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Remote sensing of vegetation in the Sudano-Sahelian zone: A literature review from 1975 to 2014

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Abstract

Scarcity of *in situ* vegetation data inhibits research and natural resource management in the Sudano-Sahelian zone (SSZ). Satellite and aerial remote sensing (RS) constitute key technologies for improving the availability of vegetation data, and consequently the preconditions for scientific analysis and monitoring. The aim of this paper was to investigate how the hands-on application of RS for vegetation analysis has developed in the SSZ by reviewing the scientific literature published between 1975 and 2014. The paper assesses the *usages* and the *users* of RS by focusing on four aspects of the material (268 peer-reviewed articles), including publication details (time of publication, scientific discipline of journals and author nationality), geographic information (location of study areas and spatial scale of research), data usage (application of RS systems and procedures for accuracy assessments), and research topic (scientific objective of the research). Three key results were obtained: i) the application of RS to analyze vegetation in the SSZ has increased consistently since 1977 and it seems to become adopted by a growing number of scientific disciplines; ii) the contribution of African authors is low, potentially signaling a need for an increased transfer of knowledge and technology from developed countries; iii) RS has primarily been used to analyze changes in vegetation productivity and broad vegetation types, whereas its use for studying interactions between vegetation and environmental factors has been relatively low. This calls for stronger collaborative RS research that enables the mapping of additional vegetation variables of high relevance for the environmental problems facing the SSZ. Remotely sensed vegetation data are needed at spatial scales that suits the requirements of both research and natural resource management in order to further enhance the usefulness of this technology.

Keywords: remote sensing, vegetation, drylands, Sudano-Sahel, monitoring, natural resource management

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1. Introduction

The semi-arid Sudano-Sahelian zone (SSZ) is located between the Saharan desert and the humid Guinean zone and stretches from the Atlantic coast to the Red Sea coast (Fig. 1). In this area, human prosperity is tightly coupled to vegetation resources since ~80 % of the rapidly growing population relies on traditional livelihood strategies, such as subsistence agriculture and livestock production (UNEP 2011). Vegetation constitutes a vital source of energy (Bailis et al. 2007), livestock fodder (Le Houerou 1980), construction material, food stuff, and medicine (Manning et al. 2009), and provides for a number of indispensable ecosystem functions (Mertz et al. 2012; Sinare and Gordon 2015), including soil erosion control (Wezel and Rath 2002), soil fertilization (Bayala et al. 2005; Gnankambary et al. 2008), atmospheric carbon sequestration (Saatchi et al. 2011), and ground water recharge (Ilstedt et al. 2007; Bargués Tobella et al. 2014). In addition, vegetation influences the regional climate by controlling the albedo, and thus land-atmosphere interactions (Charney 1975).

Fig. 1. Map showing the SSZ defined as the area between the 200 mm and 1000 mm isohyets (modified from Hijmans et al. 2005).

The condition of the vegetation in semi-arid areas in general, and the SSZ in particular, has been a matter of global concern for decades. It culminated in 1994 with the adoption of the United Nations Convention to Combat Desertification (UNCCD: Zeng 2003), which was one

of the three environmental conventions stemming from the Rio Summit in 1992. The predominating narratives of environmental change in the SSZ have conveyed a bleak picture where extensive population growth, destructive land management and strong climatic fluctuations have caused widespread and irreversible destruction of the vegetation cover and the soils, a process often referred to as desertification or land degradation (Lamprey 1975; Herrmann and Hutchinson 2005). The United Nations define desertification as ‘land degradation in arid, semi-arid and dry sub-humid areas, resulting from various factors, including climatic variations and human activities’, while land degradation is defined as ‘the reduction or loss of biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes...’ (UN, 1994). The severe droughts that hit the SSZ in the early 1970s and the 1980s both reinforced this dystopic description of the situation and initiated a surge of interest in research about the causes of land degradation and desertification processes, and the effects on the environment and the climate (Tucker and Nicholson 1999). Much of the research originating from this period presented a more balanced picture and argued that earlier conceptions of large scale environmental change in the SSZ (e.g., marching deserts) in many cases have been ill-founded and exaggerated (e.g., Helldén 1991; Thomas and Middleton 1994; Tucker et al. 1991; Tucker and Nicholson 1999; Hiernaux et al. 2009; Fensholt and Rasmussen 2011).

Much of the confusion and the sweeping generalizations that have characterized the desertification debate in the SSZ can be traced to an inadequate understanding of the regional vegetation dynamics resulting from a deficiency of field observations and rigorous scientific research (Helldén 1991; Turner 2003). Even though the situation has improved, *in situ* vegetation data are still scarce in the SSZ (Mougin et al. 2009; Kergoat et al. 2011), inhibiting possibilities to improve scientific understanding, monitoring and management of this essential resource. This is a significant problem, especially in light of the highly uncertain, but potentially detrimental, impacts resulting from anthropogenic climate change, including changes in temperature and rainfall patterns (Giannini et al. 2013), and rapid population increases (Potts et al. 2013). Adequate availability of vegetation data is a prerequisite for the design and implementation of sustainable land management strategies and natural resource monitoring programs, including measures for climate change adaptation and mitigation, and famine early warning systems. Up to date vegetation data (e.g., carbon stocks and forest cover extent) of high quality are also needed for nations to comply with global monitoring and reporting commitments, such as those imposed by the United Nations Framework Convention on Climate Change (UNFCCC) and the Global Forest Resources Assessment (FRA) of the UN Food and Agricultural Organization (FAO).

Remote sensing (RS) data, acquired by optical and microwave sensors mounted on satellites and airplanes, are important alternative sources of information for monitoring and analysis of vegetation (DeFries 2008; Ustin and Gamon 2010). The main advantages of RS include i) the ability to observe large and inaccessible areas, ii) repeated and consistent data acquisition, iii) availability of historical datasets, and iv) low costs of data acquisition relative to field observations. At present, there is a wealth of operational RS systems with different spectral,

spatial and temporal characteristics available, including the Advance Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat series (see Table 1 for details on common RS systems). New earth observation satellites are also continuously being developed, for example the Sentinel-program of the European Space Agency (ESA). RS data with global coverage are available both in the format of un-processed data (e.g., spectral bands) and pre-processed products, such as leaf area index (LAI), fraction of absorbed photosynthetic active radiation (FAPAR), net primary production (NPP) and percent tree cover. Such data can be accessed online via a range of repositories, including the United States Geological Survey (USGS) and ESA. Recent trends in open access data policies and reduced software costs now open up for an increasingly larger group of users to take advantage of RS. The improving capacity and availability of RS is particularly promising for users of vegetation data that focus on areas such as the SSZ where field data are scarce (Mbow et al. 2014).

Table 1. Remote sensing systems commonly used for vegetation analysis in the SSZ. MS: multispectral, Pan: panchromatic.

RS system	Resolution	Revisit period (days)	Scene extent (km)	Pixel size	Launch (year)
AVHRR	Coarse – MS	1-2	2400 × 2400	1 km	1978
VEGETATION	Coarse – MS	1-2	2250 × 2250	1.15 km	1998
MODIS	Coarse/moderate MS	1-2	2330 × 2330	250 m - 1 km	1999
Landsat	Medium – MS	16	185 × 185	MS: 30-80 m Pan: 15 m	1972
Satellite Pour l’Observation de la Terre (SPOT)	Medium – MS	1-5	60 × 60	MS: 8.8 - 20 m Pan: 2.2 - 10 m	1986
ASTER	Medium – MS	16	120 × 150	MS: 15 – 30 m	2000
IKONOS	High – MS and pan	3-5	11 × 11	MS: 4 m Pan: 1 m	1999

The large interest in RS for observation of vegetation in the SSZ is reflected in three recent scientific literature reviews, each focusing on a specific application area. Eisenfelder et al. (2012) review the use of RS for mapping vegetation biomass in semi-arid areas, including the SSZ. Knauer et al. (2014) present a detailed overview of how RS has been used to analyze vegetation dynamics in West Africa, and conclude that most of the research has been focusing on areas in the SSZ. Lastly, Mbow et al. (2015) provide a critical assessment of the research that has used RS for detecting desertification and land degradation in the Sahel. Together, these three papers provide a comprehensive description of the technological and methodological advancement of RS for vegetation observation in the SSZ, where the main focus is on the strengths and weaknesses of different RS systems and analytical methods. In contrast, the objective of the present paper is to investigate how the hands-on application of RS for vegetation analysis has developed in the SSZ between 1975 and 2014. The focus of this literature review is therefore on two subjects: the *usages* and the *users* of RS. Here, the usages involve the vegetation properties and processes that has been observed with RS in the

SSZ, as well as the scope of the research where RS has been used to analyze vegetation. Questions about the users aim to characterize the researchers who use RS as a tool to study vegetation in this region. Four aspects of the literature are assessed quantitatively to accomplish the objective, including i) publication details (time of publication, scientific discipline of journals and author nationality), ii) geographic information (location of study areas and spatial scale of research), iii) data usage (application of RS systems and procedures for accuracy assessments), and iv) research topic (scientific objective of the research). Information about these four aspects can enable the identification of trends in the RS usage that can help pinpoint areas in need of prioritization, and thus further improve the usefulness of RS in the SSZ.

2. The Sudano-Sahelian zone (SSZ) - environmental characteristics and implications for remote sensing

The SSZ consists of two roughly parallel ecological regions and includes areas of 17 countries (Le Houron 1980; Nicholson 1995; Fig. 1). The Sahel is located on the fringes of the Sahara desert and covers the area that receives between 200 and 600 mm mean annual rainfall, while the Sudanian zone to the south receives between 600 and 1000 mm per year. The temperature in the SSZ follows a latitudinal gradient, with mean July temperature of 36°C in the north and 26°C in the south (Nicholson 1995). January is the coldest month with temperatures between 20°C in the north and 22-25°C in the south. The main rainfall patterns are also characterized by a latitudinal gradient, and a relatively short wet season, which takes place between May and October. These two distinct seasons are the result of the West African monsoon (Nicholson 2009). A fundamental feature of the Sudano-Sahelian rainfall patterns is the strong spatio-temporal variability (Nicholson 2001; 2013). This is seen by large fluctuations in rainfall levels between decades, years, months and locations. Between 1968-1997 annual rainfall levels declined by 20-40 % compared to the period between 1930-1960. Severe droughts struck the area during the years 1972-73 and 1983-84, which caused widespread famine (Hulme 2001). Since the mid-1980s rainfall levels have generally increased (Lebel and Ali 2009; Fensholt and Proud 2012), but the risk of periodic droughts is still high as was seen in 2012. The high climatic variability is also manifested by extreme rainfall events that frequently cause devastating floods (Tschakert et al. 2010). Low economic development, strong population increases, social unrest (e.g., conflicts in Mali, Nigeria and the Central African Republic) and climate change further add to the already high vulnerability of the local population and put pressure on vegetation resources (Potts et al. 2013).

The morphological structure and the floristic composition of the vegetation in the SSZ is primarily dependent on soil properties and rainfall levels (Le Houron 1980; White 1983; Nicholson 1995), but has also been shaped by long-term human land use (Fairhead and Leach 1995; Maranz 2009). In general, the proportion of woody vegetation (i.e., trees and shrubs), vegetation height, and vegetation density increase in a north to south direction. The most northern area (Sahel) is composed of grasslands dominated by annual species, and a sparse woody cover of drought tolerant species, such as the *Acacia* genus (Hiernaux et al. 2009). A

large proportion of the land is bare and vegetation tends to grow in patches, where the most striking example is the tiger bush formation (Nicholson 1995). Livestock production is the main means for subsistence in this area (Batterbury and Warren 2001). Further south in the Sudanian zone, grassland savannas characterized by perennial grasses and woodland/agro-forestry parkland landscapes dominate (Boffa 1999). The main means for subsistence in the Sudanian zone is small scale rain-fed agriculture, in combination with livestock production. In the southern areas of the Sudanian zone the tree density increases to form dry forests, which transcend into the humid forests of the Guinean zone to the south (White 1983; Nicholson 1995).

Water is the main limiting factor for vegetation growth throughout the SSZ, which means that photosynthesis mainly takes place during the wet season (Philippon et al. 2005). This results in a distinctly phased vegetation phenology with an intense green-up shortly after the first rains and a high degree of grass and leaf senescence at the beginning of the dry season. The strong intra-seasonal and inter-annual climate variability influences the prevalence of “green” biomass (leaves and grass), and thereby the spectral properties of vegetation (i.e., spectral differences in reflection, absorption and transmittance of electromagnetic radiation, which are the main information carriers in RS). The high variability in vegetation conditions, together with the patchy landscape structure, the open vegetation canopy and the heterogeneous soil conditions, are all factors that pose challenges for RS of vegetation in the SSZ (Franklin 1991; van Leeuwen et al. 1994; Kammerud 1996; Leprieur et al. 2000).

3. MATERIAL AND METHODS

3.1 Literature search

The literature search included English peer-reviewed articles that published original research between 1975 and 2014. Relevant articles were initially identified using targeted searches in the SCOPUS and the ISI Web of Knowledge databases. The inclusion/exclusion criteria for the selection encompassed i) use of RS data for vegetation analysis, ii) geographical location (i.e., study was conducted within the SSZ) and iii) publication in a scientific journal.

Additional articles were identified in relevant literature reviews, and in the reference lists of the included articles through backward reference list checking (Gough et al. 2012). We limited this review to literature concerning RS of (semi-) natural vegetation (i.e., trees, shrubs and grasses). Thus, research that used RS for agricultural applications (e.g., crop estimation) and for bush fires mapping were omitted from the selection.

3.2 Content analysis

The articles that met the inclusion/exclusion criteria in the literature search were assessed following the steps in Fig. 2. The sections below provide additional information to the different steps of the content analysis.

Fig. 2. Flowchart that describes the content analysis process. The broken boxes indicate the main categories used for assessing each aspect of the review material. The solid boxes indicate the sub-categories and the possible options within them.

i) Publication details

Each article was assessed regarding year of publication, journal type and national affiliation of the authors. The journals were divided into five disciplinary categories based on their respective aim and scope. We acknowledge that many journals do not conform to crisp disciplinary boundaries and that such a categorization is arbitrary by default. Thus, results based on the categorization are intended to be seen as an indication of disciplinary acceptance of RS.

ii) Geographical information

The study areas of each article were assessed regarding location and spatial scale (extent) of the analysis. Information about location focused on the country and the ecological region of [Skriv här]

each study. Five categories were used to define the spatial scale of the study areas, including i) SSZ scale, ii) regional scale (areas of multiple countries), iii) national scale (whole country), iv) landscape scale ($\geq 1000 \text{ km}^2$) and v) local scale ($< 1000 \text{ km}^2$).

iii) Data Usage

The assessment about data usage included quantifying the application of different RS systems. We also identified whether accuracy assessments had been conducted and identified the type of reference data used.

iv) Research Topic

The articles were grouped into three main categories based on the objective of the research, including i) vegetation mapping, ii) vegetation and environmental factors and iii) vegetation change, following the typology for vegetation ecology proposed by van der Maarel (2005). Articles can have multiple research objectives and may therefore be included in more than one of the main categories. The three main categories are further divided into sub-categories based on the specific focus of the research (Fig. 2).

The category *vegetation mapping* includes research that uses RS to map properties of the vegetation cover, including structural, biochemical and floristic attributes. It also includes research where the quality of RS data, in particular time series, is evaluated through comparisons to *in situ* observations (e.g., derived from spectroradiometers; Fensholt et al. 2004), or observations from other satellite sensors (e.g., AVHRR NDVI vs. MODIS NDVI; Fensholt et al. 2009). The category *vegetation and environmental factors* includes research that investigates relationships between vegetation and the surrounding environment. Such analyses are achieved by correlating vegetation attributes and their dynamics with environmental factors, such as altitude, soil properties, temperature, and rainfall. Research in the last category investigates *vegetation change* resulting from climatic and/or anthropogenic disturbances (e.g., drought, land use and migration). This category includes the large body of research that has been scrutinizing desertification and land degradation processes in the SSZ. The distinction between the categories *vegetation and environmental factors* and *vegetation change* is less obvious in certain instances, in particular because of the close connection between vegetation production and rainfall in the SSZ. Specifically, analyses of vegetation change often aim to separate long term trends from short term climate fluctuations (i.e., inter-annual rainfall variability), which requires that the relationship between vegetation production and rainfall is taken into account in the analysis.

4. RESULT

4.1 Publication details

The literature search had 1975 as the starting year; however, no relevant articles were published in the first two years of the period (Fig. 3). The first publication occurred in 1977 (Oduolowu 1977), and since then the use of RS in vegetation analyses in the SSZ have been increasing steadily reaching 268 published articles at the end of 2014. The first substantial increase in publication activity occurred in the late 1980s. At the end of the 1990s and in the

early 2000s, a new relatively strong increase occurred. During the years between 2007 and 2012 the annual publication rate increased to surpass one article per month on average. The last two years of the period (2013-2014) clearly stand out because the publication rate has more than doubled compared to the preceding time period.

Fig. 3. Temporal development of published articles where remote sensing has been used to analyse vegetation.

The articles appeared in 84 different scientific journals. About half of the articles were published in journals with a specific focus on RS applications, while the distribution of the other half is more scattered between the journal categories (Table 2). Furthermore, the distribution of articles in the respective categories has changed over time. In the first period (1975-1987) the majority of the articles were published in RS journals and the other categories had limited representation (geography) or were absent (ecology, land management and ecology). Between 1988 and 2001, articles about RS started to be published more frequently in other types of scientific journals. A similar pattern can be seen in the most recent period (2002-2014) where the distribution between the journal categories has become more even and the number of articles published in ecological, geographical, interdisciplinary and land management oriented journals have increased considerably.

Table 2: Distribution of articles in journal categories and the temporal development of the place for publication.

Type of journal	1975-1987		1988-2001		2002-2014		Total	
	No	%	No	%	No	%	No	%
Ecology			8	11	20	11	28	10
Geography	1	17	11	15	20	11	32	12
Interdisciplinary			7	10	38	20	45	17
Land Management			3	4	24	13	27	10

Remote Sensing	5	83	43	60	88	46	136	51
Total no.	6		72		190		268	

The majority of the articles' first authors have been affiliated with institutions located in Europe and North America. Institutions in Africa and Asia/Australia have much lower representation (Fig. 4). Fig. 4 further shows that the African co-authorship is generally low.

<i>African lead authors</i>	
Algeria	1
Benin	1
Congo	1
Ethiopia	14
Kenya	2
Niger	2
Nigeria	3
Mauritania	1
Senegal	5
South Africa	1
Sudan	5
Uganda	1
Sum	37

		<i>% of total co- authors (n = 749)</i>	<i>No of articles</i>	<i>% of total articles (n = 268)</i>
<i>African co-authors</i>	129	17	78	29

Figure 4. National affiliation of lead- and co-authors to remote sensing literature in the SSZ.

4.2 Geographical information

As seen in Fig. 5, the geographic distribution of the scientific activities is uneven in the SSZ. Considerably more research has been conducted in the western parts of the SSZ compared to the east, and more research has been conducted in the Sahelian zone compared to the Sudanian zone. On the national level, it is clear that Chad, Mauritania, Nigeria, Somalia and South Sudan, as well as small countries (Djibouti, Eritrea and the Gambia) and countries with limited spatial overlap with the SSZ (Benin, Cameroon and the Central African Republic), have received limited attention during the 39-year period. Senegal is the country where the largest proportion of research has been conducted, followed by Burkina Faso and Niger.

Fig. 5. The percentage of articles published within each country. 49 studies conducted research on the SSZ scale, which are not included.

The largest proportion of the research, which applied RS data for vegetation analysis, was conducted on the local scale (Fig. 6). Landscape scale and SSZ scale analysis was the second and third largest categories. Figure 6 also shows the temporal development of the choice of scale for the study areas. It appears that the amount of landscape and SSZ scale research has increased over time, whereas no clear temporal trend can be seen for the other three spatial scale categories.

Fig. 6. Temporal development of the spatial scale (i.e., extent of study areas) applied to analyse vegetation using remote sensing.

4.3 Data usage

It is clear from Fig. 7 that the NOAA AVHRR and Landsat series of satellites have been the dominant RS systems for vegetation observation in the SSZ. Furthermore, coarse or moderate resolution RS systems (i.e., AVHRR, MODIS, METEOSAT, VEGETATION and SAR) are the most common choice in this region. Landsat dominates in the medium resolution category (i.e., Landsat, SPOT and Aster), while aerial photography is the most frequently applied type of high resolution RS data.

Fig. 7. Remote sensing systems used to analyse vegetation in the Sudano-Sahelian zone.

The main part of the reviewed studies assessed the accuracy of the remotely sensed vegetation variables using an independent reference dataset (Table 3). Most accuracy assessments were performed using *in situ* data. Higher resolution RS data, data from model simulations and historical photographs were used less frequently for accuracy assessments.

Table 3. Performance of accuracy assessment and use of different sources of reference data.

Accuracy assessments and reference data

	<i>Reference data</i>	<i>No of studies</i>
No		77
Yes		191
	<i>In situ</i> data	150
	Remote sensing	34
	Model data	6
	Photographs	1

4.4 Research topic

The *vegetation mapping* category was dominated by research with the objective to either map primary production directly, to estimate variables used in primary production modelling (e.g., absorbed photosynthetically active radiation and production efficiency indicators), or to generate spatially explicit forecast of primary production (Fig. 8). Relatively few studies have explored techniques for the mapping of tree cover attributes and vegetation types in the SSZ. Research on tree cover attributes has mainly focused on mapping tree canopy cover (%) and tree density (trees/ha), and to a lesser extent aboveground biomass (tons/ha) and tree height (m). Research in the RS data evaluation category did not map or analyse vegetation *per se*, but instead performed assessments of the quality of different RS dataset, including the consistency of time series. For example, the quality of NDVI datasets has been evaluated against *in situ* spectral measurements, and the consistency long-term NDVI time series (e.g., AVHRR) have been evaluated using more recent satellite systems (e.g., MODIS). This category also includes research that has explored effects on RS data resulting from external factors, such as sun-sensor geometry and cloud coverage.

Fig. 8. Temporal and thematic distribution of the category vegetation mapping (n = 104).

The category *vegetation and environmental factors* included the lowest number of articles in the typology. Research within this category has mainly focus on the relationship between vegetation and rainfall (Fig. 9a). Other environmental factors that have been studied for their influence on vegetation dynamics include soil properties and sea surface temperature. Furthermore, some articles in this category used RS data to analyse self-organization of vegetation systems in order to explain the ecological processes causing banded or spotted vegetation patterns, which are commonly occurring in parts of the Sahel (Nicholson 1995). Different vegetation variables, observed through RS, have been correlated with environmental factors (Fig. 9b). Most research has studied the influence of environmental factors on vegetation production. Other vegetation variables that has been used less

frequently in this type of research, include tree cover attributes, phenology and vegetation types.

Fig. 9. Temporal (a) and thematic distribution (b) of the category vegetation and environmental factors (n = 32).

The category *vegetation change* constitute more than half of the review material, which suggests that this is the primary application area of RS data in the SSZ (Fig. 10). Different vegetation variables have been in focus for vegetation change research in the SSZ. The largest proportion of the research has used thematic mapping approaches where high (e.g., aerial photography) or medium (e.g., Landsat) resolution RS data from selected years are processed individually to derive time series of maps that depict land cover and/or vegetation types. Vegetation changes are then typically detected using post-classification comparison. The second most common variable for vegetation change analysis in the SSZ is vegetation productivity derived from time series of coarse resolution RS data (e.g., AVHRR). Knauer et al. (2014) and Mbow et al. (2015) provide detailed descriptions of the many different approaches have been used to detect changes in vegetation productivity using coarse resolution RS data in the SSZ. Considerably less research has analysed changes in tree cover attributes and vegetation phenology using RS data. Changes in tree cover attributes (e.g., canopy cover and tree density) have primarily been analysed using high or medium resolution

RS data in order to separate trees and shrubs from the herbaceous vegetation that dominate the RS signal during the growing season. However, recent research by Horion et al. (2014) and Mitchard and Flintrop (2013) has shown that coarse resolution NDVI data acquired during the dry season is an interesting alternative for analysing tree cover changes over larger spatial extents (Brandt et al. 2015).

Fig. 10. Temporal and thematic distribution of the category vegetation change (n = 143).

5. DISCUSSION

5.1 What information can remote sensing provide about vegetation in the Sudano-Sahelian zone?

The category *vegetation mapping* include research where RS systems have been evaluated for their potential to map different vegetation variables, while *vegetation and environmental factors* and *vegetation change* include research where RS been used as a tool to analyze dynamics and changes in these remotely sensed variables. A comparison between the three categories (Fig. 8-10) shows that a few vegetation variables have dominated the applied research categories (i.e., *vegetation and environmental factors* and *vegetation change*). Vegetation production has been the main variable for research focusing on vegetation dynamics and changes on broad spatial scales, whereas mapping of vegetation types has dominated analyses that focus on smaller areas.

The large focus of RS research on vegetation production and broad vegetation types is likely a reflection of both the prevailing environmental concerns in the SSZ, in particular desertification/land degradation, and practical considerations related to availability of RS data and methods for RS data interpretation. Vegetation production has historically been a key variable to describe the state and the dynamics of the Sudano-Sahelian environment and its relation to land use (Le Houérou 1989), and is also included in the definition of desertification/land degradation used by the UNCCD (2014). In the late 1990s, widespread increases in vegetation production were observed throughout the SSZ (i.e., greening; Olsson et al. 2005) using AVHRR time series. This rather unexpected finding further challenged the

dominating narrative of environmental change in the SSZ, and is one of the main reasons for the large increase in RS research in the last 15 years shown in this review. Several researchers suggested that the greening-phenomena needed to be observed at higher levels of detail in order to establish the causative mechanisms and to better understand potential consequences (Anyamba and Tucker 2005; Herrmann et al. 2005). Time series of medium and high resolution RS data have been widely used for such analyses because fine scale processes, including human influences on vegetation, can be observed (e.g., Kelder et al. 2013; Rasmussen et al. 2014; Ruelland et al. 2008; 2010; Tappan et al. 2000; 2004). Other researchers have explored hotspots of vegetation change identified by coarse resolution RS through field based surveys and interviews with local land users (e.g., Milich and Weiss 2000; Herrmann and Tappan 2013; Brandt et al. 2014a; 2014b; Herrmann et al. 2014).

There are also practical reasons for the large focus on RS of vegetation production and vegetation types. Coarse resolution NDVI data has a long tradition in RS applications and was initially accepted as a reliable proxy for vegetation productivity in semi-arid ecosystems (Prince and Justice 1991). Consequently, analyses of vegetation productivity dynamics and changes using NDVI have been less dependent on the availability of reference data for calibration and validation, which has greatly facilitated its widespread application in the SSZ. Thematic mapping of broad vegetation types also has a long tradition in RS research in general, and the availability of established and easily accessible methods (i.e., implemented in standard software suits) for manual and automated data interpretation has contributed to their widespread adoption (Ustin and Gamon 2010). Thematic mapping requires reference data for training classification algorithms and for validation, which has largely restricted the application to local scales in the SSZ. National and regional scale analyses using thematic mapping have been conducted, for example in Senegal (Tappan et al. 2004), the Horn of Africa (Brink and Eva 2011) and West Africa (Vitek et al. 2014). However, such broad scale studies have used a systematic spatial sampling strategy instead of complete coverage imagery in order to limit the data processing burden, and have relied on local experts for data interpretation. Recent examples exist where high resolution imagery accessed from Google Earth has been used as reference data for medium resolution data interpretation (Rembold et al. 2013; Wu et al. 2013; Karlson et al. 2015). High resolution imagery represents an interesting complement to *in situ* data and may reduce the costs and risks (e.g., due to social unrest) associated with field campaigns (Rembold et al. 2013).

Both these two widely studied vegetation variables (i.e., vegetation productivity and vegetation types) have limitations to characterize the heterogeneous vegetation cover in the SSZ. Specifically, vegetation production estimates derived from coarse resolution RS data provide poor spatial detail due to their large pixel size (e.g., 1-64 km² for AVHRR). Assessments have also shown that the relationship between NDVI and vegetation production in the SSZ is complex and influenced by both internal and external factors, including species composition (Tagesson et al. 2014), water availability (Diouf and Lambin 2001; Fensholt et al. 2013) and soil reflectance (Kammerud 1996). In addition, vegetation production derived from NDVI time series mainly capture the contribution from herbaceous vegetation which dominates over the sparse tree cover in terms of spectral response at the scale of coarse

resolution pixels (Gonzalez et al. 2012), especially during the wet season (Horion et al. 2014). As for vegetation types, the crisp classification boundaries inherent to thematic mapping are far from ideal to capture subtle, yet potentially important, variations in the heterogeneous vegetation cover in the SSZ (Franklin 1991; Cord et al. 2010). Furthermore, time series of vegetation maps consisting of a few time steps (e.g., decadal) have limitations to capture the temporal dynamics that characterize vegetation in the SSZ. Consequently, these two variables may therefore conceal important aspects of both vegetation dynamics and vegetation change.

5.2 Local remote sensing capacity – a function of knowledge transfer and research infrastructure

The geographic distribution of the research is uneven throughout the SSZ (Fig. 5). A large proportion of the RS research has been conducted in the western parts of the SSZ (e.g., Burkina Faso, Niger and Senegal), whereas considerably less research has been conducted in the eastern parts. This pattern is presumably shaped by research priorities and investments made by institutions in the individual countries that is further accentuated by the placement of large international research projects, such as the Hydrologic-Atmospheric Pilot Experiment (HAPEX) in the Sahel (Goutorbe et al. 1997) and the African Monsoon Multidisciplinary Analysis (AMMA; Kergoat et al. 2011; Mougin et al. 2009). Bilateral collaborations between national governments and universities have likely contributed to this pattern as well, for example Denmark has had a strong presence in Burkina Faso and Senegal (Mbow et al. 2014). Understandably, considerably less research has been conducted in politically unstable areas, including areas where armed conflict has prevailed in the recent past (e.g., Chad, Sudan and Somalia).

The geographic publication pattern demonstrates a spatial imbalance of RS capacity within the SSZ that potentially reflects impaired preconditions for research, monitoring and management of vegetation resources in a significant number of countries. Furthermore, the low number of both lead- and co-authors with African affiliations suggests that the research conducted in the SSZ has mainly been initiated, conducted and financed by foreign institutions, generally located in Europe and North America. Even though it is well known that the general development of RS usage in Africa has been severely hampered by bureaucratic, financial and technical constraints (Abiodun 2000), it is noteworthy that the three countries (Burkina Faso, Niger and Senegal) where most of the RS research has been conducted in the SSZ have so low representation in terms of authorship. Similar observations were made by Woldai and Annegard (2010) for RS research in Africa in general. This raises questions about the degree to which RS technology and knowledge is transferred from developed countries to the countries where the research is conducted. These results further add to the conclusions by Romijn et al. (2012) who showed that countries in the SSZ have very low capacities to monitor forest carbon by RS compared to other tropical countries. Increased support for capacity building of local institutions in the SSZ, such as Centre de Suivi Ecologique (Senegal), the Centre Régional AGRHYMET (Niger), as well as local universities, may therefore be needed to promote an increased usage of RS. In addition, RS

capacity is also highly depends on RS data availability. At present, a wide supply of high quality RS data is available free of charge and in the near future there will be the launch of the Sentinel-2 satellite, which will provide free data of unprecedented high spatial as well as temporal resolution (Drusch et al. 2012). An important consideration in this regard is that the possibility to download RS data in the SSZ presently is severely hampered by insufficient internet capacity (Roy et al. 2010; Romijn et al. 2012).

5.3 Diversifying the use of remote sensing – a way forward?

This review has identified an important gap between the present capability of RS and current vegetation information requirements in the SSZ. Specifically, local scale research has shown that climate change and land use change has caused degradation of the tree cover in different part of the SSZ (e.g., Gonzalez 2001; Maranz 2009; Gonzalez et al. 2012). Tree cover monitoring by RS on larger spatial scales is therefore needed to provide comprehensive descriptions of the process and establish whether it is operating on regional or continental scales. However, previous tree cover monitoring has mainly been conducted on local scale using thematic mapping approaches, which are limited in the ability to detect subtle changes in tree cover conditions, for example modifications in density, structure and composition (Lambin 1999). Two recent examples have shown that wide scale tree cover monitoring may be feasible using coarse resolution RS data, in particular dry season AVHRR NDVI (Mitchard and Flintrop 2013; Horion et al. 2014). This is an interesting approach that uses differences in phenology to separate the spectral signals from herbaceous and woody vegetation, which merits further research efforts. Several global tree cover products derived from MODIS (Hansen et al. 2003) and Landsat (Sexton et al. 2013) that provide higher spatial detail are also available to the scientific community, but they need to be validated locally to ensure that they provide reliable information (Sjöström et al. 2013). Rigorous assessments have been performed in some areas of the SSZ for other vegetation products, including MODIS LAI (Fensholt et al. 2004) and primary production products (Fensholt et al. 2006; Sjöström et al. 2009; 2011; 2013). Herrmann et al. (2013) assessed the MODIS tree cover product visually in a *Faidherbia albida* agroforestry landscape in Senegal and found it to severe limitations. Further assessments of pre-processed vegetation products in the different landscapes types of the SSZ can be facilitated by improving the cooperation between the different actors who collect vegetation data in the field and the RS community (Pettorelli et al. 2014). An example of such an initiative is the West African Vegetation Database of the UNDESERT project that provides an online platform for vegetation data exchange.

This review demonstrates that the usage of RS for vegetation analysis has increased consistently in the SSZ since the mid-1980s, but also that the RS users have diversified. Specifically, our analysis suggests that that the range of the journal used for publishing RS research have diversified consistently in terms of their scientific disciplines: the publications have moved from strictly RS oriented journals into journals specialized in land management, geography, ecology and interdisciplinary science. This may suggest that RS is increasingly being accepted as an effective source of vegetation information by a broader group of

scientific practitioners who are active in the SSZ. The general trend of improving quality and accessibility of RS data suitable at different spatial scales will most likely facilitate this trend. However, this review also shows that vegetation change is the dominating application area for RS in the SSZ, whereas its use in analyses of relationships between vegetation and environmental factors is still limited. In other words, the usages have not diversified in the same extent as the users. Hence, additional integration of RS into scientific disciplines concerned with other types of research questions about vegetation is needed to further advance the scientific contribution of this relatively young technology (Pettorelli et al. 2014). Such integration may strengthen capacities in the SSZ to assess and understand vegetation responses to environmental change and the related impacts on natural resources and human livelihoods.

In order to make RS useful for answering other research questions than those that have dominated in the SSZ previously, additional vegetation variables need to be mapped with sufficient accuracy and detail. Important topics for future RS research in the SSZ therefore include the mapping of i) morphological structure of woody vegetation (e.g., woody biomass, tree density, canopy cover and canopy height) and ii) floristic aspects (e.g., differentiation between annual and perennial grasses and between tree species types). In particular floristic aspects are missing links in the understanding of what is driving vegetation changes observed at coarse spatial resolutions (e.g., greening; Olsson et al. 2005; Tagesson et al. 2014), and how such changes impact the local environment and livelihoods (Herrmann et al. 2014). The Sentinel-2 mission, which is planned to be operational in 2016, will provide high spatial and temporal resolution data. These are highly suitable data characteristics for mapping and analyzing different aspects of the Sudano-Sahelian vegetation.

6. CONCLUSIONS

- The use of RS for vegetation analysis in the SSZ has increased steadily from 1975 to 2014 in terms of peer-reviewed articles ($n = 268$), with the largest increase in the last seven years.
- During the last 12 years, RS appears to have become increasingly accepted as a source of information by a wider group of researchers concerned with vegetation analysis in the SSZ, as reflected by the variety of journals used for publication.
- The geographical distribution of the RS research is uneven in the SSZ, with a dominance within a few countries (e.g., Burkina Faso, Niger and Senegal). Potential factors for this pattern include multilateral research collaborations, availability of *in situ* data and research infrastructure, and political stability.
- African lead- and co-authors are underrepresented in the literature, suggesting that RS research in the SSZ has largely been dependent on resources (expertise and financing) from developed countries in Europe and North America.
- In the SSZ, RS has primarily been used to analyze vegetation change as an effect of different types of disturbance, whereas its use in research about relationship to environmental factors, such as rainfall, soil properties, groundwater and terrain, has been relatively limited.

- A few vegetation variables, namely vegetation productivity and broad vegetation types, have dominated the research where RS has been applied in the SSZ. Important topics for future RS research therefore includes improved vegetation mapping of morphological structure of woody vegetation and floristic composition at spatial scales relevant for both research and natural resource management applications.

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Wu, W., E. De Pauw, and U. Helldén. 2013. Assessing woody biomass in African tropical savannahs by multiscale remote sensing. *International Journal of Remote Sensing* 34: 4525-4549.

Zeng, N. 2003. Drought in the Sahel. *Science* 302: 999-1000.

Electronic supplementary material

This is a list of all articles (n = 268) included in the literature review. The articles are grouped into the three main categories, which are based on the research topic. References in italic are included in two of the main categories. An interpretation key is provided for each category.

1. Vegetation mapping

Key: **DE** (data evaluation), **LAI** (leaf area index), **PP** (primary production), **T** (transpiration), **TCP** (tree cover properties), **VT** (vegetation type) **WC** (water content)

Aynekulu, E., T. Kassawmar, and L. Tamene. 2008. Applicability of ASTER imagery in mapping land use / cover as a basis for biodiversity studies in drylands of northern Ethiopia. *African Journal of Ecology* 46 (Suppl 1): 19-23. (**VT**)

Bèniè, G.B., S.S. Kaboré, K. Goita, and M.F. Courel. 2005. Remote sensing-based spatio-temporal modeling to predict biomass in Sahelian grazing ecosystems. *Ecological Modelling*, 184: 341-354. (**PP**)

Biro, K., B. Pradhan, H. Sulieman, and M. Buchroithner. 2013. Exploitation of TerraSAR-X data for land use/land cover analysis using object-oriented classification approach in the African Sahel area, Sudan. *Journal of the Indian Society of Remote Sensing* 41: 539-553. (**VT**)

Boegh, E., H. Soegaard, N.P. Hanan, P. Kabat, and L. Lesch. 1999. A remote sensing study of the NDVI- T_s relationship and the transpiration from sparse vegetation in the Sahel based on high-resolution satellite data. *Remote Sensing of Environment* 69: 224-240. (**T**)

Ceccato, P., N. Gobron, S. Flasse, B. Pinty, and S. Tarantola. 2002. Designing a spectra index to estimate vegetation water content from remote sensing data: Part 1 theoretical approach. *Remote Sensing of Environment* 82: 188-197. (**WC**)

Ceccato, P., S. Flasse, and J.M. Grégoire. 2002. Designing a spectra index to estimate vegetation water content from remote sensing data: Part 2 Validation and applications. *Remote Sensing of Environment* 82: 198-207. (**WC**)

Cord, A., C. Conrad, M. Schmidt, and S. Dech. 2010. Standardized FAO-LCCS land cover mapping in heterogeneous savannas of West Africa. *Journal of Arid Environments* 74: 1083-1091. (**VT**)

Couteron, P., M. Deshayes, and C. Roches. 2001. A flexible approach for woody cover assessment from SPOT HRV XS data in semi-arid West Africa. Application in northern Burkina Faso. *International Journal of Remote Sensing* 22: 1029-1051. (**TCP**)

Dardel, C., L. Kergoat, P. Hiernaux, E. Mougin, M. Grippa, and C.J. Tucker. 2014. Re-greening Sahel: 30 years of remote sensing data and field observations (Mali, Niger). *Remote Sensing of Environment* 140: 350–364. (**DE**)

Defourny, P. 1991. Multistage and multisensor approach for woody biomass evaluation in a tree savanna region (Burkina Faso). *IEEE* 4: 2461-2464. (**TCP**)

Devineau, J-P., Aurouet, A., Douanio, M., Hladik, A. 2008. Changes in the availability and uses of wild yams according to climatic dryness and land-cover in Western Burkina Faso (West Africa): a joint ecological and ethno-botanical approach using GIS and remote-sensing. *Biodiversity and Conservation* 17: 1937-1963. **(VT)**

Diallo, O., A. Diouf, N.P. Hanan, A. Ndiaye, and Y. Prévost. 1991. AVHRR monitoring of savanna primary production in Senegal, West Africa: 1987-1988. *International Journal of Remote Sensing* 12: 1259-1279. **(PP)**

Djaroudib, K. 1993. Quantitative estimation of woody vegetation in the Sudano-Sahelian region. A textural approach applied in a region of Burkina Faso. *EARSeL Advances in Remote Sensing* 2: 56-63. **(TCP)**

Egziabher, T.B., E. Feoli, M. Ferneti, G. Oiolo, and Z. Woldu. 1998. Vegetation mapping by intergration of floristic analysis, GIS and remote sensing. An example for Tigray (Ethiopia). *Plant Biosystems* 132: 39-51. **(VT)**

Fensholt, R. 2004. Earth observation of vegetation status in the Sahelian and Sudanian West Africa: comparison of Terra MODIS and NOAA AVHRR satellite data. *International Journal of Remote Sensing* 25:1641-1659. **(DE)**

Fensholt, R., I. Sandholt, and M.S Rasmussen. 2004. Evaluation of MODIS LAI, fAPAR and the relation between fAPAR and NDVI in a semi-arid environment using in situ measurements. *Remote Sensing of Environment* 91: 490-507. **(PP + LAI)**

Fensholt, R., B. Anyamba, S. Huber, S.R. Proud, C.J. Tucker, J. Small, E. Pak, M.O. Rasmussen, I. Sandholt, and C. Shisanya. 2011. Analysing the advantages of high temporal resolution geostationary MSG SEVIRI data compared to Polar operational environmental satellite data for land surface monitoring in Africa. *International Journal of Applied Earth Observation and Geoinformation* 13: 721-729. **(DE)**

Fensholt, R., S. Huber, S.R. Proud, and C. Mbow. 2010. Detecting canopy water status using shortwave infrared reflectance data from polar orbiting and geostationary platforms. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 3: 271-285. **(WC)**

Fensholt, R., and S.R. Proud. 2012. Evaluation of earth observation based global long term vegetation trends—Comparing GIMMS and MODIS global NDVI time series. *Remote Sensing of Environment* 199: 131–147. **(DE)**

Fensholt, R. and I. Sandholt. 2003. Derivation of a shortwave infrared water stress index from MODIS near- and shortwave infrared data in a semiarid environment. *Remote Sensing of Environment* 87: 111– 121. **(WC)**

Fensholt, R., I. Sandholt, M.S. Rasmussen, S. Stisen, and A. Diouf. 2006. Evaluation of satellite based primary productions modelling in the semi-arid Sahel. *Remote Sensing of Environment* 105: 173-188. **(PP)**

Fensholt, R., A. Anyamba, S. Stisen, I. Sandholt, E. Pak, and J. Small. 2007. Comparisons of compositing period length for vegetation index data from polar-orbiting and geostationary

satellites for the cloud-prone region of West Africa. *Photogrammetric Engineering & Remote Sensing* 73: 297–309. **(DE)**

Fensholt, R., I. Sandholt, and S. Stisen. 2006. Evaluating MODIS, MERIS, and VEGETATION vegetation indices using *in situ* measurements in a semiarid environment. *IEEE Transactions on Geoscience and Remote Sensing* 44: 1774-1786. **(DE)**

Fensholt, R., and I. Sandholt. 2005. Evaluation of MODIS and NOAA AVHRR vegetation indices with *in situ* measurements in a semi-arid environment. *International Journal of Remote Sensing* 26: 2561-2594. **(DE)**

Fensholt, R., A. Anyamba, S. Huber, S.R. Proud, C.J. Tucker, J. Small, E. Pak, M.O. Rasmussen, I. Sandholt, C. Shisanya. 2011. Analysing the advantages of high temporal resolution geostationary MSG SEVIRI data compared to Polar Operational Environmental Satellite data for land surface monitoring in Africa. *International Journal of Applied Earth Observation and Geoinformation* 13: 721–729. **(DE)**

Fensholt, R., K. Rasmussen, T.T. Nielsen, and C. Mbow. 2009. Evaluation of earth observation based long term vegetation trends — Intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data. *Remote Sensing of Environment* 113: 1886–1898. **(DE)**

Fensholt, R., I. Sandholt, S.R. Proud, S. Stisen, and M.O. Rasmussen. 2010. Assessment of MODIS sun-sensor geometry variations effect on observed NDVI using MSG SEVIRI geostationary data, *International Journal of Remote Sensing* 31: 6163-6187. **(DE)**

Franklin, J. 1991. Land cover stratification using Landsat Thematic Mapper data in Sahelian and Sudanian woodland and wooded grassland. *Journal of Arid Environments* 20: 141-163. **(VT)**

Franklin, J., and P. Hiernaux. 1991. Estimating foliage and woody biomass in Sahelian and Sudanian woodlands using a remote sensing model. *International Journal of Remote Sensing* 12: 1387-1404. **(TCP)**

Franklin, J., and A.H. Strahler. 1988. Invertible canopy reflectance modeling of vegetation structure in semiarid woodland. *IEEE Transactions on Geoscience and Remote Sensing* 26: 809-825. **(TCP)**

Frederiksen, P., and J.E. Lawesson. 1992. Vegetation types and patterns in Senegal based on multivariate analysis of field and NOAA AVHRR satellite data. *Journal of Vegetation Science* 3: 535–544. **(VT)**

Frison, P., E. Mougin, and P. Hiernaux. 1998. Observations and interpretation of seasonal ERS-1 Wind Scatterometer Data over northern Mali. *Remote Sensing of Environment* 63: 233-242. **(PP)**

Frison, P.L., E. Mougin, L. Jarlan, M.A. Karam, and P. Hiernaux. 2000. Comparison of ERS Wind-Scatterometer and SSM/I data for Sahelian vegetation mapping. *IEEE Transactions on geosciences and remote sensing* 38: 1794-1803. **(PP)**

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- Jarlan, L., S. Mangiarotti, E. Mougin, P. Mazzega, P. Hiernaux, and V. Le Dantec. 2008. Assimilation of SPOT/VEGETATION NDVI data into a sahelian vegetation dynamics model. *Remote Sensing of Environment* 112: 1381-1394. **(PP)**
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- Kammerud, T.A. 1996. Soil impact on satellite based vegetation monitoring in Sahelian Mali. *Geografiska Annaler. Series A, Physical Geography* 78: 247-259. **(DE)**
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- Mangiarotti, S., P. Mazzega, P. Hiernaux, and E. Mougin. 2012. Predictability of vegetation cycles over the semi-arid region of Gourma (Mali) from forecasts of AVHRR-NDVI signals. *Remote Sensing of Environment* 123: 246-257. **(PP)**
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Qi, J., Y.H. Kerr, M.S. Moran, M. Wertz, A.R. Huete, S. Sorooshian, and R. Bryant. 2000. Leaf Area Index estimates using remotely sensed data and BRDF models in a semiarid region. *Remote Sensing of Environment* 73: 18-30. **(LAI)**

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Ritchie, J.C., M. Menenti, and M.A. Wertz. 1996. Measurements of land surface features using an airborne laser altimeter: the HAPEX-Sahel experiment. *International Journal of Remote Sensing* 17: 3705-3724. **(TCP)**

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Sandholt I., and H.S. Andersen. 1993. Derivation of actual evapotranspiration in the Senegalese Sahel using NOAA-AVHRR data during the 1987 growing season. *Remote Sensing of Environment* 46:164-172. **(T)**

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