

Chapter 5

The Map Is not the Territory: How Satellite Remote Sensing and Ground Evidence Have Re-shaped the Image of Sahelian Desertification

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Abstract Satellite remote sensing, in particular the analysis of coarse resolution time series of vegetation indices, has played an important role in challenging earlier assumptions of widespread desertification in the Sahel. Findings of such analyses show a greening trend in much of the region since the early 1980s, which seems to suggest a positive development. On the other hand, a growing number of field studies of vegetation dynamics across the Sahel offer a more fine-scaled and nuanced picture of changes. Of particular interest with respect to degradation and rehabilitation is the woody component of the vegetation cover, which is less affected by short-term fluctuations in precipitation than the herbaceous component. We synthesized findings from published field studies on changes in the abundance and diversity of woody vegetation across the Sahel and spatially compared them with the remotely sensed greenness trends. Many field sites reported a decline in the abundance of woody vegetation since before the great droughts, in particular of large trees. In addition, the woody vegetation shifted from a diverse species composition towards fewer and more drought tolerant species in the majority of sites. However, some success stories of agroforestry management stood out as well, where formerly degraded farmlands were rehabilitated and in some cases have reached even higher tree densities than in the 1960s. The discrepancy between satellite-observed greening trends and changes in woody vegetation on the ground

“The Map is not the Territory” is an aphorism that goes back to the Polish-American scientist Alfred Korzybski and emphasizes that a representation of reality (=map) must not be confused with reality itself (=territory). Thus, maps and graphical data convey images that risk developing a life of their own, with the map preceding and even becoming the territory.

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—in both directions—emphasizes the need of integrating multiple perspectives and scales in the interpretation of greening trends with respect to desertification.

Keywords Remote sensing · Time series · (Re-)greening · Tree cover · Ground truthing · Longitudinal studies · Size class distributions · Local knowledge

5.1 Introduction: Putting Desertification on the Map

The West African Sahel region has been characterized as a ‘hotspot’ of desertification since it was afflicted by a series of drought years from the late 1960s through the 1980s, following a decade of above-average rainfall years (Raynaut et al. 1996; Reynolds and Stafford Smith 2002; Middleton and Thomas 1997). The amount of human suffering that resulted from the droughts, as well as the perceived degradation of the environment, triggered much political and scientific interest in the phenomenon of desertification. In the late 1970s, a study commissioned by the United Nations to assess the spatial extent of the problem had estimated that the Sahara desert was expanding southward at the startling pace of 5–6 km annually (Lamprey 1988) (Fig. 5.1). A decade later, the expert opinion-based Global Assessment of Soil Degradation (GLASOD) provided a new official perspective on the extent of degradation (Oldeman et al. 1991), in which the entire Sahel region was classified as severely degraded (Fig. 5.2). GLASOD also formed the basis of two editions of UNEP’s World Atlas of Desertification (Middleton and Thomas 1992, 1997).

The lingering imprecision of the desertification concept and the lack of measurable criteria, however, fueled debate and controversy among scientists (Pearce 1992; Thomas and Middleton 1994; Herrmann and Hutchinson 2005). Subjects of the debate have been the spatial extent of desertification, its reversibility, as well as the relative contributions of climatic (i.e., drought) and anthropogenic (i.e., overgrazing, deforestation) driving forces of desertification.

Despite the controversy, the notion of regional desertification in the Sahel was widely accepted without question until several remote sensing-based studies challenged the mainstream paradigm of irreversible degradation by documenting a greening trend across much of the Sahel over the past 30 years (Hutchinson et al. 2005). This greening trend, which suggests a possible recovery of the vegetation, was derived from time series of the Normalized Difference Vegetation Index (NDVI) computed from reflectance measurements by a series of Advanced Very High Resolution Radiometer (AVHRR) sensors since 1981. The Land Degradation Assessment in Drylands (LADA) global project, which superseded GLASOD in 2006, adopted the analysis of time series of NDVI as part of their strategy to determine status and trends of land degradation and rehabilitation (Bai et al. 2008). A third edition of the World Atlas for Desertification is currently being compiled,

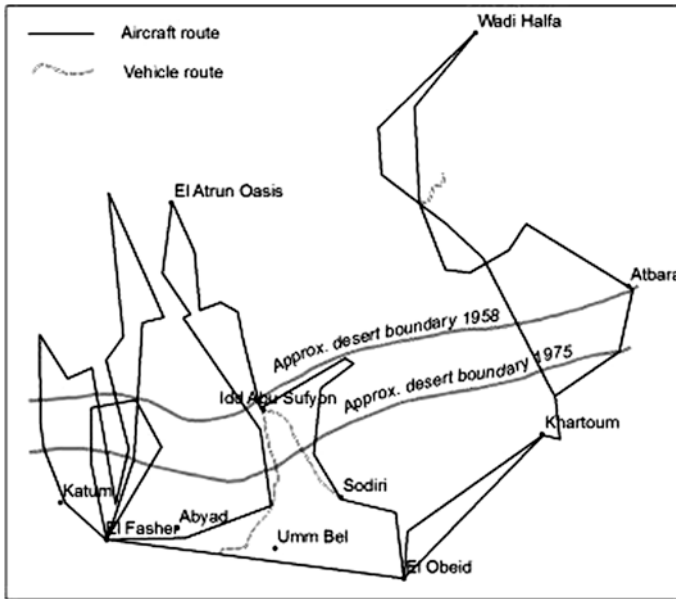


Fig. 5.1 Lamprey’s report on desert encroachment in the northern Sudan, based on a reconnaissance survey to map the desert boundary and its comparison with a previously published vegetation map (Harrison and Jackson 1958), became one of the most widely cited references for the rate of southward expansion of the Sahara desert. Different interpretations of the desert boundary, owing in part to differences in rainfall conditions in the years of assessment, led to the misnomer that the desert was advancing. Figure adapted from Lamprey (1988).

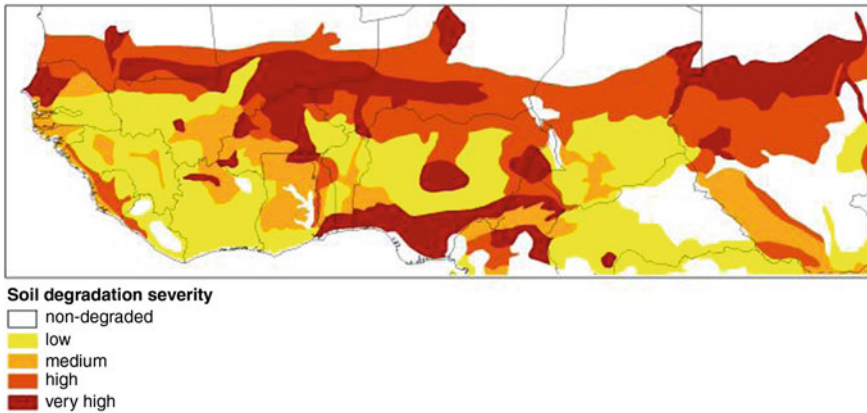


Fig. 5.2 Map of the severity of soil degradation as an indicator of desertification, compiled by the Global Assessment of Soil Degradation (GLASOD) (Oldeman et al. 1991). GLASOD has been one of the most influential global appraisals of land degradation and has majorly contributed to the perception of widespread degradation in the Sahel. For a more in-depth discussion of the GLASOD suite of maps, see Prince (this volume).

the mapping of which is also built on this satellite-based vegetation greenness data set (Joint Research Centre of the European Commission 2015).

While the ever lengthening time series of NDVI data constitute an invaluable and irreplaceable archive of land cover information (Tucker et al. 2005; Dardel et al. 2014a), their interpretation with respect to the nature of vegetation changes is not straightforward. In order to be useful for assessing and monitoring land degradation and rehabilitation, the synoptic overview provided by satellites needs to be related to the physical realities on the ground. The process of “ground truthing”¹—gathering field data to complement remote sensing data and to establish a link between the radiometric characteristics of a surface and the information desired by a particular application or study—is an integral part of every remote sensing project (Steven 1987). Although the need for field data appears self-evident, there are a number of practical and conceptual challenges, ranging from the timing of the field data collection to coincide with the satellite overpass to the decision of what variables to collect and at what spatial scale. Relating remote sensing data to ground observations is further complicated when working with historical or time series of remote sensing data, as field visits allow direct assessment only of the current state of the environment.

In the case of the satellite-observed NDVI trends in the Sahel, simply visiting a number of locations on the ground and taking stock of the current state of the land cover alone cannot confirm or dispute that greening has taken place. Nor does it inform about the nature of the greening in the sense of a rehabilitation or recovery of the vegetation cover. Inter-comparison between NDVI trends derived from different satellite sensors has been used to verify the direction of trends (e.g., Fensholt et al. 2009; Fensholt and Proud 2012). For some sites, historical field data on woody and herbaceous vegetation are available from prior studies, which give insights into the land cover and vegetation conditions in the past (e.g., Herrmann and Tappan 2013; Dardel et al. 2014a). Although those earlier studies had not necessarily been designed as baselines for longitudinal studies and might not have collected the most desired variables, they present a valuable resource for characterizing vegetation changes on the ground and relating them to satellite-observed trends. In addition, the knowledge of the local inhabitants on changes in vegetation cover over time has been used to support findings from ground surveys and remote sensing data (Herrmann et al. 2014).

In the following, we will outline how regional-scale remote sensing-based findings have shaped the image of Sahelian desertification over past two decades (Sect. 5.2). We will then review different approaches using field data to reconstruct vegetation changes, focusing on the woody component of the vegetation (Sect. 5.3), and synthesize findings from published field studies across the Sahel region

¹Although the term “ground truth” is widely used in the remote sensing community to describe field observations that help interpret remote sensing imagery, it is disliked by many remote sensing scientists, because it might imply that satellite data are erroneous in some way and because reference data can come from sources not necessarily involving ground investigations. Despite its shortcomings, we use this term here for lack of a better and equally short alternative.

(Sect. 5.4). Finally, we will discuss agreement and discrepancies between coarse-resolution regional scale remote sensing-based observations of trends in vegetation greenness (NDVI) and local scale findings from field studies of woody vegetation dynamics (Sect. 5.5).

5.2 Remote Sensing Perspectives on Regional Greening

Remote sensing products, such as air photos and early Landsat images, were used in early mapping of the formation of desert patches around villages (Ibrahim 1978) and the southward expansion of the Sahara desert (Lamprey 1988) (Fig. 5.1). However, this early use of remote sensing was limited to local scales and did not take into account the seasonality and interannual variability of rainfall and vegetation cover. Based on spatial extrapolation of such studies, often without disclosure of methodologies employed or presentation of primary data, widespread degradation in the Sahel was largely treated as an established fact in the 1970s. A few case studies on the ground (Warren and Agnew 1988; Mortimore 1989) and using remote sensing (e.g., Hellden 1991) had begun questioning the extent of desertification as early as the 1980s. At a regional scale, however, it was not until the 1990s that sufficiently long time series of high frequency, coarse resolution remote sensing observations became available, the analyses of which shed new light on vegetation dynamics and desertification (National Research Council 2008).

These analyses have been based on the Normalized Difference Vegetation Index (NDVI), a greenness index derived from the red and near infrared spectral bands, which is strongly correlated with photosynthetically active biomass (Rouse et al. 1973; Tucker 1979). Time series of bi-weekly NDVI at a spatial resolution of 8 km, derived from reflectance measurements by the Advanced Very High Resolution Radiometer (AVHRR) sensors (James and Kalluri 1994; Tucker et al. 2005), begin in 1981. This series is the longest continuous data record of its kind, and has formed the basis of several influential research studies on vegetation trends in West Africa:

Tucker et al. (1991) were the first to show the high interannual variability of NDVI in the Sahel zone, which directly responds to precipitation. Their findings helped refute the hypothesis of a continuous expansion of the Sahara desert to the south. In a follow-up study, Tucker and Nicholson (1999) confirmed the variability of NDVI over an extended time period as well as the interannual movements of the critical 200 mm precipitation isohyet. Both studies show the close link between precipitation and bio-productivity, contesting the existence of man-made desertification.

Prince et al. (1998) used rain-use efficiencies—the ratio of satellite-derived net primary production (NPP) to precipitation—as an indicator of vegetation degradation, postulating that degrading lands would be marked by declining rain-use efficiencies. However, their analysis showed locally variable rain-use efficiencies with overall upward trends over the period studied, and thus did not demonstrate widespread Sahelian desertification.

Eklundh and Olsson (2003) found strong increases in seasonal NDVI over large areas of the Sahel and Sudan ecological zones from 1982 to 1999, which they interpreted as a vegetation recovery after the drought years of the 1980s. This positive trend was confirmed by Anyamba and Tucker (2005), who described two distinct periods of NDVI patterns, with below average NDVI in the 1980s and above average NDVI in the 1990s and 2000s, in agreement with temporal patterns of rainfall anomalies. Since the AVHRR NDVI time series happens to begin in a very dry period in the Sahel, when the vegetation was arguable in its most desiccated state, it is not too surprising that the positive trend in precipitation since then (which has not canceled out the secular negative trend in precipitation) is accompanied by a greening trend over the same period (Fig. 5.4; Giannini, in this volume).

Herrmann et al. (2005) analysed linear trends in the residual NDVI after removal of the precipitation signal and concluded that precipitation is indeed an important causative factor for the positive NDVI trend, but not the only one, leaving room for interpretations of a potential anthropogenic factor. Seaquist et al. (2009) used a modeling approach to test the hypothesis that humans have had a measurable impact on vegetation dynamics in the Sahel. Their model, which included coarse resolution demographic, pasture and cropping data, suggested that land use pressures do not have a significant influence on the observed NDVI dynamics in the Sahel.

Investigating vegetation phenology—the characteristics of the seasonal vegetation cycle—Heumann et al. (2007) differentiated between two types of greening trends. In the Sudanian zone, where perennial grasses and woody cover are common, greening was associated with an increase in the length of the growing period; in the Sahel zone, where annual grasses predominate, greening was associated with an increase in NDVI at the peak of the growing season.

More recent studies using a new and extended AVHRR NDVI time series have corroborated earlier findings of the close link between vegetation dynamics and precipitation variability. They show positive trends in rain use efficiencies in most of the Sahel, confirming once more that land degradation unrelated to precipitation is not widespread (Fensholt et al. 2013). In addition to the increased precipitation during the period of observations, CO₂ fertilization (the enhancement of photosynthesis due to rising CO₂ levels) may have played an important role in the greening across the warm drylands globally, including the Sahel (Donohue et al. 2013).

In one of the few studies that compare NDVI trends with long-term field data collection of herbaceous biomass, Dardel et al. (2014a) attributed the greening trend to a large-scale increase in herbaceous production over the time period 1981–2011, spurred by increasing rainfall. While greening dominates across the Sahel, their study also found a smaller occurrence of decreasing NDVI in southwestern Niger, taking only the months of August and September into consideration. Although they found bio-productivity had increased and rain-use efficiencies were stable—both indicators of recovery or resilience rather than degradation—Dardel et al. (2014b) also noted an increase of runoff coefficients over the same period, which can be

interpreted as a sign of degradation. They concluded that degradation in a small part of the landscape, in particular on shallow soils, is counteracted by resilience on the more productive sandy soils.

Some differences between studies in the reported greening trends may be due to slight differences in the calibrated time series developed from the AVHRR data (McCloy et al. 2005), in the length of the time series (Dardel et al. 2014a), in the inclusion or exclusion of particular months and in trend analysis procedures employed (Fensholt et al. 2013).² Despite disagreements on best methodological approaches, underlying assumptions, and interpretation of results (Hein and De Ridder 2006; Prince et al. 2007), two findings have emerged as rather robust across all studies: (1) It seems indisputable that parts of the Sahel and Sudan zones have become greener since the early 1980s, at least from the perspective of coarse-resolution satellite-derived NDVI data (Fig. 5.3). (2) This greening trend has been paralleled by and is closely related to an increase in rainfall amounts over the same time period (Fig. 5.4).

What these findings imply in terms of vegetation changes on the ground, however, remains mostly unaddressed in these satellite-based studies. The land cover of this semi-arid environment is characterized by a fine mosaic of woody vegetation, annual and perennial herbaceous cover, agricultural crops, and bare ground. Virtually all pixels at the 8-km AVHRR resolution are mixed pixels, made up of those components in varying proportions. The proportions of woody and herbaceous vegetation are difficult to extract from the integrated satellite signal, as their seasonal greening cycles are very similar in this region (Akpo 1997). Global-scale efforts to estimate proportions of woody, herbaceous, and bare soil cover per pixel, while adequate for regions with medium to high tree cover, have proven notoriously unreliable for semi-arid regions where tree cover is low and interannual variability of the underlying grass cover high (Hansen and DeFries 2004; Schwarz et al. 2004). Hence, the relative contributions of woody and herbaceous vegetation, let alone different species compositions, to the observed greening trend cannot be assessed by means of remote sensing alone. Yet, such changes in the vegetation composition can be as important indicators of degradation or rehabilitation as changes in bio-productivity. Regional scale remote sensing observations have contributed to uncovering the interannual variability of

²Since the NOAA AVHRR NDVI time series from 1981 to present combines observations from two different sensors flown on a series of fourteen satellites, inter-sensor calibration and bias correction for orbital drifts are prerequisites for the creation of long term stable NDVI time series (Pinzon and Tucker 2014). Much of the time series development has been done by the Global Inventory Modeling and Mapping Studies (GIMMS) group. As calibration and correction algorithms have evolved over time, each generation of the GIMMS NDVI time series shows slight differences from the previous one. One of the authors of this chapter compared trends of the most recent 3rd generation GIMMS NDVI with trends of the previous 2nd generation and found considerable differences in the spatial patterns of those trends for West Africa over an identical time period. Such differences, which are explained by data preprocessing alone, call into question the interpretability of NDVI trends from the NOAA AVHRR time series with respect to land degradation and desertification.

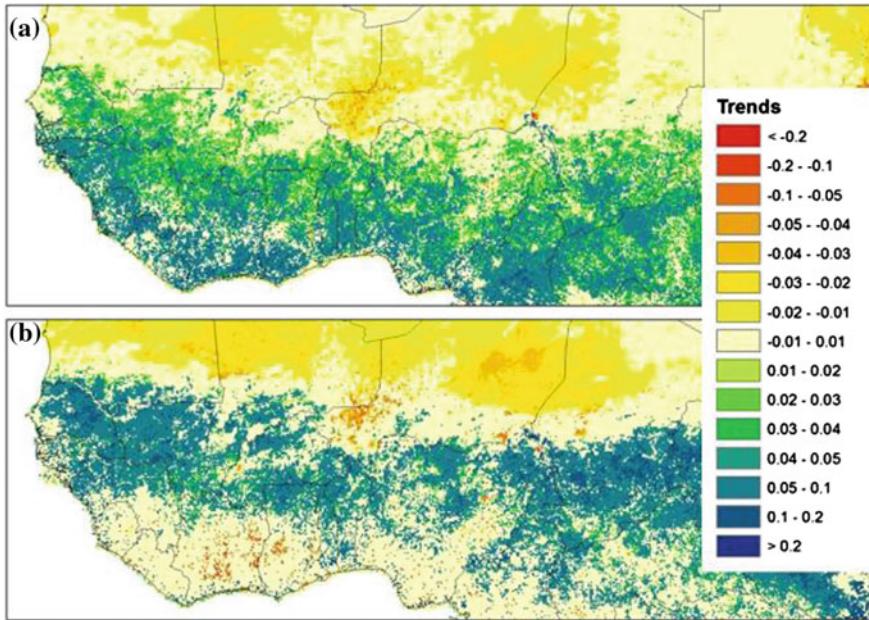


Fig. 5.3 Regional trends in **a** mean annual NDVI and **b** mean growing season (July–October) NDVI, derived from the NOAA AVHRR time series 1982–2011 (GIMMS 3G dataset) (Pinzon and Tucker 2014), show predominantly positive trends in the Sahel and Sudan zones. Note the differences in spatial patterns of greening depending on inclusion of annual or seasonal NDVI.

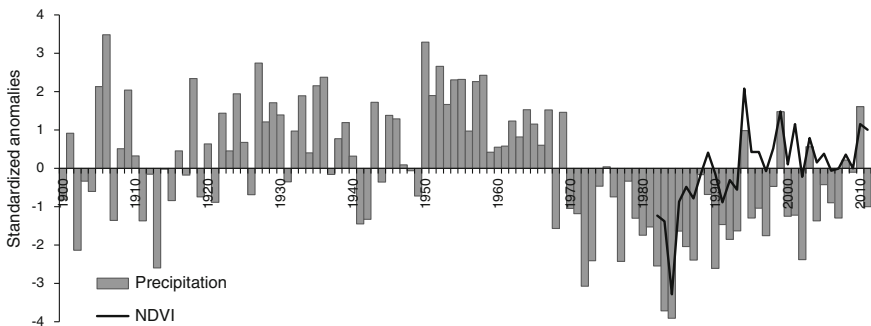


Fig. 5.4 Standardized June–October Sahel precipitation anomalies (10° – 20° N and 20° W– 10° E) from 1900 to 2011 (doi: [10.6069/H5MW2F2Q](https://doi.org/10.6069/H5MW2F2Q)) and standardized NOAA AVHRR NDVI anomalies for the same region from 1982 to 2011. Both indices show a similar temporal pattern (Pearson’s linear correlation coefficient: 0.82) for the three decades of overlap, illustrating the strong link between rainfall and vegetation greenness. Temporal trends in both variables are positive since 1982; at a secular timescale, however, the rainfall trend is negative.

vegetation cover in the Sahel and to refuting exaggerated claims of the extent of desertification. But longitudinal ground studies remain indispensable for providing a more detailed understanding of the nature of vegetation changes, and their ecological and livelihood implications. Of particular importance in this respect are assessments of changes in the woody vegetation cover, which as a slow variable is a more robust indicator of ecosystem health than the highly dynamic herbaceous cover.

5.3 Approaches and Challenges of “Ground Truthing”

When the AVHRR NDVI data first became available, there were no adequate ground observations of vegetation productivity against which the new index could be directly compared, prompting the establishment of a new field data collection programme in the Sahelian grasslands of Senegal (Prince 1991a). The studies emerging from this programme all indicated a positive correlation between integrated growing season NDVI and total dry biomass collected at the end of each growing season for a range of dry and wet years of the 1980s. This positive correlation suggested that the NDVI could be used for monitoring the spatial and temporal variability of biomass production over large areas (Tucker et al. 1983; Tucker et al. 1985; Prince 1991a)—a promising technical advance of great interest for the desertification and global change communities.

Analogous studies in the dry grasslands of the US-Mexican border region, however, found that the NDVI failed to capture significant differences in biomass between sites (Beck et al. 1990; Huete and Jackson 1987). They warned of the indiscriminate use of the NDVI in every grassland and called for more research into the appropriate interpretation of NDVI for biomass parameters. A study by Prince (1991b) established that the relationship between biomass production and NDVI is not static but is also influenced by variable factors such as incident radiation, temperature and water stress of plants. Despite the obvious inconsistencies and documented need for more research on the interpretation of the NDVI and its trends over time, longitudinal studies linking NDVI time series data and ground observations of vegetation cover, let alone degradation status, are few and far between (e.g., Milich and Weiss 2000; Dardel et al. 2014a, b).

Even if the relationship between NDVI and biomass were assumed perfect, desertification remains difficult to assess, as the relationship between biomass and ecosystem health is complex: increasing biomass in the Sahel does not necessarily indicate continued improvement (Warren 2002; Warren and Olsson 2003). In the following sections, we will review three ways in which vegetation changes and trends in the Sahel, assessed in the field, could be used for “ground-truthing” NDVI trends with respect to land degradation: comparison of current with historical vegetation data (Sect. 5.3.1); assessment of regeneration potential of woody vegetation from current size class distributions (Sect. 5.3.2); and ethnobotanical knowledge (changes in vegetation perceived by local inhabitants, Sect. 5.3.3) (Fig. 5.5).

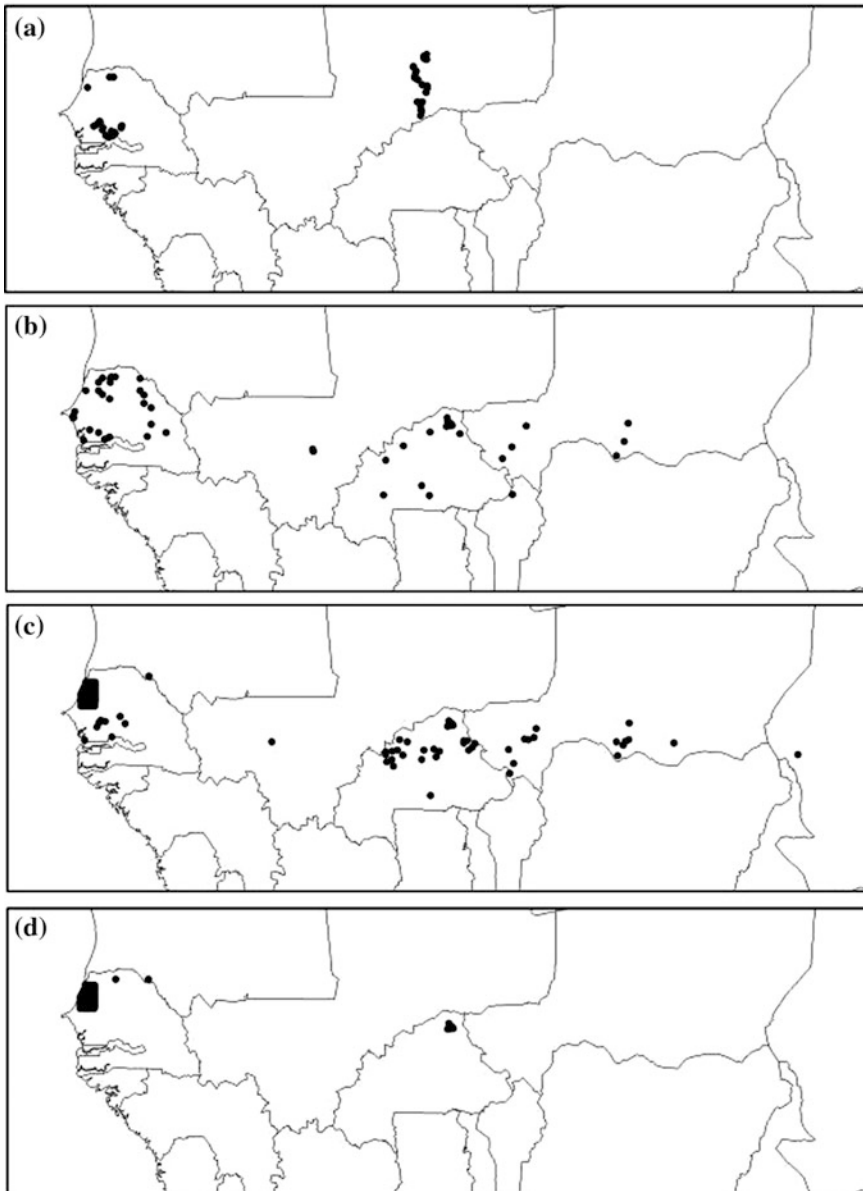


Fig. 5.5 Location of field sites of published studies (see Sects. 5.3.1–5.3.3) of woody vegetation change in the Sahel and Sudanian zones: **a** sites of studies using historical data, **b** sites of studies using size class distributions, **c** sites of studies using ethnobotanical knowledge, **d** sites of studies using high resolution remote sensing imagery.

5.3.1 *Comparison of Current with Historical Vegetation Data*

The availability of repeatedly collected historical field data of vegetation cover obviously presents the ideal case for “ground-truthing” remote sensing-derived trends. However, only for few locations throughout the area of interest are such historical datasets available. While some observations may have been made by environmental, forestry or livestock agencies during past decades, not all records were systematically archived or made accessible to researchers. Moreover, the available and accessible vegetation data were not necessarily collected with the goal of longitudinal studies of land degradation in mind, and may not have focused on the most pertinent variables for this type of study, nor did sampling designs and data collection always follow rigorous quantitative research protocols.

A few notable field studies in the semi-arid Sahel and Sudanian zones have nonetheless contributed to land cover change and desertification research. Long-term controlled grazing experiments were carried out at a field site in the Senegalese Ferlo region (Wendou Thiengoly), where quantitative field data on herbaceous biomass, composition of the herb layer and rainfall were recorded annually over a period of 27 years starting in 1981 (Miehe et al. 2010). Herbaceous biomass data were also collected annually in sites along an aridity gradient in the Malian Gourma region over 28 years. These data collections were carried out first by the International Livestock Research Institute (Hiernaux and Turner 1996), to assess the impact of droughts on fodder resources, and then as part of the African Monsoon Multidisciplinary Analysis (AMMA) project (Mougin et al. 2009; Hiernaux et al. 2009a, b) to better understand ecosystem functioning and dynamics. Another well studied field site is located in southwestern Niger (Fakara), where field observations of vegetation in a set of 24 sites began in 1994 (Hiernaux and Ayantunde 2004) and were carried on until 2010 (Cappelaere et al. 2009). The temporal trends in herbaceous biomass data from the field sites in Mali and Niger were later re-analysed by Dardel et al. (2014a) and compared with the satellite-observed NDVI trends.

Woody plant population dynamics were assessed in the Malian Gourma region (Hiernaux et al. 2009a, b; this volume). In this study, patterns of changes in woody plant population density, size, foliage and woody biomass and species composition were documented between 1984 and 2006. Vincke et al. (2010) analysed the temporal dynamics of the woody vegetation in the Senegalese Ferlo and explored spatial differences in regeneration. Herrmann and Tappan (2013) repeated an inventory of woody vegetation in 18 field sites in central Senegal after 25 years, albeit with the challenge of reliably replicating the expert-driven, semi-quantitative method used in the baseline assessment. In addition to estimating relative abundance by woody species and overall woody cover densities, the authors used repeat photography to document vegetation cover changes. In a similar fashion, Ganaba and Guinko (1995) compared the abundance and diversity of woody species to historical data in the Mare d’Oursi region of Burkina Faso.

A number of studies used historical air or satellite photography as a substitute for field assessments of woody vegetation, because historical field assessments are only scarcely available (e.g., Lykke et al. 1999; Gonzalez 2001; Gonzalez et al. 2012). Air photos and very high resolution satellite imagery resolve enough spatial detail for reliably estimating woody vegetation densities, but like all remotely-sensed observations, cannot replace field data when it comes to determining species composition.

5.3.2 Assessment of Regeneration Potential from Current Size Class Distributions of Woody Vegetation

In the absence of historical ground data, potential changes in woody vegetation have been inferred from an analysis of size class distributions of current tree stands. Size class distributions refer to the frequencies of tree species in a number of defined size classes, with size commonly denoted by the trunk diameter at breast height. Originating from forest ecology, size class distributions have commonly been used to describe the population structures of forests in humid West Africa (e.g., Aubréville 1938; Poorter et al. 1996) and other tropical forests (e.g., Condit et al. 1998). However, they were also found to offer potential for identifying declining and increasing species in dry ecosystems characterized by slow growing plants (Lykke 1998).

These ecosystems are particularly vulnerable to both anthropogenic and natural disturbances, which directly affect population structures (Feely et al. 2007; Venter and Witkowski 2010). Based on the sampling of size class distributions, variables such as health, vitality, regeneration potential and population structures of tree species can be revealed (Sop et al. 2011). Figure 5.6 illustrates the size class distributions of three fictitious species: The size class distribution of Species A drops abruptly with increasing diameter and is described as a reverse J shape, which is characteristic of species with good regeneration and recruitment. Species B shows a flat size class distribution, which is indicative of lack of recruitment and a possible change in species composition (Hall and Bawa 1993; Lykke 1998). The positive slope of Species C denotes poor regeneration (Shackleton 1993).

Several studies have analysed size class distributions to infer past changes and predict future variations in species populations in the Sahel. Lawesson (1990) sampled woody vegetation along strip transects in 15 sites located in reserves or protected forests across northern Senegal, with the goal of assessing the structure and composition of woody vegetation along soil and precipitation gradients. Lykke (1998) used size class distributions to analyse trends in 22 common woody species in a fire-disturbed savanna ecosystem in the Saloum Delta on the west coast of Senegal.

Analysis of size class distributions was also a part of the methodology employed by Lykke et al. (1999) to document vegetation changes and their consequences for local resource users in Sahelian Burkina Faso, in conjunction with air photo interpretation and ethnobotanical surveys. Sop et al. (2011) focused their analysis on three widely used multipurpose species in sub-Saharan Burkina Faso—*Acacia seyal*, *Balanites aegyptiaca* and *Pterocarpus lucens*—and compared their population structures and

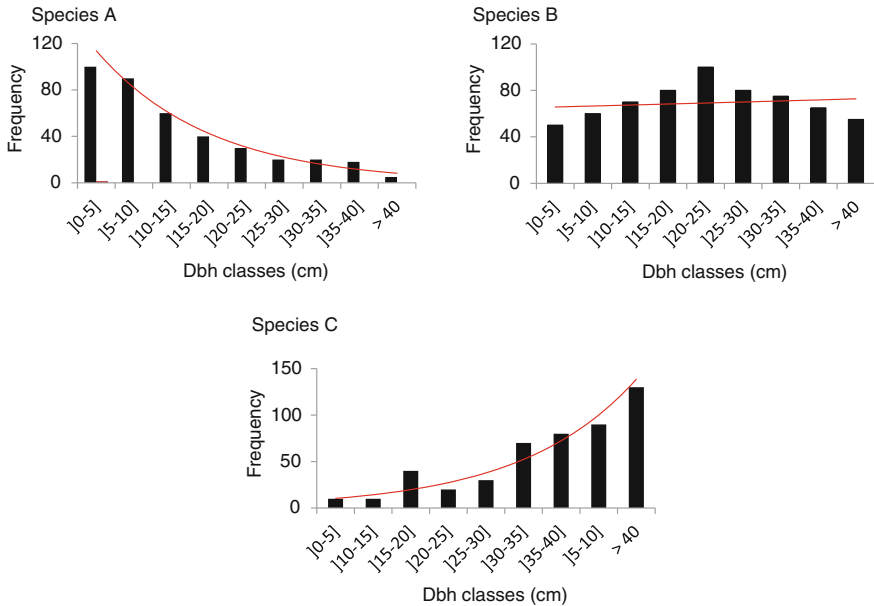


Fig. 5.6 Size class distributions (Dbh = diameter at breast height) illustrate high regeneration potential (*Species A*), lack of recruitment with possible decline (*Species B*) and no regeneration leading to extinction (*Species C*).

regeneration patterns. Traoré et al. (2013) carried out a similar study in the Sudanian phytogeographical zone of western Burkina Faso, focusing on the Sudanian species *Diospyros mespiliformis*, *Prosopis africana* and *Sterculia setigera*, with the goal of evaluating the effectiveness of protected areas in conserving these species.

The analysis of size class distributions is not without limitations for estimating potential trends in past and future vegetation compositions: (1) Size class distributions of trees in a stand are static representations of the population composition at a certain time and inferring rates of change from them can be problematic (Sokpon and Biauou 2002). (2) Size class distribution curves depend not only on population health but also differ between fast growing species with higher survival rates and slow growing species with lower survival rates (Condit et al. 1998). Notwithstanding these shortcomings, the analysis of size class distributions has made important contributions to our understanding of changes in vegetation structure and species compositions in the Sahel, in particular in combination with ethnobotanical knowledge.

5.3.3 Ethnobotanical Knowledge

In contrast to researchers, who might visit field sites only infrequently and over a limited time period, local populations are permanently present in specific sites or

areas and as plant resource users have a strong interest in the fate of the vegetation. Thus, while they do not make systematic vegetation assessments as researchers would do, their observations and recollections provide invaluable evidence of stability and changes in vegetation. Ethnobotanical knowledge has been shown to be a relatively accessible and reliable source of information on historical distribution ranges of species, especially rare or endangered species which are generally difficult to assess using classical ecological methods (Lykke et al. 2004). In the past two decades, scientists have increasingly taken account of the local knowledge of rural farmers to reconstruct vegetation dynamics in the Sahel, particularly in combination with other botanical assessment and analysis methods (e.g., Lindskog and Tengberg 1994; Lykke 1998; Lykke et al. 1999, 2004; Wezel and Haigis 2000; Wezel and Lykke 2006; Ayantunde et al. 2008; Sop et al. 2011, 2013; Sop et al. 2012; Herrmann and Tappan 2013).

A number of qualitative and quantitative social science methods have been used to elicit information on the status and the cultural importance of plant species in the Sahel from informants, including structured and semi-structured interviews and focus group discussions. Typically, informants are asked to list woody plants occurring in their communities, rank them by their use value, and identify those perceived as increasing or declining in abundance or that need priority for conservation initiatives (Fig. 5.7).



Fig. 5.7 Local informants—pastoralists of the Peulh ethnic group—use illustrated cards of woody species as visual aids in a discussion of changes in vegetation composition in the Senegalese Sahel (Herrmann et al. 2014).

Lindskog and Tengberg (1994) used local knowledge as part of their multidisciplinary case study of land degradation in Sahelian Burkina Faso. They solicited villagers' perceptions on environmental deterioration by means of in-depth household interviews and used this qualitative information in support of assessments of degradation of the vegetation cover from air photos and a satellite image. Also in Sahelian Burkina Faso, Lykke (1998) and Lykke et al. (2004) assessed the use preferences and dynamics of woody species using a quantitative ethnobotanical method based on structured interviews. In the context of the much reported satellite-observed greening trend in the Sahel, Sop and Oldeland (2013) conducted semi-structured interviews with 87 groups of informants from twenty villages belonging to the Mossi, Fulani and Samo ethnic groups in order to sample the perceptions of local people on vegetation dynamics in the sub-Sahel of Burkina Faso. They compared the information obtained on usage, abundance, conservation status and priority as well as ranking of socio-economic importance of all the woody plants listed by the informants with an analysis of size class distributions of key species (Sop et al. 2011, 2012).

In semi-arid Niger, Wezel and Haigis (2000) solicited observations of past and present species occurrence and abundance from men and women and explored preferences for leaving certain species on cultivated fields. Wezel (2005) re-analysed local knowledge on changes in woody vegetation species from five case studies in Burkina Faso, Senegal and Niger, which had been obtained in household interviews and focus group discussions. Wezel and Lykke (2006) extended the scope of the re-analysis to seven case studies.

Gonzalez (2001) conducted an extensive study in northwestern Senegal, in which he systematically sampled villages in an area of 7600 km² and recorded elders' recollections on the presence and absence of each of a predefined set of 126 woody species around 1945 and 1993. Biomass estimates made by the author as well as quantification of tree densities from air photos complemented the perceptions of the local inhabitants. In a study spanning 15 research sites in Senegal, Mali, Burkina Faso, Niger and Chad, a similar methodology was employed to obtain perceptions of species abundance in 1960 and 2000, which were analysed in conjunction with changes in tree densities estimated from air photos and very high resolution satellite imagery (Gonzalez et al. 2012). Herrmann and Tappan (2013) included local perceptions of occurrence, abundance and trends of woody species in a study which compares ground evidence of woody vegetation change in sites that appear to have greened up according to coarse resolution satellite observations with change in sites that appear not to have greened up.

Although a good correlation between local knowledge and the physical reality of the environment has been documented (e.g., Lindskog and Tengberg 1994; Reed et al. 2007), some challenges associated with the use of such knowledge in ethnobotanical assessments should not be ignored: People's perceptions reflect the informants' subjective experience of environmental change, which may be subject to biases and exaggerate or mask trends (Daw 2010). Informants tend to focus on the species most useful to them, while overlooking rare and less used species. Environmental knowledge also depends on the age of the informants (Hanazaki

et al. 2013). The absence of standardized data collection protocols to assess local perceptions and knowledge can make data integration problematic. Despite these shortcomings when judging ethnobotanical knowledge by scientific standards, the first-hand experience of local land users is an invaluable source of information, and large sample sizes can at least in part make up for these shortcomings.

5.4 Synthesis of Ground-Based Vegetation Studies Across the Sahel

The vegetation studies reviewed in this chapter followed various methodological approaches and data collection protocols and they do not cover identical time periods, which precludes quantitative, statistical meta-analysis. On the other hand, the qualitative synthesis of these studies offers a more reliable picture of vegetation changes across the Sahel than any single study could. The consistency of the findings, despite the different approaches—the comparison of current with historical data, the analysis of size class distributions, and people’s perceptions—adds validity to the changes we document. A total of 301 field sites from 20 of the studies reviewed could be located precisely in space (Fig. 5.5) and interpreted with respect to changes in abundance and/or diversity of woody vegetation. By abundance, we mean any indication of the number of trees, density or percent cover; by diversity, we mean any indication of the number of different species present at a site. We summarized the changes in woody vegetation at each site into the three simple categories of “increasing”, “stable” or “decreasing” over time, in order to obtain a general representation of change and to allow for comparison with remote sensing-based trends over time (Figs. 5.8, 5.9 and 5.10).

This synthesis documents findings on the changes in woody vegetation at a point in time (May 2014), which will continue to be revised as new studies are carried out in this very dynamic field.

5.4.1 Long Term Changes in the Abundance of Woody Vegetation

Most of the studies across the region comparing historical to current vegetation data point to an overall decline in the abundance of woody vegetation between the pre-drought period and the late 1990s or early 2000s (e.g., Gonzalez 1997, 2001; Lykke et al. 1999; Vincke et al. 2010; Gonzalez et al. 2012; Herrmann and Tappan 2013; Herrmann et al. 2013) (Fig. 5.8a). Local inhabitants also observed a substantial reduction of woody vegetation with the disappearance or decreasing abundance of many species (e.g., Lykke et al. 1999; Wezel and Haigis 2000; Gonzalez 2001; Sop et al. 2011) (Fig. 5.8b). Analyses of size class

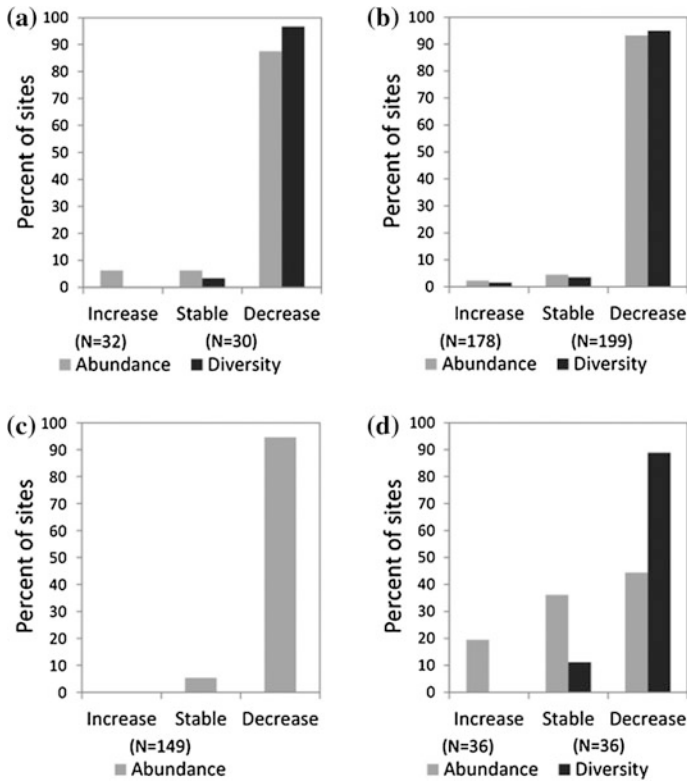


Fig. 5.8 Proportion of field sites showing increasing, stable and decreasing abundance and diversity of woody vegetation as assessed by **a** studies based on historical ground data, **b** studies based on people’s perceptions of vegetation change, **c** studies based on very high resolution imagery, **d** studies based on size class distributions. N is the number of sites included in the count for each variable. The number of sites per study ranged from only one to 135, meaning that findings from some studies are more heavily represented in this assessment than from others.

distributions generally confirmed the lack of rejuvenation of many, but not all woody species (e.g., Lykke 1998; Lykke et al. 1999; Bognounou et al. 2009; Sop et al. 2013) (Fig. 5.8c).

The observed changes are not uniform. At finer scales, the magnitude of the decline appears to vary depending on the location of the site within the landscape. Lykke et al. (1999) found that valley sites in Sahelian Burkina Faso were most severely affected by the loss of trees. In contrast, Ganaba and Guinko (1995) and Vincke et al. (2010) found that regeneration of the vegetation was better in depressions and along valleys, where runoff induces greater accumulation of water, fine soil particles and organic matter, than on the plateaus.

Exceptions to the general reduction in the abundance of the woody vegetation cover were found in the shrub layer, which, as opposed to the tree layer, has increased in some sites studied in central Senegal (Herrmann and Tappan 2013) and

in the Gourma region of Mali (Hiernaux et al. 2009a, b). Expansion of fruit tree plantations have also accounted for localized increases in tree densities over the past four decades, particularly in the vicinity of the urban centers of Dakar and Thies (Herrmann et al. 2013). The most noteworthy exceptions to the general decline in tree cover, however, are the success stories of farmer-managed natural regeneration (Reij et al. 2009; see Sect. 5.4.3).

5.4.2 Long Term Changes in Woody Vegetation Composition

With the exception of farmer-managed natural regeneration, virtually all ground studies point to a progressive impoverishment of the woody vegetation cover in several respects: overall species diversity has been decreasing; a shift towards more xeric species has taken place; and the species most valued by the local inhabitants have declined most dramatically.

For example, studies comparing current and historical woody vegetation documented reductions in or disappearance of a number of woody species at sites in the Senegalese Ferlo (Vincke et al. 2010), central Senegal (Herrmann and Tappan 2013), and the Mare d'Oursi in northern Burkina Faso (Ganaba and Guinko 1995), leading to a less diverse woody cover. These findings are corroborated by ethnobotanical studies, in which informants listed more decreasing than increasing species at a majority of sites. Even parkland species such as *Parkia biglobosa* and *Vitellaria paradoxa*, which are traditionally protected on farmers' fields for soil fertility management and fruit production, were decreasing in some villages in Niger (Wezel and Haigis 2000). The only exceptions were villages where tree planting had been promoted by development projects, mostly of fast growing exotic species, including *Azadirachta indica* (neem), *Mangifera indica* (mango) and *Eucalyptus camaldulensis* (Wezel and Haigis 2000; Wezel and Lykke 2006). While those newly planted species provided some wood and other tree products for rural households, they were not able to compensate for the cutting of the natural vegetation (Wezel and Haigis 2000).

Among the most dramatically declining tree species were the more mesic and less drought-resistant Sudanian and Guinean species (Ganaba and Guinko 1995; Gonzalez 2001; Vincke et al. 2010; Sop et al. 2011; Herrmann and Tappan 2013). The more drought-resistant Sahelian woody species were left to dominate not only in the Sahel but increasingly also in the Sudanian zone, indicating a possible shift of the vegetation belts southward (Gonzalez 2001). The mesic species being lost include large canopy trees, characterized by hard wood and edible fruits, which makes them highly valued. The most severely declining species listed in a study of 25 villages in Burkina Faso, Niger and Senegal are *Acacia ataxacantha*, *A. senegal*, *A. seyal*, *A. ehrenbergiana*, *Adansonia digitata*, *Boscia senegalensis*, *Ceiba pentandra*, *Dalbergia melanoxylon*, *Ficus gnaphalocarpa*, *Grewia bicolor*,

Khaya senegalensis, *Maerua crassifolia*, *Pterocarpus lucens*, *Sclerocarya birrea* and *Tamarindus indica* (Wezel and Lykke 2006). This list includes highly valued species that are relied upon for food, fodder, medicines, construction and craft materials, and as energy sources (Sop et al. 2012).

Size class distribution analyses show a mixed picture, with good regeneration potential, i.e., higher frequency of young individuals, in some sites (Bognounou et al. 2009; Sop et al. 2012, 2013). Rejuvenation was however limited to a single or very few hardy species per site, indicating that the reduction in species diversity seen in the past is likely to continue into the future. Some examples include increasing dominance of *Acacia raddiana* in the Mare d'Oursi (Ganaba and Guinko 1995), of *Calotropis procera*, *Boscia senegalensis* and *Balanites aegyptiaca* in the *Senegalese Ferlo* (Lawesson 1990; Vincke et al. 2010), of *Acacia tortilis* and *Leptadania pyrotechnica* around Gorom-Gorom in Sahelian Burkina Faso (Lykke et al. 2004), and of *Combretum glutinosum* and *Guiera senegalensis* in the Sudanian domain of central Senegal (Herrmann and Tappan 2013).

As shown by the good agreement between historical vegetation surveys, ethnobotanical studies and analyses of size class distributions, the degradation of the woody vegetation cover does not appear to be a localized problem, but has been documented at sites throughout the Sahel and Sudanian zones.

5.4.3 *The Case of Farmer-Managed Natural Regeneration*

In contrast to the widespread negative changes in the woody vegetation cover, two “success stories” stand out: (1) farmer-managed soil and water conservation in the central plateau of Burkina Faso, where vast stretches of degraded and barren farmland have been rehabilitated and (2) farmer-managed natural regeneration of agroforestry parklands in southern Niger (Reij et al. 2009). Both practices began to be implemented at the height of the environmental crisis in the early 1980s, when innovative farmers and non-governmental organizations experimented with traditional planting pits and stone bunds to reclaim severely degraded farmland (Reij et al. 2005) and protected on-farm trees to reduce wind speeds, improve soil fertility and provide fodder for livestock (Tougiani et al. 2009).

Reportedly large in scale—an estimated 200,000–300,000 ha rehabilitated in Burkina Faso (Botoni and Reij 2009) and an area of nearly 5 million ha under farmer-managed natural regeneration in Niger (Reij et al. 2009)—these developments have not been rigorously quantified for such large areas. However, evidence from air photography and high resolution satellite imagery in 30 sample locations in the Mirriah-Magara-Matameye triangle of Niger show that average field tree cover, after having dropped from 2.8 % in 1957 to 1.5 % in 1975, had almost tripled to 4.4 % in 2005, with local concentrations of up to 16 % (Reij et al. 2009). Thus, the practice of farmer-managed natural regeneration seems to have allowed tree densities in the parkland to reach higher levels than in 1957. With a high percentage of young trees among the current field tree population, the percent cover is expected to

continue to increase significantly over the next decade. Mahamane et al. (2012) confirm the regenerative potential of field tree cover in three village territories in the Maradi region.

In the Central Plateau of Burkina Faso, Belemviré (2003) counted an average of 126 trees per ha on rehabilitated fields, compared with 103 trees per ha in control fields. Trees in rehabilitated fields were also larger and of higher species diversity than those in the control fields. Species that persisted through the environmental degradation crisis include *Combretum glutinosum*, *Guiera senegalensis* and *Piliostigma reticulatum*. These species continue to be dominant, while species that had been severely decimated or lost—such as *Diospyros mespiliformis*, *Anogeissus leiocarpus*, *Sclerocarya birrea*, *Butyrospermum parkii* and *Lannea sp.*—have re-appeared in rehabilitated fields (Reij et al. 2005).

As farmer-managed natural regeneration has shown, human population growth and agricultural intensification do not have to entail losses in vegetation productivity and environmental degradation (Mortimore et al. 1999). On the contrary, where sound management is practised, farmers' fields stand out by improved vegetation cover and diversity, while unprotected woodlands and unmanaged fields continue to degrade.

5.5 Linking Remote Sensing Observations to Ground Evidence

With few exceptions, regional-scale trends of vegetation productivity in the Sahel, observed from satellite data, and local-scale changes in the vegetation cover on the ground have so far mostly been addressed separately and by different researchers. The findings from those two perspectives have led to differing and sometimes conflicting conclusions on the nature and extent of degradation/desertification in the Sahel.

The simplified three-class summarization of changes in the abundance and diversity of woody vegetation as “increasing”, “stable” or “decreasing” (see Sect. 5.4) was spatially overlaid with an equally simplified interpretation of the satellite observed greening trends, (binary data layer of “greening” versus “not greening”). “Greening” denotes a significantly ($p < 0.05$) positive slope of the linear fit of a trend line to the time series of AVHRR NDVI from 1982 to 2011 for each 8 km pixel, disregarding the magnitude of the trend; “not greening” is the absence of such a trend. No significantly negative trends in vegetation greenness were present at the field sites. While trends in both integrated annual and growing season (July-October) NDVI were considered, only trends in growing season averages are shown here, as their spatial patterns appear to be more consistent across different versions of the NDVI dataset and across different studies. Figure 5.9 illustrates the differences between the two types of information in just one 100×100 km subset in

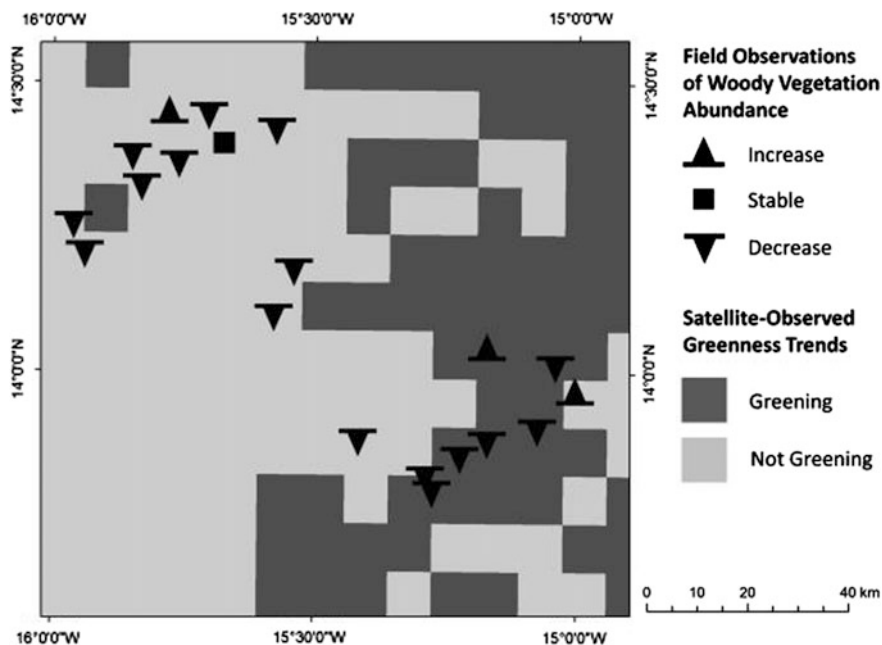


Fig. 5.9 Spatial overlay of the direction of changes in woody vegetation abundance as observed on the ground and of a binary map of satellite-observed greenness trends (greening vs. not greening) for a subset of study sites in central Senegal. Ground observations of decreasing woody vegetation cover appear to dominate throughout the area, whether coinciding with the satellite-observed greening trend or not.

central Senegal, as the clustered distribution of field sites (Fig. 5.5) precludes a legible display of changes at a small scale over the entire Sahel and Sudan zones.

Whereas positive trends in vegetation greenness prevail—65 % of the full set of field sites are associated with significant greening according to growing season NDVI trends—ground evidence shows that a perceived degradation of the woody vegetation cover is predominant. In 85 % of the field sites, a majority of which was associated with positive greening trends, a decrease in woody vegetation density was noted (Fig. 5.10). In 10.5 and 4.5 % of the field sites, woody vegetation cover was stable and increasing respectively. Paradoxically, more than half of the sites with increasing woody vegetation cover did not show significant greening in satellite observations. This is in line with earlier observations that the areas of farmer-managed natural regeneration in southern Niger, where field tree cover is said to have improved, do not stand out in the satellite-derived greenness trend maps (Reij et al. 2009). It has to be noted that in our comparison of remote sensing observations and ground evidence, farmer-managed natural regeneration is not well represented, as very little data on increases in tree cover have been reported in the spatially explicit way necessary for a direct comparison with NDVI trends. Another limitation and potential source of bias in the comparison is introduced by the

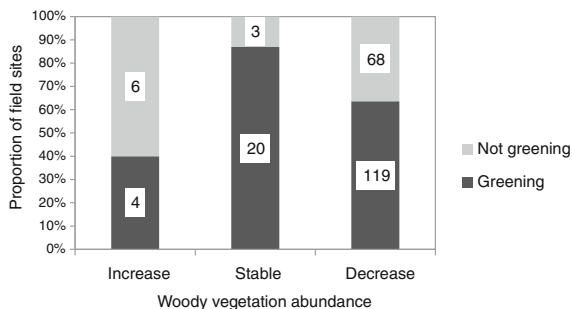


Fig. 5.10 Proportion and number of field sites with increasing, stable and decreasing woody vegetation abundance that spatially coincide with satellite-observed greening and not greening respectively. Satellite-observed greening—represented by growing season (July–October) trends in NDVI from 1982 to 2011—dominates by 65–35 %, whereas on the ground increase in woody cover was observed in only 10 sites compared to decrease in 187 sites.

constraint that the start and end dates of the various field studies and the period over which NDVI trends were computed correspond only approximately.

Diversity in the woody vegetation cover was reported to have decreased even more dramatically than its abundance. A majority of the 95 % of field sites that reported decreasing species diversity are associated with significant greening trends according to satellite observations. There is no reason to expect a causal link between the two variables; rather, they are independent indicators of degradation or desertification. However, what these findings tell is that any increase in bio-productivity was generally accomplished by very few species at the expense of species diversity.

Discrepancy between the two indicators (woody vegetation changes observed in the field and satellite observations of bioproductivity) can be explained by the fact that much of the biomass production in the Sahel and Sudan zones is made up of herbaceous vegetation, which responds fast to precipitation variability (Anyamba and Tucker 2005; Hiernaux, this volume). Precipitation has increased over the past two decades (Nicholson 2013), triggering a growth response of the herbaceous vegetation and consequently an increase in biomass production (Anyamba et al. 2014). This increase, however, is not to be mistaken for a recovery from degradation and a return to pre-drought vegetation conditions, as shown by the simultaneous impoverishment of the woody vegetation cover. In an environment where trees form a small, yet ecologically and economically crucial, fraction of the overall green vegetation cover, the coarse spatial resolution of long time series of NDVI has proven insufficient for capturing the woody component of vegetation dynamics. Thus, in the absence of ancillary data that allow for more intricate analyses but are rarely available at regional to global scales, NDVI time series alone are of limited use for identifying or monitoring desertification or land degradation (Prince, this volume).

5.6 Conclusions

Satellite remote sensing has given us an unprecedented synoptic perspective on global vegetation dynamics by providing consistent, repeatable observations. As the only source of long term vegetation greenness data, the NDVI time series derived from the NOAA AVHRR satellite sensors (Tucker et al. 2005; Pinzon and Tucker 2014) have played an important role in uncovering the interannual variability of vegetation cover in the Sahel and have helped refute exaggerated claims of the extent of desertification (e.g., Prince et al. 1998). Based on NOAA AVHRR NDVI data, a growing number of satellite-based studies has documented a greening trend in the Sahel since the early 1980s.

While these findings indicate that biomass production has likely increased in response to a moderate recovery in rainfall since the great droughts, it can be argued that bio-productivity is not the only indicator of the state of desertification or rehabilitation. Rain use efficiencies and trends in residual NDVI have been used to better distinguish between the effects of rainfall variability and degradation on biomass production, neither of them suggesting regional-scale degradation.

A number of field studies, however, have painted a less positive picture of vegetation changes at local scales. Focusing on the woody vegetation, a key component of the savanna ecosystem and of the livelihood system of rural populations, the prevailing story is one of degradation. The abundance of woody vegetation has declined in many sites. Most importantly, the loss of large trees is ubiquitous, while shrub cover was observed to have increased in some locations. The remaining woody cover has shifted towards fewer and more drought tolerant species, with a few dominating and replacing a more diverse vegetation. This trend, which is not incompatible with increases in bio-productivity as measured by the NDVI, has been observed in longitudinal botanical field studies and in ethnobotanical studies alike. An important exception has emerged where field trees are explicitly protected and diversity promoted in farmer-managed natural regeneration initiatives. Such successes have been documented mainly in the Central Plateau of Burkina Faso and in southern Niger, with positive impacts on soil fertility, crop productivity, and food security. However, these positive developments on the ground, able to halt or reverse degradation, do not stand out above other areas by their NDVI trend.

While the satellite-observed, region-wide greening trend is encouraging in the face of earlier claims of widespread desertification in the Sahel, it is based on rather coarse resolution data and masks developments at finer scales, both negative and positive. The contrasting interpretations of findings from the field and of remote sensing observations with respect to desertification illustrate that the availability of remote sensing data does not ultimately remove the need for ground-based data. The perspective from the field remains indispensable in order to provide “ground truth” for the NDVI data and to put desertification and land rehabilitation on the map. The divergent findings also highlight the need for more research that bridges scale differences and takes account of both physical and social science perspectives.

In particular, field studies explicitly targeting greening and control areas should be encouraged. Individual field studies are spatially confined, so sharing regional archives, field data and collection protocols from different studies across the region would benefit our understanding of NDVI trends and derivative metrics in the context of land degradation and rehabilitation.

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