Final Authors Response

We thank both reviewers for their extensive and insightful feedback.

Anonymous Reviewer #1

The paper by Räsänen et al. explores carbon dioxide fluxes measured with the eddy covariance method for three years at a grazed savanna grassland in Welgegund, South Africa. The material is appropriate for a scientific study and the data obtained appear to be high-quality. It is relevant for many African ecosystems to focus on CO2 fluxes response to environmental drivers in order to better predict fluxes patterns in the context of climate change. Therefore, the work is interesting and worthy of publication in Biogeosciences Journal because of the lack of knowledge regarding the carbon cycle for Africa continent. However, I have a number of issues with the paper which lead me to suggest that it requires major revisions before it becomes acceptable for publication in BG.

General Comments:

1) Firstly, while the study site is located on a savanna grassland which is grazed by cattle and sheep, authors did not provide any information on the average stocking rate and the management of the site during the studied period. Is the site grazed intensively or not? What was the stocking rate? How the grassland was managed?

Authors' response: Unfortunately more detailed measurements of cattle respiration were not available for this study. We added a paragraph to the site description about the farm management which is a typical commercial farm in South Africa.

"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 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."

What is the slope of the field? At the measurement height what is the fetch? Was the fetch adequate to characterize the carbon dioxide and water vapor fluxes of the vegetation type? These are important for understanding and interpreting the results.

Authors' response: The measurement site is surrounded by flat homogeneous thornveld. As shown by the footprint climatology and the land-use map, the fetch is adequate for measuring fluxes over this vegetation type.

2) It is also well known (see references below) that grazing affects a range of ecological and biogeochemical processes and properties, including plan community composition, soil physical properties, soil C and nitrogen content and the magnitude of C and carbon dioxide exchanges which in turn influence soil organic carbon storage. This study could have been more attractive if the impact of grazing on carbon dioxide exchange had been investigated. This probably would help to better assess for example the relation between the total ecosystem respiration and environmental drivers.

Authors' response: It is true that there is heavy grazing within the measurement footprint and that affects a range of processes. Unfortunately, more detailed study of the grazing effects was not possible here.

3) Authors used the Kaimal cospectra in the computation of the correction factors that are used to correct the high frequency losses (L129 – 130). However, recent studies (Mamadou et al., 2016) showed that Kaimal cospectra can be significantly different from sensible heat cospectra, and the high-frequency loss correction for CO2 using these different cospectra resulted in the large difference in CO2 flux calculations, i.e., using Kaimal cospectra can result in an overestimation of CO2 fluxes even if the site could not be considered as difficult (i.e., fairly flat, homogeneous, low vegetation, sufficient measurement height). Especially, at their studied site, authors found that the choice of Kaimal rather than sensible heat cospectra reversed the annual carbon balance from being a net C sink to being a weak C source. Did the authors verify if their kaimal cospectra differ or not from sensible heat cospectra before chosen them as idealized cospectra?

Authors' response:
The use of the so-called Kaimal cospectra is a common practice in eddy covariance studies (e.g. Aubinet et al.: Eddy Covariance, A Practical Guide to Measurement and Data Analysis, 2012). We followed this practice and used Kaimal cospectra with a system-specific transfer function for correcting for the flux losses in question. Mamadou et al. (2016) have very recently (unavailable at the time of writing of our paper) published a paper that indicates that, for an unspecified reason, the local cospectra at their site differ from the generic Kaimal cospectra. While this is an interesting observation that deserves attention in the future, it is not obvious that the implications of the potential differences would be as significant at other sites as their results may imply. It should be noted that the cut-off frequency of their measurement system was 0.37 Hz, while we were able to resolve much higher frequencies (half-power frequency 1.6 Hz). Thus our flux loss corrections are much smaller than those applied by Mamadou et al. (2016), 5% on average and <10% in 98% of the data. If we assume that our correction coefficients are uncertain by a factor similar to that estimated by Mamadou et al. (2016), the flux uncertainty resulting from these small correction coefficients would be minor. Therefore, in the present study, we do not pursue the issue of spectral corrections any further; however, we did add the uncertainty related to flux loss corrections in our uncertainty estimate for the annual CO_2 balance.

4) Most of results presented in the section 3.4 are too much qualitative, superficial and descriptive and should be supplemented with additional statistical analyses in order to provide more quantitative rigor.

Authors' response: The data covered only three years and thus a statistical analysis of annual averages is not very meaningful. To improve the presentation, the differences between the years were analysed from monthly data, including statistical analysis.

5) The uncertainties associated to the annual carbon dioxide balance estimation are not evaluated. This remains a great lack for the study. The authors also clearly mentioned in their introduction that environmental drivers for the inter-annual variation in NEE are poorly understood. Unfortunately no progress regarding this point has been made within the present study.

Authors' response: New subsection about error estimation was added to the methods section and the uncertainty of annual carbon dioxide balance was estimated.

Specific comments

L18-19: What about the dependence, at monthly scale, of the nighttime respiration on soil moisture or soil temperature?

Authors' response: For the gap-filled monthly sum of the night-time respiration, the relation with soil temperature is exponential. For the soil moisture the relation is not clear.

L24-25: by increasing autotrophic respiration?

Authors' response: Probably, but we cannot infer that from total ecosystem respiration.

L32: The seasonal cycle of what? Please clarify.

Authors' response: Rephrased. "The savanna ecosystems are generally characterized by alternating wet and dry seasons, during the latter of which wildfires can occur."

L32-33: The alternation of "wet and dry seasons" cannot in my view be generalized for the "whole Africa". In other regions of Africa, the dry and wet seasons are separated for example by two transitional seasons...

Authors' response: Added a sentence about transtional seasons.

L67, in site description section: Please, give values of the roughness length, zero-displacement height and site's slope.

Authors' response: The median of the aerodynamic roughness length was estimated to be 0.42 m assuming a low zero-plane displacement height.

L102-103: Specify the sampling rate of the meteorological variables.

Authors' response: The meteorological variables were sampled every minute and 15 min averages were recorded.

L113: Specify the type of the gas analyzer.

Authors' response: Specified.

L115-118: What are the characteristics of the sampling tube (inner diameter etc.), the pump and the gas used for the zero and span?

Authors' response: Corrected. *"The material of the inlet tube (ID 4mm, OD 6mm) was PTFE, and the pump was Dürr A-062 E1. The gas analyzer was calibrated every month with a high-accuracy* CO_2 *span gas (378 ppm verified by the Cape Point GAW station), and Afrox instrument grade synthetic air with* $CO_2 < 0.5$ *ppm was continuously used as a reference gas."*

L127: Give an indication of the magnitude of low frequency correction factors.

Authors' response: We added statististics on the magnitude of spectral corrections to the text according to the data presented above.

L129-130: Provide an illustration of kaimal and the sensible heat cospectra according atmospheric stability to attest that both cospectra match.

Authors' response: Since the flux loss corrections required for our data are small, irrespective of the reference cospectrum adopted, we did not study the spectral characteristics further here; however, we included a related uncertainty estimate, as explained above.

L133: Replace the calculated fluxes by "the corrected fluxes".

Authors' response: Corrected.

L133: What was the fraction of data excluded this way?

Authors' response: u* filtering excluded 18 % of the data.

L133-136: Do you only use u* filtering criteria to discard bad data? if Yes, explain why.

Authors' response: *"In addition,* CO_2 *fluxes were filtered by setting an acceptable range for average* CO_2 *concentration (300–500 ppm), Licor pressure (50–120 kPa) and* CO_2 *concentration variance (0–10* ppm^2*), which resulted in a 3 % loss of flux data in total."*

L181: Complete "air" with temperature.

Authors' response: Corrected.

L182: You never indicated how water vapor data have been treated. What is the cut-off frequency for H2O fluxes? How these data have been corrected for low and high frequency losses? Which criteria have been used for the filtering of bad data?
L183: Explain how high evapotranspiration rate were due to higher precipitation and transpiration rate during the rainy season? What about soil evaporation?

Authors' response: The evapotranspiration data were excluded from the present analysis.

L206: air or soil temperature?

Authors' response: Soil temperature

L211- 215: The low (high) values of the correlation coefficients cannot only be used to attest the robustness of dependences. These must be accompanied with the p-values.

Authors' response: The method comparison was removed and the Lloyd and Taylor (1994) model was used for fitting the night-time respiration data. The modelled respiration rates agreed well with the measured respiration (R^2=0.56, p-value < 0.01).

L225- 226: showed how?

Authors' response: The peak carbon uptake can be seen from the darkest pixels in Figure 6. Peak radiation was checked from data (data not shown).

L232: I cannot get this conclusion...

Authors' response: Added supporting figure to the supplement. Relationship between bin averaged VPD and daytime NEE was plotted.

L223–L233: Why is there so much interpretation in the results?

Authors' response: The text in this section was rephrased and an analysis of diurnal cycle of GPP, respiration and VPD was added to the section.

L301: most or must?
Authors' response: most

L305-310: I am afraid that because of the difference of their climate, the Dahra site and cannot be easily compared to the Welgegund site. You should mention this in your discussion.

Authors' response: Removed the sentence and added "The large difference in the carbon balance is due to much larger carbon uptake at Dahra during the rainy seasons which might be explained by moderately dense C_4 ground vegetation and high soil nutrient availability."

L315, L317: Write Nalohou not Nolohou. . .

Authors' response: Corrected.

L475: Figure 1 and also in the title: "air" or "soil" temperature?

Authors' response: Corrected.

L500: Figure 3: Is it necessary to show evapotranspiration curve?

Authors' response: The evapotranspiration curve was removed.

L522: Figure 4: bin averaged for how many data?

Authors' response: The figure shows 2814 values and each bin contains at least 100 values.

Anonymous Reviewer #2

Major concerns:

Generally, the language needs to be improved and the manuscript must be much more concise. This goes for all sections. A large section of the results is about testing different partitioning methods, but it is not included as an aim in the introduction. In case an aim of the study is to investigate different partitioning methods, please clarify this already in the introduction. Otherwise, I would recommend using the one that works the best. I fully understand why the night-time methods are not working well, since it has generally been seen that at a diurnal time scale respiration is not strongly linked to temperature for savanna ecosystems. But I cannot understand why the daytime method is working so poorly. Are you sure that you fitted the equation correctly? After putting a lot of effort into partitioning of the data, the partitioned data is not even shown except in the format of monthly averages. Please, show the partitioned data as well.

Authors' response: The testing of partitioning methods was not a major goal of this study. The method comparison has been removed and the Lloyd and Taylor (1994) model was used for fitting the night-time respiration data. The manuscript was made more concise and the language was improved.

Why did you use monthly averages in the investigation of seasonal variation? I cannot see any reason for not using daily sums or averages. By using monthly estimates you hide a lot of the variability and it is more difficult to see the relationship to the environmental variables.

Authors' response: The kind of analysis we had done would be very difficult to do at daily time scale because the daily data is noisier and the data covered three years.

There is no statistical testing of relationships of the fluxes to the environmental variables. It is just stated that high flux values can be explained by some variables. But you do not explain how you have tested for this.

Authors' response: Results of linear regression analysis between NEE and environmental drivers were added to the section 3.3.

Specific comments:

L19-20. There is a contradiction in this sentence: are the balances yearly or are they for the growing season,please rephrase.

Authors' response: Corrected.

L23-24 Please clarify in the abstract why: This study underlines the difficulty in establishing a functional relation between the total ecosystem respiration and the environmental drivers in savanna ecosystems.

Authors' response: Sentence removed.

L24-25 There must be something that explains the inter-annual variability, even though it might be that you have not seen any explanations in your data sets.

Authors' response: Sentence removed.

L32 reference for the 20% of global area please.

Authors' response: Same reference.

L35. Please rephrase, it sounds like the humans are grazing.

Authors' response: Corrected.

L42 reference please

Authors' response: Added.

L45 . instead of ,

Authors' response: Corrected.

L51 This is not correct: Tagesson, Ago and Quansah is all sites affected by either grazing or agriculture, there are also EC towers in Wankama Falls, Agofou, and Demokeya, which are all affected by grazing or agriculture; see (Tagesson et al., 2016a)

Authors' response: Corrected.

L55 please include (Tagesson et al., 2016a) that investigated annual budgets for 6 different sites across the Sahel.

Authors' response: Included.

L61 I do not understand why you use NDVI as a proxy for GPP. You have EC measurements, why not use them directly? Please clarify.

Authors' response: This was done to assess the long-term (in this case 12 years) productivity at the measurement site.

L70 Do you have any data on number of sheep and cattle?

Authors' response: We added a paragraph to the site description about the farm management which is a typical commercial farm in South Africa.

"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 approximately 6000 hectars, which consists of natural grazing (e.g. at the measurement site), planted grazing and maize/sunflower fields that are 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 on the grazing patterns but they do move the cattle around to optimize grazing and protect the field against overgrazing."

L86 please give exact sampling dates.

Authors' response: Exact sampling dates were added to the Table 3.

L91 What do you mean, did you count all plants inside the 100m2 plot or did you identify all species?

Authors' response: *"All of the plant species were counted and identified up to species level,and their major growth form was recorded."*

L101 Are not all these measurements relevant to Ecosystem dynamics? Please use a different word than ecosystem dynamics.

Authors' response: Carbon cycle dynamics.

L103 At 2 and 8 m height or at several heights between 2 and 8 m? What was the height of the tipping buckets?

Authors' response: Rephrased. Tipping bucket was installed at 1.5 m height.

L102 What sensors were used for the meteorological measurements?

Authors' response: Corrected.

"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)"

L108 What sensor? what did it measure?

Authors' response: Soil moisture sensor at 5 cm depth.

L115 Why 20 m when height of the sensor was only 9m, should be possible to have a much shorter tube than this. What sort of tube did you use, inner diameter? No filter between the IRGA and the incoming air?

Authors' response: The gas analyzer is located inside a trailer that is some distance away from the measurement mast. The gas sampling tube was PTFE (ID 4mm, OD 6mm) and it had a filter.

What was the separation length between the inlet tube and the anemometer?

Authors' response: 20cm

L137-140 and Figure 2. The footprint is never this uniform for different wind directions, if you have estimated the footprint for each 30 min period; it would be easy to show an average for the different wind directions.

Authors' response: Added contour of the mean 80% cumulative footprint.

L140 If the footprint is homogeneous thornveld, why do you report vegetation sampling for all other vegetation types? Looking at figure 2 with the footprint, is seems like the only vegetation cover which is affecting the EC measurements are the thornveld. If you want to present all the other data as well, I think you should you must incorporate a reason for this in the introduction, and a link to the EC data.

Authors' response: The reviewer is correct: thornveld clearly dominates the flux footprint and that is the vegetation type we focus on. For clarity, Section 2.2 on vegetation sampling and the tabulated soil data, which are included to characterize a larger area, were moved to Supplement.

L145-151 Please give equations for the all partitioning models.

Authors' response: The method comparison has been removed and the Lloyd and Taylor (1994) model was used for fitting the night-time respiration data.

L163 Why in two steps? Why give E0 an annual value and not using the moving window?

Authors' response: This makes the fitting procedure more robust.

L166 What is Fp? Why fitting this at all? Why not using the light response function that was used in the "daytime method"?

Authors' response: Fp is GPP. The fitting was done following the method by Kutsch et al. (2008).

L170 This is probably a good choice, but why not always use 1 September to 31 August or something similar? Why only estimating the growing seasons?

Authors' response: Rephrased the sentence. The analysis covered the whole years.

L174 This is incorrect MCD43A4 is not an NDVI product, it is a BRDF product, please rephrase. Why using monthly averages, when data is available as an 8 day product? It is not clear if you extracted the values of one single pixel, or did you use an average of several pixels?

Authors' response: Rephrased. Monthly average value of one 500 m pixel was used.

L176 What do you mean by that NDVI is better to use than the LAI and GPP product for vegetation structure? First, you are not studying vegetation structure, you are studying fluxes. Different products are good for different things. I agree that NDVI is a useable parameter, but it is not a real value like LAI and GPP. You cannot claim that it is better to use than these other parameters for studying vegetation dynamics. It is so far very unclear what you are going to use these data for. Please clarify. I would state that NDVI is a proxy for vegetation phenology.

Authors' response: Removed the last sentence. The NDVI was used to study long-term productivity at the measurement site.

L180 please give sum of rain

Authors' response: Corrected.

L192 In figure 4, it does not look like a linear increase until the saturation level. It is rather asymptotic

Authors' response: Removed "linear".

L197 How could the parameters get unrealistically high? In case data looks like in Figure 4, parameters should be fine. In case the relationship is very linear, the saturated GPP level gets unrealistically high, but this does not really matter for the partitioning as long as the equation is well fitted to the data. As the manuscript is written now, it seems like you want to test several different partitioning methods, if this is the case then you must show how all these different partitioning methods differ in their output. In the results section, you do not show the output of the different methods at all.

Authors' response: The method comparison has been removed.

L209 I would not say that it was fitted successfully in case the R2 value is 0.11.

Authors' response: This result was removed.

L210-215, in case you want to make a proper comparison of the different partitioning methods, you should give statistics for all methods. Please also show a figure with modelled versus measured values. In order to make a proper comparison you must separate a part of the data set to be used for the model parameterisation and one part for the model evaluation. A suggestion would be to use a bootstrapping simulation methodology.

Authors' response: The method comparison has been removed and the Lloyd and Taylor (1994) model was used for fitting the night-time respiration data. The modelled respiration rates correlated with the measured respiration (R^2=0.56, p-value < 0.01).

L216 Where did this suddenly come from. If you want to write a section about the effect of one point and two point measurements of the storage term this should be given a section of its own. Please clarify in the method section how the one point and two point storage terms were estimated. This has nothing to do with partitioning.

Authors' response: This paragraph was moved to the section 3.4.

Section 3.2

What about the partitioned GPP and ecosystem respiration data? Why did you not show the diurnal cycle of them? Additionally, what was the environmental variables controlling the diurnal dynamics. You set out in the introduction to investigate which environmental variables that affect the diurnal, seasonal and interannual dynamics, but there is no proper description of what controls the diurnal dynamics.

Authors' response: The diurnal cycle of GPP, ecosystem respiration and VPD was added to the section 3.2 and their relation to the diurnal cycle of NEE was analyzed.

Section 3.3

L235 Why did you analyse using monthly averages? Is there any reason for not using daily averages? A lot of dynamics can be hidden in case you average like that. How did you test for all these things that you claim? You state that rainfall and low VPD causes the seasonal dynamics, but there is absolutely no statistical tests done to show that these variables are determining the fluxes? A large part of the section is rather about interannual dynamics than about seasonal variation.

Authors' response: The kind of analysis would have been very difficult to do at daily time scale because the daily data is noisier and the data covered for three years. Linear regression analysis between NEE and the environmental variables was added to the section.

L266 from which date to which date?

Authors' response: from 1st of September to 31st of August

Why is NDVI included as an own section and not just incorporated in the other sections as an explanatory variable giving the phenology of the vegetation?

Authors' response: It is used to assess the long-term productivity at the measurement site. *"Based on the NDVI data, the year 2010-2011 represents a common pattern at this site, whereas the years 2011-2012 and 2012-2013 have lower NDVI peak values."*

L274 The Merbold study is rather in the spatial domain than in the temporal domain, and it is comparing sites from tropical rain forest to semi-arid savanna ecosystems so it is not strange that they see a spatial relation to rainfall.

Authors' response: Removed the sentence.

L275 Which results show this?

Authors' response: The sentence was removed.

What about interannual variation in respiration?

Authors' response: The relation between the annual respiration and environmental drivers was not clear.

L285 Demokeya has approximately 7% tree cover, i.e. about half of Welgegund. This is not a similar canopy cover.

Authors' response: Corrected.

L287 Why is it that NDVI over and underestimates at different parts of the season?

Authors' response: The sentence was removed.

L309 The strong grazing pressure cannot explain the difference as there is a very strong grazing pressure at the Dahra field site as well. Please see (Tagesson et al., 2016b). How come that the missing data of Tagesson et al can explain the difference between Dahra and Welgegund? The uncertainty estimates of Tagesson et al indicate that the missing data should not be a reason for huge uncertainty in the annual budgets?

Authors' response: Removed the sentence and added "The large difference in the carbon balance is due to much larger carbon uptake at Dahra during the rainy seasons which might be explained by moderately dense C_4 ground vegetation and high soil nutrient availability."

Have you tried to make any uncertainty estimate of the annual budgets?

Authors' response: New subsection about error estimation was added to the methods section and the uncertainty of annual carbon dioxide balance was estimated.

Table 1, please explain what the abbreviations under Species are? Example what does P.J.H.Hurter mean?

Authors' response: Specified. The plant species names include the name of the publishing author.

Table 3 and 4, please give exact sampling dates instead of column 1-4, it seems like Table 3 and 4 can be combined.

Authors' response: Exact sampling dates were added and Table 3 and 4 were combined.

Figure 1, please include error bars.

Authors' response: Corrected.

Figure 2. Why did you use a different point for the NDVI comparison? If this is the case, then it is more important to show the MODIS pixel surrounding that point. In case you want to present the results for all different vegetation types, please show the transects used for the vegetation samplings.

Authors' response: The NDVI for the measurement site was calculated at the 500 m pixel indicated by the red square in Figure 2. The NDVI comparison point in Figure 2 indicates the moist sandy grassland area which is not grazed. The NDVI signal between these two areas were compared.

"From September 2001 to August 2013, the yearly maximum values of the measurement site NDVI were 0.02 units smaller on average than a nearby moist sandy grassland area which is not grazed (land-use class 6 in Figure 2). This difference is most probably due to heavy grazing at the measurement site."

Figure 3 please include GPP and respiration

Authors' response: Time series of daily sums of NEE, GPP and respiration was added to the Supplement (Figure S5).

Figure 4 Why was the data binned and what was the size of the bins? When was this data used?

Authors' response: To better visualize the light response curves during the wet and dry seasons. The figure shows 2814 values and each bin has about 100 values.

Figure 5 how come that soil moisture is up to 20% during the dry season, this is very high.

Authors' response: There was a 22 mm precipitation event in 7th of June 2011. During that time the soil moisture peaked at 18 %.

Figure 6 I like this figure, except why monthly sum per hour, it is just a confusing unit. Why not hourl average, it would make more sense?

Authors' response: Correct to mean NEE for each hour of day.

Figure 7 why not include all months? Again why hourly per month. February with 28 days will be different than January just because of # of days in the month.

Authors' response: All months were included. Changed units to mean diurnal cycle of NEE.

References

Kutsch, W. L., Hanan, N., Scholes, B., McHugh, I., Kubheka, W., Eckhardt, H. and Williams, C.: Response of carbon fluxes to water relations in a savanna ecosystem in South Africa, Biogeosciences, 5(6), 1797–1808, doi:10.5194/bg-5-1797-2008, 2008.

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 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 Welgegund, 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 yearly carbon dioxide balances of the years growing seasons 2010–11, 2011–12 and 2012–13 were -85 ± 16, 67 ± 20 and 139 ± 13 g C m^{-2} yr^{-1}, 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. This study demonstrates the difficulty in establishing a functional relation between the total ecosystem respiration and the environmental drivers in savanna ecosystems. Furthermore, the high inter-annual variation of carbon balance in savanna ecosystems is difficult to relate to environmental drivers.

1 Introduction

Savannas are highly dynamic ecosystems which cover about 40 % of Africa ~~(Scholes and Walker, 1993)~~ and 20 % of the global land area (Scholes and Walker, 1993). The ~~seasonal cycle in~~ savanna ecosystems are~~is~~ 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 ~~anthropogenic~~ 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 ~~as~~ 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). ~~Most of these sites are located inside national parks or nature reserves.~~ 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) g C m^{-2} 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 g C m^{-2} 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.

To understand these human-influenced savanna ecosystems, we analysed three years of eddy covariance CO_2 flux data from a grazed semi-arid savanna in central southern Africa. The carbon balance of this ecosystem was determined for ~~a~~ 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 ~~Gross Primary Production (~~GPP~~)~~. The main objective of this study is to quantify the carbon balance and its inter-annual 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 Welgegund atmospheric measurement station (26°34'10"S, 26°56'21"E, 1480 m a.s.l.; www.welgegund.org) in South Africa has been measuring atmospheric aerosols and trace gases since May 2010. This site is located on a flat savanna 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.~~ure~~ 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 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 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_4 grass species (Table 1). The dominant grass species are *Eragrostis trichophora*, *Panicum maximum* and *Setaria sphacelata.* There is also a considerable amount of 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~~2~~. The soil around the site is loamy sand. ~~The soil organic carbon content was 0.93 % and the pH was 5.69.~~

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

~~2.2 Vegetation sampling~~

~~The vegetation surrounding the measurement station was classified based on land-use and vegetation structure (Figure 2), for which a detailed sampling was performed four times during the period from April 2011 to January 2012. Seven homogeneous land-use units were identified, including maize fields, dry sandy grassland, moist sandy grassland, disturbed grassland, thornveld savannah, woodland savannah and plantation. Grasslands had a tree cover of less than 15 %, whereas in savannas it was greater than 15 %. Furthermore, savannas were divided into thornveld, which had sparsely distributed large trees, and woodland with a tree cover greater than 50 %.~~

~~The central region of each homogeneous unit was sampled along a transects, which resulted in 42 plots in total, six per transect. Each of these plots had an area of 100 m^2. All of the plant species were counted and identified up to species level, and their major growth form was recorded. In addition, for all the woody species higher than 1 m, the mean height, mean canopy height and width of each species were determined.~~

~~Within each plot, leaf material was collected from four 1 m^2 subplots during each of the four periods, and a one-sided leaf area index (LAI) of all the leaves was determined for grasses, forbs, shrubs and trees. After this all the plant material was dried for three days and weighed.~~

2.2~~3~~ Instrumentation

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~~ecosystem~~ 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)~~s~~. The meteorological measurements were sampled every minute and the 15 min 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.

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.

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_2 concentrations were measured using a Li-Cor LI-7000 closed~~-~~path 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 centrer of the anemomer was 20 cm. The flow rate of the sampling system was 6 L min^{-1}. 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 with a high-accuracy CO_2 span gas ~~, and synthetic air with a zero CO_2 concentration was continuously used as a reference gas~~(378 ppm verified by the Cape Point GAW station), and Afrox instrument grade synthetic air with CO_2 < 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~~to~~ 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.

2.3~~4~~ 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_2 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_2. 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_2 flux loss was 5 % on average.

The storage flux was calculated by assuming a uniform distribution of CO_2 between the soil surface and the measurement height. During the last measurement year, the CO_2 concentration was also measured at a 1.5 m height, which enabled us to calculate a two-point estimate of~~for~~ the storage flux for comparison.

The corrected fluxes of CO_2 were filtered by discarding the data with a friction velocity lower than 0.2 m s^{-1} (18 % of data excluded). In addition, CO_2 fluxes were filtered by setting an acceptable range for average CO_2 concentration (300–500 ppm), gas analyzer sample cell pressure (50–120 kPa) and CO_2 concentration variance (0–10 ppm^2), 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_2 flux values in the final time series were missing or discarded, which is similar to the 19-site average~~a mean value~~ of 35 % ~~of missing data (19-site average) (~~reported by Falge et al.~~,~~ (2001).

The flux “footprint” area~~”~~ was estimated using the~~an~~ analytical model~~function~~ introduced by Kljun et al. (2004). According to this model~~It was estimated that,~~ 90 % of the flux originated within a distance of 324 m upwind from the measurement tower. Figure S1~~2~~ shows the distance of ~~circles with the radius of~~ the mean ~~50% and~~ 80 % cumulative flux footprint as a function of wind direction. ~~The real flux footprint is not a circle and it varies by being larger during the night and smaller during the daytime.~~ Th~~is~~e footprint area is predominantly located within~~a~~ homogeneous thornveld (Fig.~~ure~~ S1).

2.4~~5~~ Partitioning and gap filling of the ~~net~~ CO_2 flux data

The measured net CO_2 flux was partitioned into GPP and ecosystem respiration, R_{eco}, by fitting a respiration function to the night-time data and calculating GPP as the difference between NEE and R_{eco}. Night-time and daytime periods were separated by a threshold PAR value of 20 µmol m^{-2} 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.

~~There are several approaches to partitioning the measured net CO_2 flux to its GPP and respiration components. In this study, the partitioning of the flux was tested with both night-time and daytime based methods. Night-time and daytime periods were separated by a threshold PAR value of 20 µmol m^{-2} s^{-1}. In the “night-time method” only night-time data is used to directly determine a respiration function, and GPP is calculated as a difference between NEE and respiration. Three different respiration functions were tested: an exponential temperature function (Lloyd and Taylor, 1994), an exponential temperature function with a soil moisture effect (Reichstein et al., 2003) and a general Poisson function (Archibald et al., 2009). The Poisson function describes both the exponential increase of respiration with the temperature and its decrease at higher temperatures.~~

~~The “daytime method” was tested by fitting a model to the daytime NEE measurements. The model parameters are the initial slope of light response, the CO_2 uptake at light saturation, vapour pressure deficit (VPD) and respiration. The details of this approach are described in Tagesson et al. (2015).~~

~~For both the daytime and night-time methods, the fit parameters were calculated in a moving window which was defined for every day. The data set did not have gaps longer than 15 days, and thus the moving window was expanded from 6 to 20 days in order to cover at least 50 measurement points. The fitting of all model functions was done using “lsqnonlin” command in MATLAB Release 2015b, which uses a trusted region least square algorithm.~~

We did the partitioning using algorithm by Lloyd & Taylor (1994). In this algorithm t

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 individually for each year and then fitting the R_b parameter for each data window separately. 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:

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

where $F_{p,max}$ is the canopy assimilation at light saturation and *d* is the initial slope of light response (von Stamm, 1994). The 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.

2.5 Uncertainty estimation

The uncertainty in the annual CO_2 budget was estimated by considering the most significant error sources, for both random and systematic errors. For the former, we included the stochastic measurement error inherent in eddy covariance measurements, the error resulting from the gap -filling of the CO_2 flux time series for missing data and the uncertaintyerror, due to data filtering by a minimum friction velocity limit. The random error related to both 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.,

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2002), and for the gap-filling error also includes the effect of this random variability on the model fit. The annual 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.

The annual 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^{-1}) (Aurela et al., 2002). E_{ustar} was estimated as an average deviations from the annual carbon balance calculated using the optimal friction velocity limit (0.20 m s^{-1}).

In addition to the random error, we estimated the systematic error due to the correction for flux losses described in Sect. 2.34, 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_2 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, mMonthly averagesvalues of NDVI were calculated from theMODIS NDVI (MODIS BRDF product MCD43A4, (one 500 m pixel) at the flux footprint of the eddy covariance measurement (Figure S12). 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). Therefore, it is better suited for studies of long-term variation in vegetation structure than the MODIS LAI or MODIS GPP products.

3 Results and discussion

Figure 23 shows a time series of incoming PAR, air temperature, precipitation, evapotranspiration and CO_2 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. Heavy rain events were followed by high evapotranspiration events, and the total evapotranspiration was higher during the rainy season due to higher precipitation and transpiration rates. The peak evapotranspiration events in different years were similar in magnitude but their frequency varied. The highest inter-annual variation in CO_2 flux occurred during the wet season, whereas during the dry season CO_2 fluxes were rather similar in magnitude.

Based on the vegetation sampling described above, the LAI within the flux footprint had a maximum value of 2.32 m^2 m^{-2} in April and a minimum of 0.37 m^2 m^{-2} in July (Table 3). The leaf biomass followed the same trend, with a maximum value of 644 g m^{-2} and a minimum of 233 g m^{-2} (Table 4).

3.1 Partitioning of the net CO_2 fluxCO_2 exchange dynamics

Figure 2 shows a time series of incoming PAR, air temperature, precipitation and CO_2 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_2 flux occurred during the wet season, whereas during the dry season CO_2 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_2 uptake increased flux increased linearly with increasing incoming PAR until it reached a saturated value (Fig.ure 34). The dry season (JJA) CO_2 flux rates were an order of magnitude lower than the wet season rates and canopy assimilation was rarely saturated with respect to PAR. The "daytime method" fitting (Tagesson et al., 2015) was not successful because all parameters had unrealistically high values, and thus the modelled respiration values were unrealistic. On average, Tthe mean daytime NEE decreased with increasing VPD when VPD exceeded a limit of 1 kPa (Fig.ure S2).

The night-time respiration did not show a clear exponential relationshipincrease 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 ~2 µµmol m^{-2} 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.ure 45). 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.

The exponential temperature function with soil moisture effect (Reichstein et al., 2003) was successfully fitted to each window, but a large part of the respiration values calculated with the resulting parameters were negative. In addition, the

~~correlation between the modelled and measured respiration rates was poor (R^2=0.11). The fit based on the Poisson function (Archibald et al., 2009) was not successful either. Due to these findings the night-time respiration for gap filling was determined using the exponential temperature function by Lloyd and Taylor (1994), Eq. (1).~~ Even though the temperature dependency was weak, the respiration rates modelled with Eq. (1) ~~this function~~ correlated well with the measured respiration (R^2=0.56, $p < 0.01$).

~~The annual NEE for the growing season 2012-2013 using the two-point estimate for the storage flux was 88 g C m^{-2}, which was 51 g C m^{-2} less than that balance obtained with one-point storage estimates. 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 that the difference between the storage calculation methods leads to similar differences in the annual NEE, the NEE of the growing season 2011-2012 remains slightly positive, while that of 2010-2011 becomes even more negative.~~

3.2 Diurnal CO_2 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.~~ure~~ 5~~6~~~~, Figure~~ and 6~~7~~). The highest values of carbon uptake occurred every year in December or January ~~at~~ from 10 am to 12 am (the darkest pixels in Fig.~~ure~~ 5), whereas the incoming PAR had its peak between 11 am and~~to~~ 1 pm (data not shown). This phase difference is most likely caused by the stomata closure before the radiation peak, as plants ~~in order to~~ avoid water loss~~es~~.

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.~~ure~~ S3). The mean monthly diurnal cycle of the VPD values above a 1 kPa threshold, VPD_1, shows marked differences from September to November between different years (Fig.~~ure~~ S4).

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 μ~~μu~~mol m^{-2} lower than during the other years, which could be due to VPD ~~that w~~as VPD_1 was 1 kPa higher than during the other years. In November 2010, the diurnal pattern of NEE showed~~had~~ a sharp dip ~~and a levelling~~ 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 years (Fig.~~ure~~ S3c). 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.

~~Later on, during the middle part of the wet season, the afternoon dip was reduced and the diurnal pattern was closer to that observed in September.~~

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~~The daytime NEE values were found to decrease with increasing VPD above a 2 kPa limit. This response was also found in all C_3 plant-dominated sites in a previous 11-site inter-comparison between African ecosystems (Merbold et al., 2009).~~

3.3 Inter-annual ~~Seasonal~~ variation in CO_2 fluxes~~of the carbon balance~~

In this section, we analys~~z~~e the differences in carbon fluxes and their environmental drivers at a monthly scale during the three measurement years. ~~Figure 8 shows the monthly sums of respiration, GPP, NEE, and precipitation together with the monthly averages of air temperature, soil temperature, soil moisture and daily maximum VPD.~~

The highest carbon uptake was observed during~~In~~ the growing season 2010~~-~~–2011 (Figs.~~ure~~ 7 and S5) ~~the carbon uptake was the highest~~. Heavy rainfall occurred ~~in~~from November to January, and soil temperature was relatively low. This contributed to the strong growth of vegetation and large net carbon uptake. Furthermore, ~~the low values of~~ VPD was low from January to April, which resulted in continued uptake of carbon. Due to the relatively low ~~values of~~ soil temperatures throughout the growing season, the yearly respiration in 2010–2011 ~~i~~was lower than during the year 2012~~-~~–2013.

During the year 2011~~-~~–2012 the annual rainfall was ~~the~~ lower~~st~~ than during~~in comparison with all~~ the other years; ~~.~~ e~~Specifically~~specially, the December~~-~~–January precipitation was ~~relatively~~ low. Moreover, ~~the~~ VPD was relatively high during this period and thus the growth of vegetation was weak~~low~~. ~~The total LAI was 1.32 in January 2012 (Table 3).~~ In February and March, the carbon balance was positive possibly due to ~~the~~ enhanced~~growth of~~ heterotrophic respiration and a relatively small LAI.

During the year 2012~~-~~–2013, the total respiration was relatively high already in September. The early rainfall may have le~~a~~d to an~~the~~ early growth of soil microbial populations that enhance~~d~~ the soil respiration capacity during~~for~~ the whole season. Furthermore, ~~the~~ respiration was high throughout the growing season due to the consistently higher air ~~temperature~~ and soil temperatures. From December to February, the monthly GPP was relatively high but the net carbon uptake was less than during the year 2010~~-~~–2011 due to the much higher respiration rates. From February to April ~~the~~, 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. Furthermore, ~~during the transition from wet to dry season,~~ 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~~is~~ largely due to the variation during the wet season.

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 ~~months~~ to 6 months.

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 Inter-annual variation of the carbon balance~~ 3.4 Annual carbon balances

The carbon balances (± uncertainty) from 1st ~~of~~ September to 31st ~~of~~ August for the years 2010–~~-~~2011, 2011–~~-~~2012 and 2012–~~-~~2013 were -85 ± 16, 67 ± 20 and 139 ± 13 g C m^{-2} yr^{-1}, respectively (Table 3~~5~~). The total uncertainty for these years was 19 %, 30 % and 9 % of the corresponding annual balance. The mean annual ~~average~~ 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~~in~~ 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_2 balance calculated using the two-point estimate for the storage flux was 88 g C m^{-2} yr^{-1}, which was 51 g C m^{-2} yr^{-1} less than the balance based on a single CO_2 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_2 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 ~~are~~ 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 ~~limit~~ of 7 % is thought to be a critical limit below~~under~~ which plants become~~are~~ water stressed (Archibald et al., 2009). Given that ~~the~~ our data only covered ~~only~~ three years, it ~~might be~~is not possible~~difficult~~ 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 ~~a~~were not correlated (Table 3~~5~~).

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. ~~.~~

~~The precipitation response was also found in a previous 11-site inter-comparison between African ecosystems (Merbold et al., 2009).~~

~~These results show that it might not be possible to relate the annual carbon balance to any set of annual aggregates of the environmental drivers.~~ As shown in Sect. 3.3~~#the previous section~~, the environmental drivers such as~~like~~ soil moisture and soil temperature do partly control the wet season carbon fluxes, while~~ereas during the dry season~~ 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. ~~of~~ carbon uptake by photosynthesis and ~~the~~carbon release ~~of carbon~~ to the atmosphere by respiration, ~~and thus~~ the NEE sum is sensitive to small changes in its components.

3.5 NDVI as proxy for GPP

There was a strong positive correlation between the monthly sum of GPP and the monthly mean ~~of~~ NDVI (R^2=0.83, p<0.001) (Fig.~~ure~~ 8~~9~~). Sjöström et al. (2009) also found ~~also~~ a high correlation between the 8-day NDVI mean and GPP sum in Sudanian savanna with a tree cover of 7 %~~canopy cover comparable to the Welgegund site~~. ~~The deviations of the regression and observation based GPPs were largest during the middle of the wet season, when NDVI underestimated GPP, and during the early dry season, when NDVI overestimated GPP.~~

Figure 9~~10~~ 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~~one~~ or 2 ~~two~~ 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. Based on the NDVI data, it can be concluded that the year 2010~~-~~–2011 represents a common pattern at this site, whereas ~~the years~~in 2011~~-~~–2012 and 2012~~-~~–2013 ~~have lower~~the NDVI peak values were lower than the long-term average.

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.

From September 2001 to August 2013, the yearly maximum values of the measurement site NDVI were on average 0.02 units smaller ~~on average~~ than those of a nearby moist sandy grassland area which is not grazed (land-use class 6 in Fig.~~ure~~ S1~~2~~). This difference is most probably due to heavy grazing at the measurement site.

3.6 Comparison to other sites

The annual NEE sum and its inter-annual variation at our site differs significantly from the results reported by~~in~~ a previous study at a grazed savanna grassland in Dahra, Senegal (Tagesson et al., 2015, ~~Tagesson et al.,~~ 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, ~~At Dahra,~~ the yearly carbon balance at Dahra, which varied from -336 to -227 g C m^{-2} ~~year-1~~ 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~~might~~ be explained by the moderately dense C_4 ground vegetation and high soil nutrient availability. ~~The high grazing pressure at Welgegund and large amount of missing data at Dahra may explain the large difference in the carbon balance between these sites.~~

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 ~~similar~~ 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 ~~due to~~ the large mammalian herbivore population and fires at the Skukuza site, which ~~contribute to the more positive~~ make the carbon balance more positive.~~than without these factors. at the Skukuza site.~~

At the savanna sites of Na~~o~~lohou, Benin and Bontioli, Burkina Faso, which have significantly higher annual precipitation (852 and~~to~~ 1190 mm, respectively~~/yr~~) and ~~higher~~ LAI ~~values~~, the carbon balance varied from -429 to -136 g C m^{-2} yr^{-1} (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 Na~~o~~lohou 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. However, at Welgegund the dry season fluxes ~~a~~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~~have~~ significant differences at grassland, crop~~-~~land and nature reserve sites in the Sudanian Savanna which receives a similar amount of precipitation to~~as~~ the Welgegund site (Quansah et al., 2015).

4 Conclusion

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 ± 16, 67 ± 20 and 139 ± 13 g C m^{-2} yr^{-1}, respectively. This is similar to~~compares with~~ the variation at the Kruger National Park where the annual NEE ranged from -138 to 155 g C m^{-2} yr^{-1} during a 5-year measurement period (Archibald et al., 2009).

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 ~~and highlights the importance of testing various partitioning methods for the flux data from savannas~~.

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~~NEE~~. An ~~E~~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.

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.

Acknowledgements

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Tables

Table 1.: Dominant plant species withinat the flux footprint. The plant species names include the name of the publishing author.

Species	Growth form	Mean leaf area (cm^2)	Mean height (m)	Mean canopy (m)	Number of individuals
Vachellia erioloba (E.Mey.) P.J.H.Hurter	Tree	5.9	3.2	1.8	16
Searsia pyroides (Burch.) Moffett	Tree	8.2	2.9	1.2	9
Celtis africana Burm.f.	Tree	18	3.4	1.4	6
Ehretia rigida (Thunb.) Druce	Tree	4.1	2.5	1.8	5
Vachellia karroo (Hayne) Banfi &	Tree	9.4	2.4	1.6	3

Galasso					
Diospyros lycioides Desf.	Shrub	7.9	1.8	0.8	7
Asparagus laricinus Burch.	Shrub	0.7	1.5	1.1	6
Asparagus suaveolens Burch.	Shrub	0.5	1.3	0.9	4
Grewia flava DC.	Shrub	6.7	2.2	1.8	3
Pentzia globosa Less.	Forb		< 0.5		18
Walafrida densiflora Rolfe	Forb		< 0.5		11
Hermannia depressa N.E. Br.	Forb		< 0.5		8
Dicoma tomentosa Cass.	Forb		< 0.5		6
Euphorbia inaequilatera Sond.	Forb		< 0.5		4
Panicum maximum Jacq.	Graminoid		< 1.5		18
Setaria sphacelata (Schumach.) Stapf & C.E.Hubb. ex Moss	Graminoid		< 1.5		14
Eragrostis trichophora Coss. & Durieu	Graminoid		< 1.5		11
Themeda triandra Forssk.	Graminoid		< 1.5		10
Eragrostis curvula (Schrad.) Nees	Graminoid		< 1.5		9

~~Table 2: Soil structural and chemical composition of each homogeneous land-use unit. MF, Maize fields; WL, Woodland; TV, Thornveld; P, Plantation; DSG, Dry sandy grassland, MSG, Moist sandy grassland, DG, Disturbed grassland.~~

Table 2.3: 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^2 m^{-2}]	Herbaceous LAI/ Total LAI [%]	Herbaceous [g m^{-2}]	Woody [g m^{-2}]	Total [g m^{-2}]
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

~~Table 4: Leaf biomass within the footprint flux area in 2011-2012.~~

	~~Year~~	~~Months~~	~~Sampling month~~	~~Herbaceous [g m^{-2}]~~	~~Woody [g m^{-2}]~~	~~Total [g m^{-2}]~~
~~Autumn~~	~~2011~~	~~March-May~~	~~April~~	~~383~~	~~261~~	~~644~~
~~Winter~~	~~2011~~	~~June-August~~	~~July~~	~~147~~	~~86~~	~~233~~
~~Spring~~	~~2011~~	~~September-November~~	~~October~~	~~108~~	~~169~~	~~277~~
~~Summer~~	~~2012~~	~~December-February~~	~~January~~	~~157~~	~~224~~	~~381~~

Table 3.~~5:~~ Annual carbon balance and key environmental drivers calculated for each year from September to the August of the following year.

	NEE [gC m^{-2} yr^{-1}]	GPP [gC m^{-2} yr^{-1}]	Respiration [gC m^{-2} yr^{-1}]	Annual precipitation[mm]	Rainy season length [days]	Peak NDVI	Number of days when soil moisture was higher than 7 %	Annual total PAR [mol m^{-2}]
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

Figures

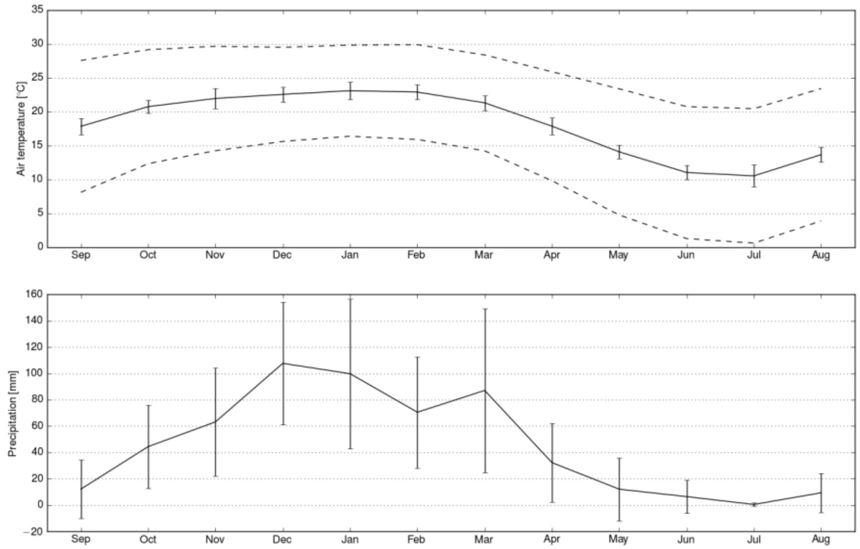

Figure 1.: Monthly mean meteorological data from a nearby weather station in Potchefstroom during 1998-2014. The upper figure shows the mean (solid line) and minimum and maximum (dashed lines) air temperatures. The lower figure shows the mean precipitation. Error bars indicate ±1 standard deviation.

~~Figure 2: Satellite image of the Welgegund measurement site showing the seven different sampling regions based on different vegetation and land-use classes. The red square shows a MODIS NDVI pixel at 500 m spatial resolution. The blue circles indicate the diameter of the mean 50% and 80% cumulative flux footprint.~~

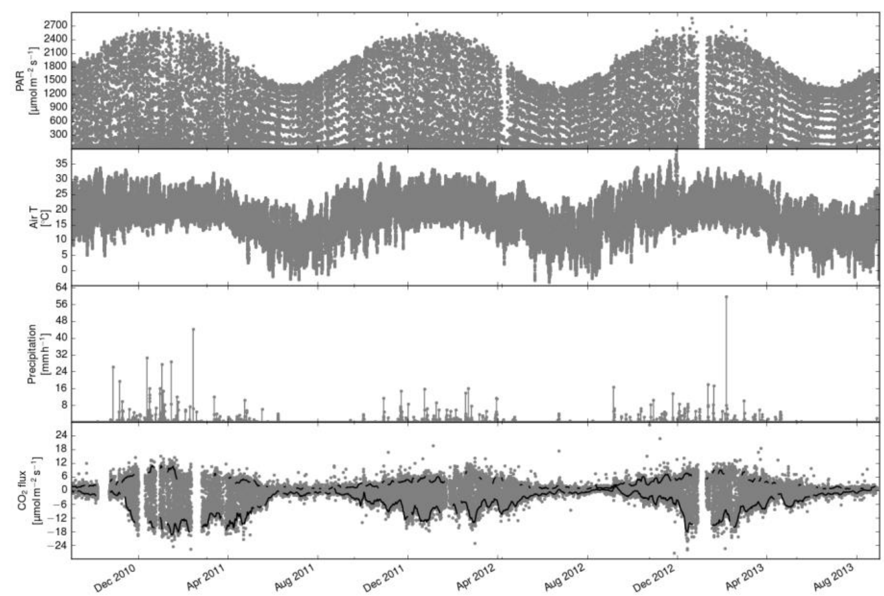

Figure 23.: Time series of incoming PAR, air temperature, precipitation~~, evapotranspiration~~ and CO_2 flux for the measurement period from September 2010 to August 2013. The solid lines within the CO_2 flux data show the five day centered mean of minimum daytime and maximum night-time CO_2 flux. Incoming PAR, air temperature and CO_2 flux data are 30 minute averages.

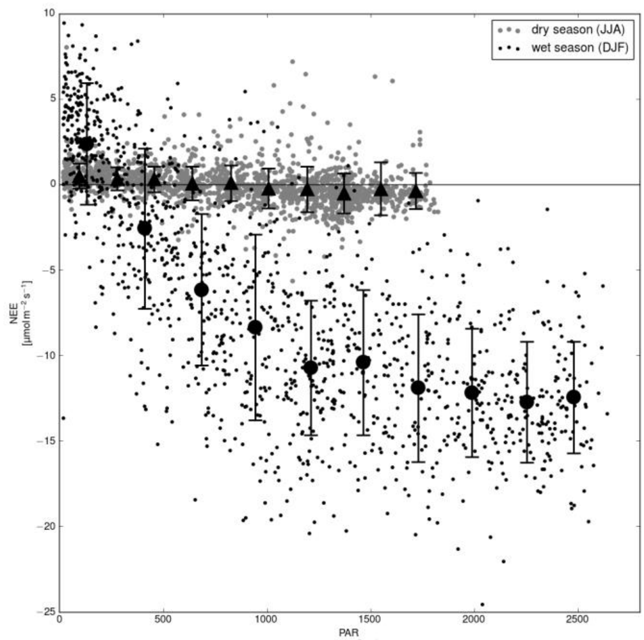

Figure 34.: Relationship between PAR and daytime NEE for wet (DJF) and dry (JJA) seasons from September 2010 to August 2011. The triangles (dry season) and circles (wet season) indicate bin averaged values and error bars indicate ±1 standard deviation. Daytime was defined as periods when PAR is higher than 20 µµmol m^{-2} s^{-1}. The figure shows 2814 values and each bin contains at least 100 values.

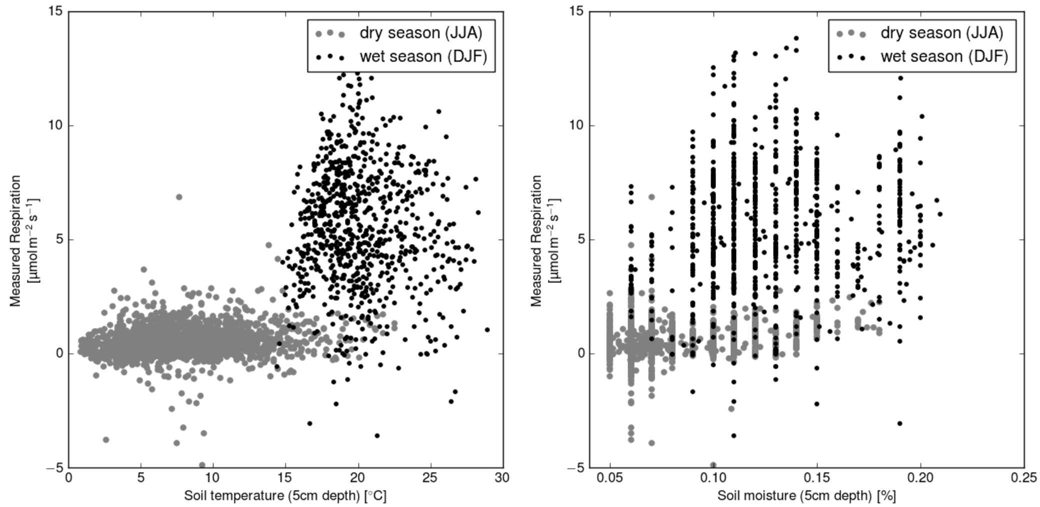

Figure 45.: Relationship between night-time respiration and soil temperature (left) and soil moisture (right) for wet (DJF) and dry (JJA) seasons from September 2010 to August 2011. Night-time was defined as periods when PAR is less than 20 μμmol m^{-2} s^{-1}.

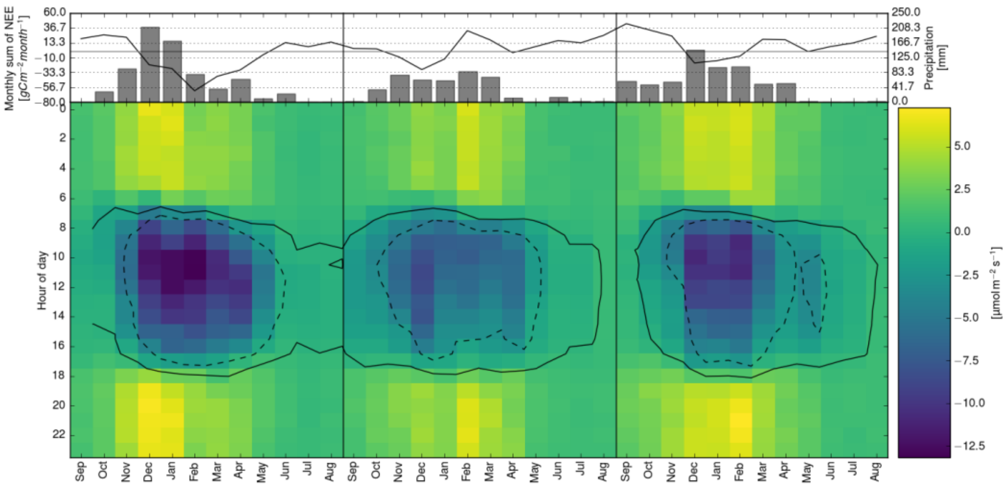

Figure 56.: Contour plot of monthly mean NEE sums for each hour of day. The solid line shows the zero isoline and the dashed line shows the NEE values less than –0.14 µµmol m^{-2} s^{-1} g C m-2 h-1 mo-1. The upper panel shows the monthly NEE as a solid line and the monthly precipitation as bars.

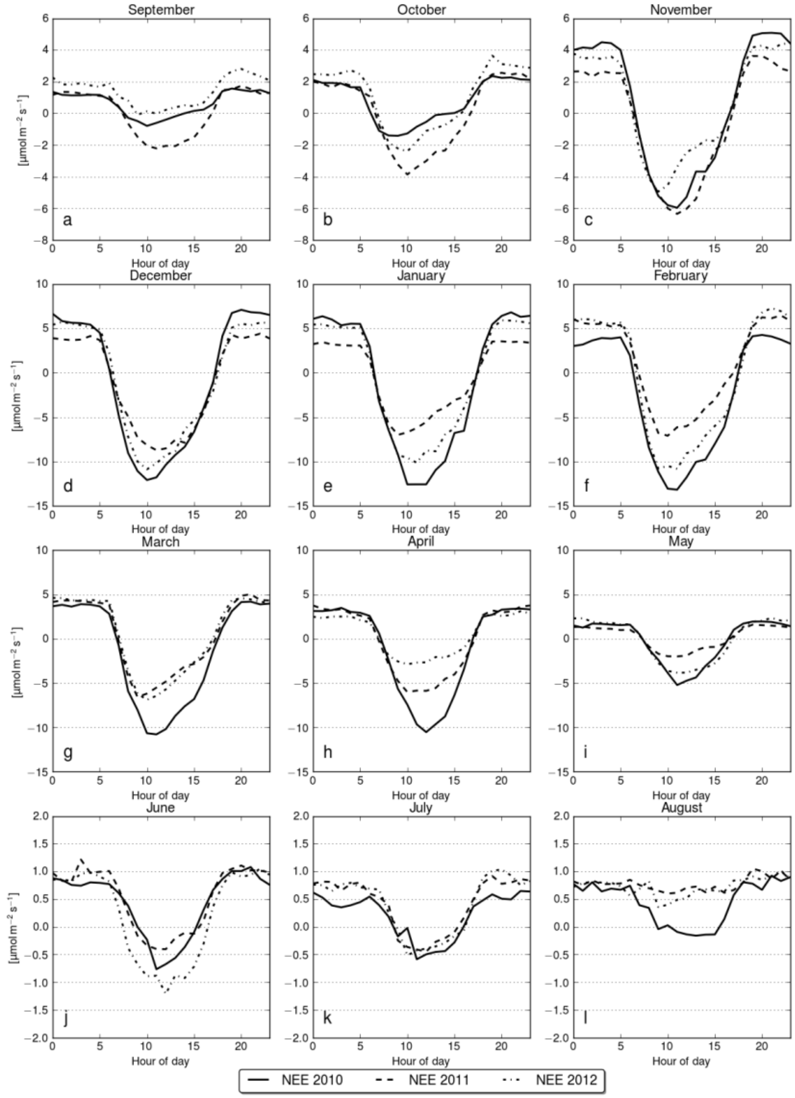

Figure 6~~7~~~~.~~: Monthly mean diurnal cycle of NEE for ~~the early and mid-season months of the wet season~~each month of the years ~~in~~ 2010, 2011 and 2012.

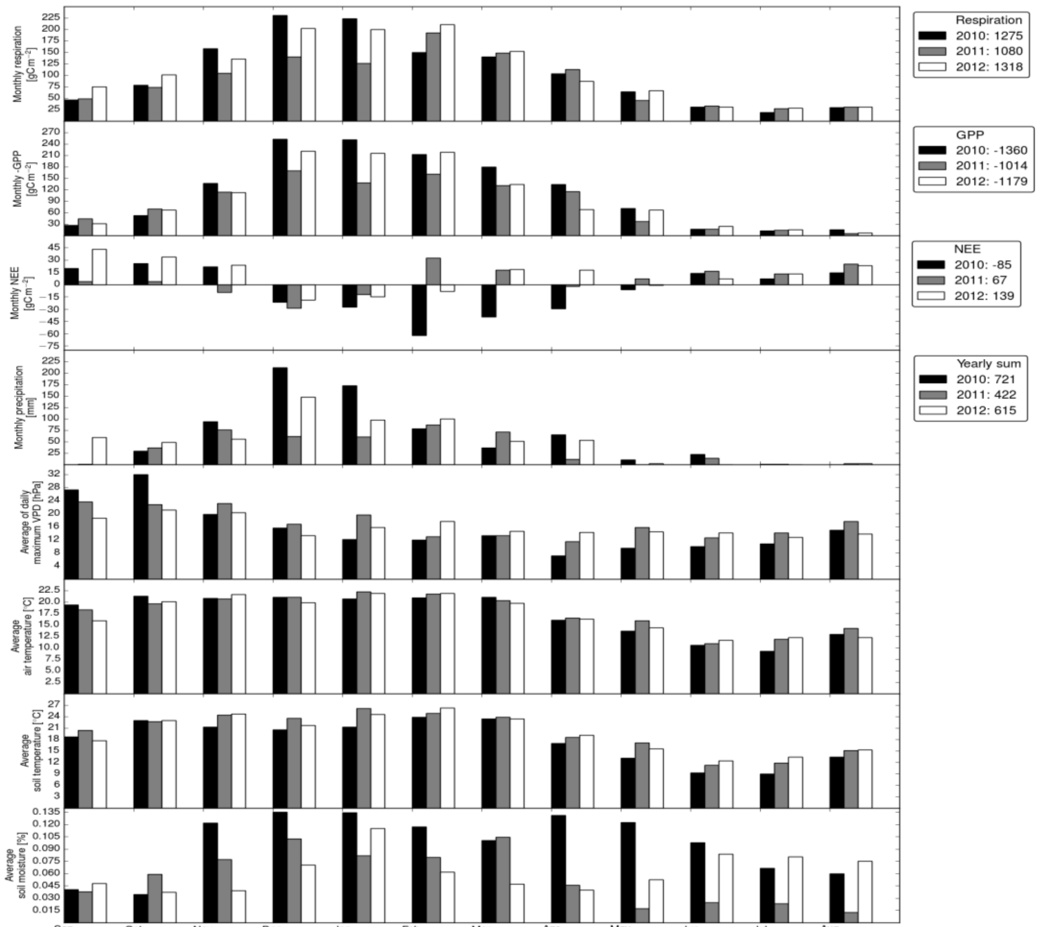

Figure 7.: Monthly sums of respiration, GPP, NEE, precipitation and the monthly average of air temperature, soil temperature, soil moisture and daily maximum VPD. The panels on the right side show the yearly sums for the years 2010 -2011, 2011-2012 and 2012-2013.

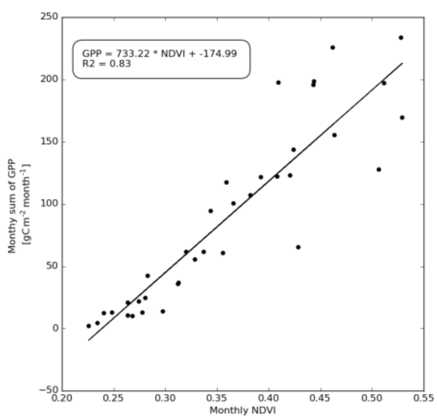

Figure 89.: Linear regression between monthly NDVI and monthly sum of GPP.

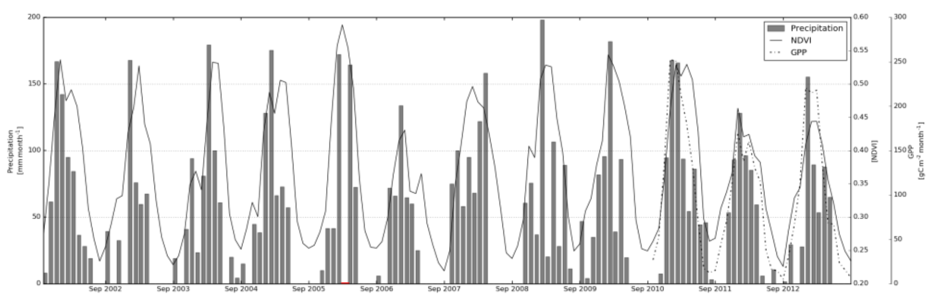

Figure 9~~10~~.~~:~~ Time series of monthly precipitation (bars), NDVI (solid line) from September 2001 to August 2013 and GPP from September 2010 to August 2013. The precipitation was measured at a nearby weather station (SAWS) in Potchefstroom. The r~~R~~ed bar~~axis~~ denotes a missing precipitation value ~~of precipitation~~ in February 2006.