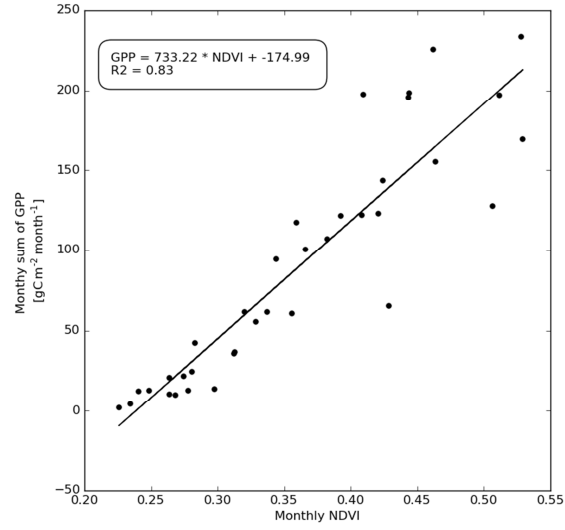
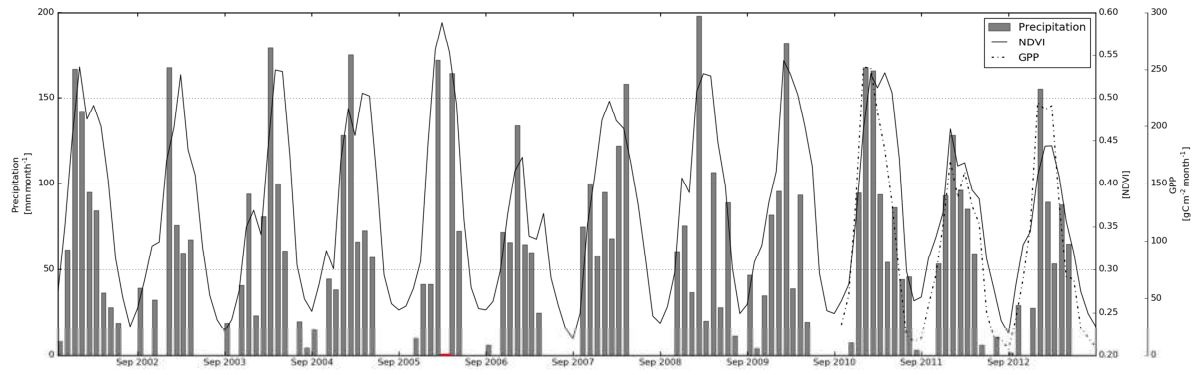


Figure 28. Linear regression between monthly NDVI and monthly sum of GPP.

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**Figure 109.** Time series of monthly precipitation (bars), NDVI (solid line) from September 2001 to August 2013 and GPP from September 2010 to August 2013. The precipitation was measured at a nearby weather station (SAWS) in Potchefstroom. The red bar denotes a missing precipitation value in February 2006.