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# Exploring the potential of MODIS EVI for modeling gross primary production across African ecosystems

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ABSTRACT

One of the most frequently applied methods for integrating controls on primary production through satellite data is the light use efficiency (LUE) approach, which links vegetation gross or net primary productivity (GPP or NPP) to remotely sensed estimates of absorbed photosynthetically active radiation (APAR). Eddy covariance towers provide continuous measurements of carbon flux, presenting an opportunity for evaluation of satellite estimates of GPP. Here we investigate relationships between eddy covariance estimated GPP, environmental variables derived from flux towers, Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) and GPP across African savanna ecosystems. MODIS GPP was found to underestimate GPP at the majority of sites, particularly at sites in the Sahel. EVI was found to correlate well with estimated GPP on a site-by-site basis. Combining EVI with tower-measured PAR and evaporative fraction (EF, a measure of water sufficiency) improved the direct relationship between GPP and EVI at the majority of the sites. The slope of this relationship was strongly related to site peak leaf area index (LAI). These results are promising for the extension of GPP through the use of remote sensing data to a regional or even continental scale.



## 1. Introduction

Africa's role in the global carbon cycle has been increasingly recognized, particularly with the challenges it faces with respect to climate change (Hulme et al., 2001). According to Williams et al. (2007), the African continent contributes as much as one-fifth of the net primary production and a half of the interannual variability of the carbon balance at the global scale. Even though Africa as a whole appears to be approximately carbon neutral (Williams et al., 2007), estimates are highly uncertain and there is a need to better understand the temporal and spatial dynamics of ecosystem productivity across the continent. In 2006, CarboAfrica was established with the purpose of increasing our knowledge of Africa's role in the global carbon cycle (Bombelli et al., 2009). The project's objectives included a synthesis of flux data from existing eddy covariance sites in Africa (e.g. Merbold et al., 2009), as well as to support new observations. The eddy covariance technique (e.g. Aubinet et al., 1999; Baldocchi et al., 2001; Lindroth et al., 1998; Wofsy et al., 1993) has become a standard for measuring fluxes of $CO_2$, water and energy between the land and atmosphere at the ecosystem scale and provides an excellent opportunity for validation of model estimates of carbon flux from terrestrial ecosystems.

Although eddy covariance towers can provide estimates at high temporal resolution, the number of stations is limited spatially across the African continent. Satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), which has been acquiring data in 36 spectral bands across the entire globe since 2000, may therefore significantly contribute to our knowledge on vegetation dynamics and responses to changing environmental conditions. Data from MODIS are used in numerous biophysical products for which a number of studies over tropical dryland ecosystems have helped provide confidence too (Fensholt et al., 2004; Fensholt et al., 2006; Huemmrich et al., 2005; Kanniah et al., 2009; Privette et al., 2002). However, further attention is required in comparing spatially extensive satellite data to eddy covariance measurements over tropical dryland ecosystems to improve predictions and modelling of ecosystem primary productivity.

One of the most widely applied approaches to extrapolate ecosystem primary productivity measurements from the site-scale

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to larger spatial scales is the concept of light use efficiency (LUE, Monteith, 1972, 1977). In this concept gross primary production (GPP), the total carbon assimilated by plants—which can be derived from eddy covariance measurements through estimates of net ecosystem exchange (NEE) and ecosystem respiration ($R_{eco}$)—is a function of the absorbed photosynthetically active radiation (APAR) by plants and the conversion efficiency of absorbed light energy (ε). APAR is estimated as the product of incoming photosynthetically active radiation (PAR) and the fraction of PAR absorbed by the canopy (FAPAR), whereas ε is a quasi-constant, typically modified by functions of temperature and moisture. Through the established relationship between the normalized difference vegetation index (NDVI) and FAPAR (Asrar et al., 1984; Daughtry et al., 1983; Sellers et al., 1994) the concept of LUE has been applied in a number of satellite-based modeling studies (e.g. Fensholt et al., 2006; Seaquist et al., 2003). NDVI has however been reported to be sensitive to variations in background reflectance and to saturate at intermediate to high leaf area index (LAI) resulting in a lack of sensitivity to seasonal changes. With the advent of MODIS, the enhanced vegetation index (EVI) was developed to enhance the vegetation signal by reducing influences from the atmosphere and canopy background and to improve sensitivity in high biomass regions (Huete et al., 2002). Both the NDVI and EVI quantify the difference in reflectance in the visible red, where absorption in green leaves dominates, and the near-infrared (NIR) wavelengths, where light scattering by cell walls dominates (Tucker, 1979). However, unlike NDVI, EVI also incorporates a soil adjustment factor as well as an atmosphere resistance term using the blue band in its formulation:

$$EVI = 2.5 \times \frac{NIR - RED}{NIR + (6 \times RED - 7.5 \times BLUE) + 1} \quad (1)$$

Several studies have previously shown consistent linear relationships between eddy covariance GPP and EVI in various environments, whereas NDVI has either shown little variation in seasonality or a poorer correspondence with GPP (Huete et al., 2008; Xiao et al., 2004). It remains unclear to what extent EVI can be used to model GPP, since the relationships have been shown to differ greatly between ecosystems (e.g. Rahman et al., 2005; Sims et al., 2006). Xiao et al. (2004) distinguished between the photosynthetically active and non-photosynthetically active components of FAPAR and incorporated EVI, together with scalars of ε, into the satellite-based Vegetation Photosynthesis Model (VPM) as equivalent to the photosynthetically active chlorophyll component of FAPAR. Recently, Zhang et al. (2005) reported EVI to be closely related to FAPAR if the effects of chlorophyll were taken into account. In this study, we focus on exploring MODIS GPP and EVI and their relationships with eddy covariance GPP in African ecosystems. Using the LUE concept, we further determine whether the inclusion of other environmental variables (derived from eddy covariance towers) can improve upon the direct relationship of eddy covariance based GPP with EVI for assessing whether EVI can be a useful input for satellite-based modeling of GPP over tropical dryland ecosystems, specifically in Africa.

## 2. Data and methods

### 2.1. Eddy covariance and meteorological data

Seven CarboAfrica-associated sites were used, representing a variety of African ecosystems and rainfall regimes (Table 1, Fig. 1). The sites covers a diversity of vegetation and climate types with three in the semi-arid Sahel (Wankama millet and fallow in Niger and Demokeya in the Sudan), three in the semi-arid and sub-humid regions of Southern Africa (Maun in Botswana, Mongu in Zambia and Skukuza in South Africa) and one in the more humid region close to the equator (Tchizalamou in the Republic of the Congo).

Eddy covariance data were either collected from participating site researchers or downloaded directly from the CarboAfrica network website (gaia.agraria.unitus.it/database/carboafrica). For all sites, except Wankama millet and fallow, the gap-filled and flux-partitioned weekly aggregated Level 4 CarboAfrica product was used (Papale et al., 2006; Reichstein et al., 2005). This product contains a number of gap-filled meteorological and environmental variables, including GPP calculated from NEE. In the Level 4 CarboAfrica product NEE is either estimated through the storage correction obtained by applying the discrete approach (same for all sites) or by using the storage correction determined by the principal investigator at each site. NEE is then gap-filled using the Marginal Distribution Sampling (MDS) method (Reichstein et al., 2005) or the Artificial Neural Network (ANN) method (Papale and Valentini, 2003). For sites for which the Level 4 CarboAfrica product was available we used standardized GPP data calculated from NEE filled using the MDS approach, whereas GPP from Wankama millet and fallow was derived from NEE gap-filled according to the MDS approach by using publicly available methods at *bgc-jena.mpg.de/bgc-mdi/html/eddyproc/index.html* (Reichstein et al., 2005).

The evaporative fraction (EF) was used to represent moisture availability for plants. It is the ratio of the energy exported as evaporated water (i.e., as latent heat, LE) to the sum of latent and sensible heat (H). EF

**Table 1**
Site descriptions including name, latitude and longitude (lat/long, decimal degrees), general ecosystem type, dominant species, mean annual long-term precipitation (MAP, mm), mean annual temperature (MAT, °C), years of data used, number of weekly data points used and references for each eddy covariance site. For detailed information regarding eddy covariance instrumentation set-up at sites see Merbold et al. (2009).

| Name | Country | Lat | Lon | General ecosystem type | Dominant species | MAP (mm) | MAT (°C) | Years | Weeks | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Wankama fallow | Niger | 13.65 | 2.63 | Shrubland | Sparse *Guiera senegalensis* interspersed w/ *Zornia glochidia, Mitracarpus scaber Zucc.* | 560 | 28.5 | 2005–2006 | 55 | Ramier et al. (2009) |
| Wankama millet | Niger | 13.64 | 2.63 | Cropland | *Pennisetum glaucum* | 560 | 29.5 | 2005–2006 | 50 | Boulain et al. (2009) |
| Demokeya | Sudan | 13.28 | 30.48 | Grassland | *Aristida pallida, Eragrostis tremula, Cenchrus biflorus* w/ sparse *Acacia sp.* | 320 | 26 | 2007–2008 | 47 | Ardö et al. (2008) |
| Tchizalamou | Rep. of the Congo | −4.29 | 11.66 | Grassland | *Loudetia simplex, Ctenium newtonii* | 1150 | 26 | 2006–2007 | 53 | Merbold et al. (2009) |
| Mongu | Zambia | −15.44 | 23.25 | Woodland | *Brachystegia sp.* w/sparse understory | 945 | 24.5 | 2007–2008 | 41 | Scanlon and Albertson (2004) |
| Maun | Botswana | −19.92 | 23.56 | Woodland | *Colophospermum Mopane.* w/sparse understory | 465 | 22 | 2000–2001 | 65 | Veenendaal et al. (2004) |
| Skukuza | South Africa | −25.02 | 31.50 | Wooded grassland | *Combretum* sp., *Acacia sp.* w/well developed understory | 545 | 22 | 2007–2008 | 39 | Kutsch et al. (2008) |