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Woody plant cover estimation in drylands from Earth Observation based seasonal metrics

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ABSTRACT

From in situ measured woody cover we develop a phenology driven model to estimate the canopy cover of woody species in the Sahelian drylands at 1 km scale. The model estimates the total canopy cover of all woody phanerophytes and the concept is based on the significant difference in phenophases of dryland trees, shrubs and bushes as compared to that of the herbaceous plants. Whereas annual herbaceous plants are only green during the rainy season and senescence occurs shortly after flowering towards the last rains, most woody plants remain photosynthetically active over large parts of the year. We use Moderate Resolution Imaging Spectroradiometer (MODIS) and Satellite pour l'Observation de la Terre (SPOT) — VEGETATION (VGT) Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) time series and test 10 metrics representing the annual FAPAR dynamics for their ability to reproduce in situ woody cover at 43 sites (163 observations between 1993 and 2013) in the Sahel. Both multi-year field data and satellite metrics are averaged to produce a steady map. Multiple regression models using the integral of FAPAR from the onset of the dry season to the onset of the rainy season, the start date of the growing season and the rate of decrease of the FAPAR curve achieve a cross validated r^2/RMSE (in % woody cover) of 0.73/3.0 (MODIS) and 0.70/3.2 (VGT). The extrapolation to Sahel scale shows agreement between VGT and MODIS at an almost nine times higher woody cover than in the global tree cover product MOD44B which only captures trees of a certain minimum size. The derived woody cover map of the Sahel is made publicly available and represents an improvement of existing products and a contribution for future studies of drylands quantifying carbon stocks, climate change assessment, as well as parametrization of vegetation dynamic models.

1. Introduction

Trees, shrubs and bushes are an important element of savanna ecosystems and for livelihoods in dryland areas dependent on fuel–wood supply. During the past decades, several studies have seriously questioned prevailing narratives of a widespread and Sahel-wide decrease in woody cover (Rasmussen, Fog, & Madsen, 2001; Rasmussen, Nielsen, Mbow, & Wardell, 2006; Spiekermann, Brandt, & Samimi, 2015), commending the relevance of large scale woody cover monitoring systems.

Most studies estimating tree canopy cover with remote sensing rely on high resolution imagery which allow direct mapping at a scale recognizing trees of a certain size as objects (e.g. Herrmann, Wickhorst, & Marsh, 2013; Karlson, Reese, & Ostwald, 2014; Rasmussen et al., 2011; Sterling & Orr, 2014; San Emeterio & Mering, 2012). However, imageries with a spatial resolution of 1–5 m are cumbersome to process, expensive, susceptible to clouds, and do only provide a static situation for a limited spatial area. Moreover, considering trees as objects, smaller isolated woody plant are missed and individual woody plants are hard to separate in dense thickets (Spiekermann et al., 2015). Global tree cover products at 30 m using Landsat (Sexton et al., 2013) and 250 m using Moderate Resolution Imaging Spectroradiometer (MODIS) are trained with higher resolution imagery (Defries, Hansen, Townshend, Janetos, & Loveland, 2000; Hansen et al., 2003) and are available for assessing states of canopy cover and deforestation rates. However, the reliability of these products in semi-arid regions with open tree cover is contested (e.g. Gessner, Machwitz, Conrad, & Dech, 2013; Hansen, Townshend, DeFries, & Carroll, 2005; Herrmann et al., 2013) and limited evaluations against

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ground observations have been done for drylands in general and for the Sahel in particular.

The leafing of trees and shrubs in semi-arid areas like the Sahel is not temporally uniform. This suggests that large scale woody cover modeling from moderate to coarse spatial resolution Earth Observation (EO) data can potentially be improved by including vegetation metrics covering various stages of the growing season cycle, and not only images or variables representing snapshots in time. This is particularly important in the Sahelian zone, where the vegetation is characterized by a rapid phenological cycle driven by the short rainy season where most of the observations in the optical domain are missing or affected by noise due to cloud cover. The spatial resolution of MODIS (250–1000 m) and Satellite Pour l'Observation de la Terre, (SPOT) - Vegetation (VGT) (1000 m) is traditionally considered a limitation for vegetation monitoring, however, major morphological units, widespread deforestation and regional climate dynamics are visible at this scale and represent the spatial characteristics of the Sahel area (Vintrou et al., 2014). Given the high temporal sampling frequency of MODIS and VGT, noise from cloud cover can be suppressed and various seasonal metrics related to phenology of the green vegetation mixed in a pixel can be derived (Horion, Fensholt, & Ehammer, 2014). Recent studies show that the dominant woody species in the Sahel have a significant footprint in long-term trends of coarse satellite data time series (Brandt et al., 2015), but it remains unclear how woody cover affects the annual vegetation curve as measured by EO data.

We suggest an approach driven by vegetation phenology including in situ measured woody cover data across the Sahel and seasonal metrics from time series of MODIS and SPOT-VGT. The method is an indirect estimation of the canopy cover of all woody phanerophytes including trees, shrubs and bushes (thus the expression woody cover is used), and is based on the significant difference in phenophases of woody plants as compared to that of the herbaceous plants (De Bie, Ketner, Paasse, & Geerling, 1998; Horion et al., 2014; Wagenseil & Samimi, 2007). In the Sahel, annual herbaceous plants are only green during the rainy season from June to October (depending on the latitudinal position and of the vagaries of annual rain distribution) and senescence occurs after flowering in September towards the last rain events of the season. The leafing of most trees and shrubs is longer (De Bie et al., 1998; Mbow, Chhin, Sambou, & Skole, 2013), with several evergreen species, and many woody species green-up ahead of the rains during the last month of the dry season, while annual herbaceous are dependent on the first rains to germinate (Horion et al., 2014; Hiernaux, Cissé, Diarra, & de Leeuw, 1994; Seghieri, Do, Devineau, Fournier, et al., 2012). The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) quantifies the fraction of the photosynthetic active radiation absorbed by green vegetation (Baret et al., 2013; Myneni & Williams, 1994). FAPAR seasonal metrics derived from EO data highlighting the differences in phenology between annual herbaceous and woody plants are considered suitable indicators of photosynthetic activity of woody canopies.

Based on the observation that the phenology of woody vegetation in semi-arid areas is distinctive in the dry season, our objectives are (1) to find evidence for the relationship between satellite derived seasonal metrics of FAPAR and in situ measured woody cover, (2) to create a woody cover map for the 1999–2013 period for the Sahel belt, and (3) to compare the modeled and in situ measured woody cover with an existing global tree cover product.

2. Materials and methods

2.1. Conceptual approach

The concept of this study is to establish a multi-linear regression between ground based woody cover measurements from Mali and Senegal and satellite derived seasonal metrics from VGT and MODIS time series (Fig. 1). Both field and satellite data are averaged over

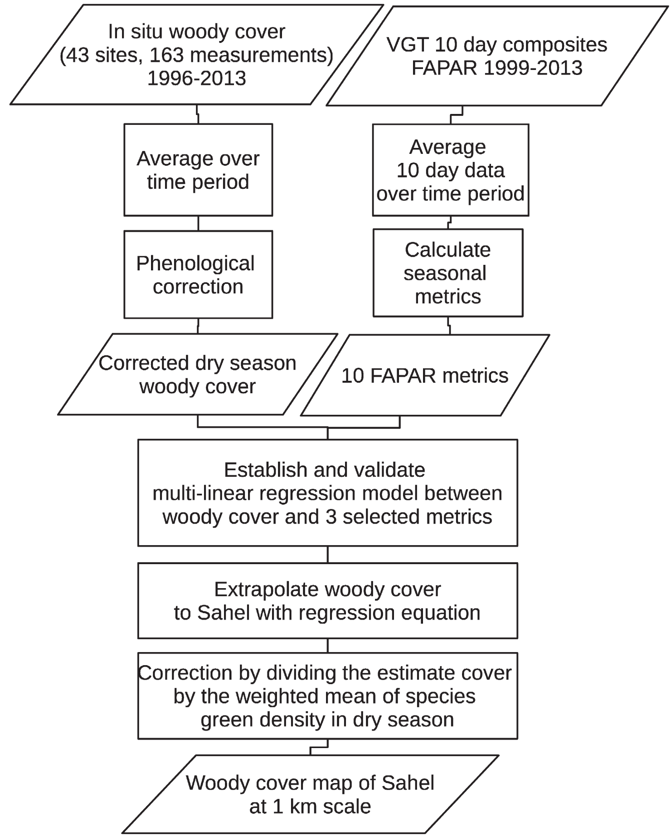

Fig. 1. Conceptual approach of this study exemplified for VGT FAPAR.

their period of acquisition to produce a steady map. Based on the assumption that dry season greenness can be used to separate woody from herbaceous production 10 metrics representing the annual FAPAR dynamics are tested to model the total canopy cover of woody plants. The woody canopy cover measured at the field sites is adjusted prior to correlation with satellite data relating to the degree of leaf-out typically occurring in the dry season months. This phenological correction depends on the typical phenological behavior of the component woody species and is thus site specific. To predict the total woody cover at Sahel scale, the correction is based on an estimated mean phenology of all woody plants of the Sahel region.

2.2. Study area

The Sahel extends from the Atlantic Ocean in the west to the Red Sea in the east (approximately 6000 km). The bioclimate is considered tropical arid in the north and semi-arid in the south (Le Houérou, 1980; Sayre et al., 2013). The average annual precipitation varies between 150 mm and 700 mm from north to south. The delineation (Fig. 2) is derived from African Rainfall Climatology Version 2 (1982–2013) satellite based rainfall data (Jobard, Chopin, Berges, & Roca, 2011). The rainy season is directly linked to the West African Monsoon with a length of 1–4 months, an annual peak in precipitation in August (Barbé & Lebel, 1997), and an increasing rate of annual rainfall along the north–south gradient with approximately 1–2 mm per km (Le Houérou, 1980). The Sahel is subdivided into three biogeographical zones matching the rainfall zones (Fig. 2): the northern Sahel (Saharo–Sahelian), the central Sahel (Sahelian proper) and the southern Sahel (Sudano–Sahelian) where rainfed crops largely extend. The northern Sahel is characterized by the abundance of spiny trees *Acacia* (*Mimosoidae*), *Balanites*, *Ziziphus* and also of *Capparidaceae.* In central Sahel spiny *Mimosoidae* associate with broadleaf *Combretaceae*, while in southern Sahel woody plants