A Quantitative Evaluation of the Multiple Narratives of the Recent Sahelian Regreening*

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ABSTRACT

A spatial analysis is presented that aims to synthesize the evidence for climate and social dimensions of the "regreening" of the Sahel. Using an independently constructed archival database of donor-funded interventions in Burkina Faso, Mali, Niger, and Senegal in response to the persistence of drought in the 1970s and 1980s, the spatial distribution of these interventions is examined in relation to population density and to trends in precipitation and in greenness. Three categories of environmental change are classified: 1) regions at the northern grassland/shrubland edge of the Sahel where NDVI varies interannually with precipitation, 2) densely populated cropland regions of the Sahel where significant trends in precipitation and NDVI decouple at interannual time scales, and 3) regions at the southern savanna edge of the Sahel where NDVI variation is independent of precipitation. Examination of the spatial distribution of environmental change, number of development projects, and population density brings to the fore the second category, covering the cropland areas where population density and regreening are higher than average. While few, regions in this category coincide with emerging hotspots of regreening in northern Burkina Faso and southern central Niger known from case study literature. In examining the impact of efforts to rejuvenate the Sahelian environment and livelihoods in the aftermath of the droughts of the 1970s and 1980s against the backdrop of a varying and uncertain climate, the transition from desertification to regreening discourses is framed in the context of adaptation to climate change.

1. Introduction

a. *Definitions of the Sahel*

The Sahel is a large and multifaceted region of sub-Saharan Africa. The climate and ecology, history, and political organization of Sahelian countries are diverse and dynamic (Raynaut et al. 1997). Historically, scholarly investigations of the Sahel have revolved around three subjects: the ancient kingdoms and trade routes, the legacy of colonialism and the formation of the modern nation state, and the drivers and impacts of the harsh environment. This paper falls within the third discourse and explores a quantitative, spatial, and interdisciplinary approach to understanding the climatic and social context of the recent environmental change that is presently described as the regreening of the Sahel.

Garnering its name from the Arabic word for "shore," the physical Sahel covers the ~3 million km^2 semiarid transition zone between the Sahara desert of northern Africa and the tropical savanna to its south (Giri 1983). Climatically, the Sahel delineates the northernmost reach of the African monsoon during its annual migration following the sun. The general pattern is dry for

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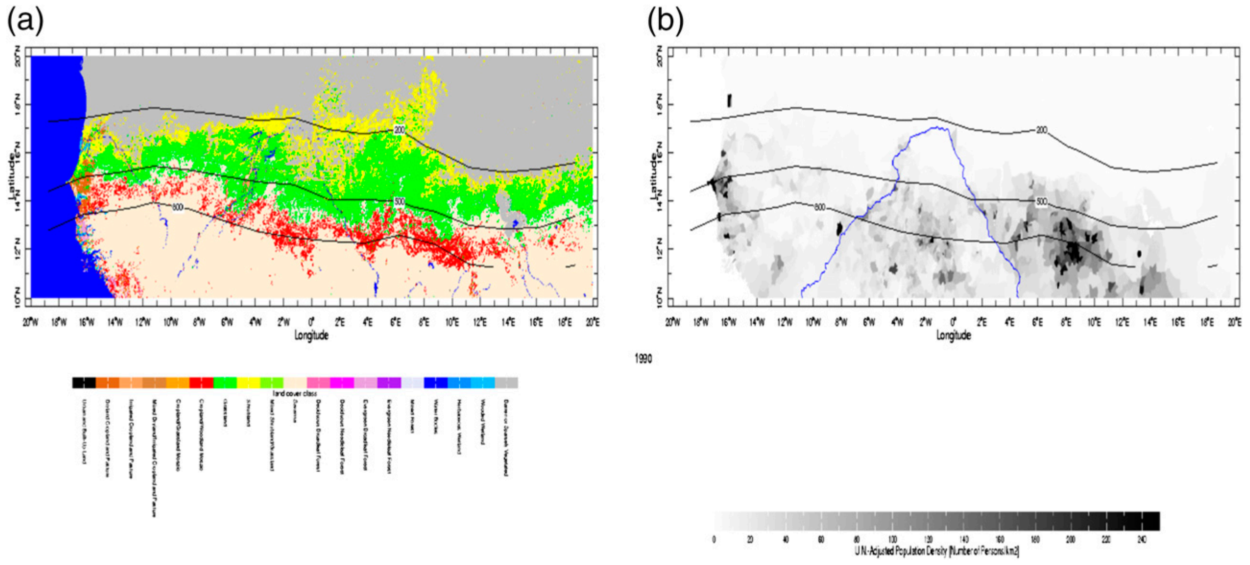

FIG. 1. (a) Land cover classification (Loveland et al. 2000). (b) Population density from the GPW v3 (CIESIN/CIAT 2005). In both panels contour lines represent annual mean precipitation (computed over the period of study, i.e., 1982–2003) equal to 200, 500, and 800 mm.

most of the year and wet during a short, intense rainy season from July through September, further characterized by significant year-to-year and decade-to-decade variation (Nicholson 2005). In Fig. 1a, which depicts the climatology of West African land cover derived from satellite retrievals (Loveland et al. 2000), the Sahel sensu stricto is the region classified as grassland in bright green, between the 200- and 500-mm isohyets. In the West African area of interest, it covers northern Senegal and southern Mauritania, central Mali, northern Burkina Faso, and the southern tier of Niger. However, in this paper we are interested in environmental change in the broader region of gradation from shrubland/grassland in the north, through cropland, to savanna in the south, encompassing the latitudinal range between 12° and 18°N, between the 200- and 800-mm isohyets. Annual mean rainfall decreases dramatically from south to north, from more than 800 mm to less than 200 mm, and is a major determinant of land cover type. It also drives the smooth gradation, and intermingling, between the dominant economic activities of sedentary agriculture and nomadic pastoralism. Despite the strong imprint of climate on the ecology, environment, and livelihoods, from the spatial variation in population density depicted in Fig. 1b it is clear that climate alone may not be sufficient to explain environmental change. While population density does generally decrease from south to north, as a relatively wetter climate, able to more stably sustain agriculture, progressively gives way to a semiarid, highly variable climate, nonetheless understanding the poles of relatively higher population density in coastal Senegal, southeastern Mali, and central Burkina Faso, as well as northern Nigeria just outside our region of direct interest, also requires consideration of history (Raynaut et al. 1997; Club du Sahel 1998; Watts 1983). While in no way causal, this variation hints at the independent role that society may play in explaining spatial variation in environmental change.

b. *Scientific and institutional responses to late-twentieth-century drought*

The Sahel reached its current prominence in the study of human–environment interactions because of the well-documented environmental crisis that occurred with the abrupt onset and persistence of multiyear drought in the late 1960s (Glantz 1977). Persistent drought led to widespread food insecurity into the 1970s and 1980s, with acute episodes during 1968–73 and 1982–84 causing significant human loss.

The climatic shift from wet conditions in the 1950s and 1960s to persistent dry conditions in the 1970s and 1980s is, in magnitude and spatial extent, unparalleled globally in the instrumental record (Nicholson 2000; Hulme 2001; Trenberth et al. 2007; Greene et al. 2009). During the early 1970s, meteorologists posited that the drying was the result of local human activity in a positive feedback loop between poor land use practices, land degradation, and atmospheric response (Charney 1975). Predating acid rain and global warming, the drying and decreased plant production of the Sahelian drought came to represent the ‘‘quintessence of a major environmental emergency’’ (Raynaut et al. 1997) precipitated by human activity. Western countries began to provide substantial aid to the region that was directed at boosting agricultural productivity through technological modernization, mechanization, and Green Revolution–style techniques (Sanders et al. 1996; McMillan 1995).

The 1968–73 drought and humanitarian crisis instigated the formation of many regional and global institutions, most notably the Comité permanent Inter-États de Lutte contre la Sécheresse au Sahel (CILSS; Permanent Interstate Committee to Combat Drought in the Sahel); the Club du Sahel of the Organization for Economic Co-Operation and Development (OECD, later renamed the Sahel and West Africa Club); the United Nations (UN) International Fund for Agricultural Development (IFAD); and the UN Convention to Combat Desertification (UN CCD), one of three environmental conventions tabled at the UN Conference on Environment and Development held in Rio de Janeiro, Brazil, in 1992. The CILSS originally included nine countries in the West African Sahel: Burkina Faso, Cape Verde, Chad, The Gambia, Guinea-Bissau, Mali, Mauritania, Niger, and Senegal. In a report for the U.S. Agency for International Development (USAID), Skinner (1980) reiterates CILSS top priorities in 1974 as 1) rural water supply for livestock and villages, 2) veterinary services, 3) herd reconstruction, 4) reforestation, and 5) food relief. In 1974 CILSS established AGRHYMET, the regional center for agrohydrometeorology, an institution that provides training and information in support of food security and land and water resource management to CILSS member states.

A first major shift in physical scientists' perception of the Sahel and desertification, defined as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (United Nations 1994), occurred following the introduction in the early 1980s of novel remote sensing technology to monitor vegetation cover. A decade later, analyses of satellite imagery demonstrated that the desert boundary had not been expanding southward as a result of the drying, meaning that there was no irreversible encroachment of desert, but rather that vegetation at the desert boundary responded dynamically to variations in rainfall (Tucker et al. 1991; Helldén 1991). Independent of evidence from remote sensing, climate research had already demonstrated that large-scale drying could be explained by factors external to the region, namely, changes in the surface temperature of the global oceans (Folland et al. 1986), with no need to invoke regional-scale land degradation and its interaction with atmospheric dynamics as originally envisaged. More recent research has confirmed the dominant role of global sea surface temperature patterns in driving the twentieth-century shifts in Sahelian climate, including the anomalously wet decades of the 1950s and 1960s, immediately prior to the persistence of drought that characterized the 1970s and 1980s (Giannini et al. 2003). Realization that these temperature patterns have been changing in part as a result of the influence of emissions of greenhouse gases and aerosols from industrialization has brought the issue of anthropogenic climate change to the fore in debates over the cause of drought in the Sahel (Rotstayn and Lohmann 2002; Held et al. 2005; Biasutti and Giannini 2006; Ting et al. 2009; Chang et al. 2011).

In parallel with these developments in the late 1980s and 1990s, social scientists had begun to incorporate indigenous and culturally relativistic approaches into the scope of research on the Sahel (Painter 1993; Reij et al. 1996; Mertz and Reenberg 1999; Reij and Smaling 2008; West et al. 2008). As the shift in thinking regarding the cause of the drying moved from land degradation owing to population pressure and poor agricultural practices to anthropogenic climate change, the mandate of the CILSS also ultimately shifted to its present manifestation: "To invest in research for food security and the fight against the effects of drought and desertification for a new ecological balance in the Sahel through: (1) The formulation, analysis, coordination and harmonization of strategies and policies; (2) The strengthening of scientific and technical cooperation; (3) The collection, processing and dissemination of information; (4) Capacity building of various stakeholders including the private sector; (5) The accumulation and dissemination of experiences and achievements; and (6) The support in the implementation of strategies, policies and programs" (http://www.agrhymet.ne/presentation.html; accessed 15 January 2016).

In sum, whether willingly or not, the Sahel has been the testing ground for interdisciplinary work between the natural and social sciences for the better part of the last 40 years (Raynaut et al. 1997; Batterbury 1998; Batterbury and Warren 2001, and accompanying articles in a special issue of *Global Environmental Change*, 2001, Vol. 11, Issue 1; Herrmann and Hutchinson 2005, and accompanying articles in a special issue of *Journal of Arid Environments*, 2005, Vol. 63, Issue 3; Fraser et al. 2011, and accompanying special feature articles in *Ecology and Society*). Here, we seek to revisit the connections between physical climate, land use/land cover change, and societal response to drought in light of the recent demonstration that the persistence of drought throughout the 1970s and 1980s, and subsequent "partial recovery" in the 1990s and 2000s (Nicholson 2005), were climatic phenomena driven by forces external to the region (Giannini et al. 2003). However, demonstration of the heterogeneous nature of the regreening of the Sahel (Herrmann et al. 2005)—a working definition of the phenomenon is given in the next subsection—demands that in order to resolve attribution, evidence for human-induced land cover change be assessed vis-à-vis recent climatic trends. Given the role of climate in desertification and regreening, resolving the attribution question (i.e., of land cover change to climatic or human factors) is of relevance to adaptation to climate change: if, indeed, a signature of human activity can be identified in regreening, above and beyond what may be explained by rainfall recovery, then there may be a margin for building resilience in the face of further climatic change through replication of these interventions (Kandji et al. 2006). The question then becomes, will the innovation expressed in "sustainable land management" (Reij et al. 2005; Botoni and Reij 2009; Tougiani et al. 2009; Mortimore 2010; Larwanou and Saadou 2011) be sufficient for the rural Sahel to adapt to the projected increase in variability of rainfall on all time scales, from intraseasonal to multidecadal (Giannini et al. 2013)?

c. *The regreening of the Sahel*

There are three lines of research and evidence that claim a stake in the definition of the regreening of the Sahel, which in its broadest sense is an increase in vegetation cover, independent of its relation to agricultural productivity, biodiversity, or ecosystem services. The first line of evidence comes from remote sensing and finds expression in a positive multidecadal trend in the normalized difference vegetation index (NDVI) at subcontinental scale (Anyamba and Tucker 2005; Herrmann et al. 2005; Fensholt et al. 2012) since inception of continuous observations in the early 1980s. This research is complemented by a second line of evidence, which comes from aerial photography and manifests itself in a decrease in land degradation (Rasmussen et al. 2001; Reij et al. 2005) or an increase in tree cover at village scale, when comparing snapshots taken in the 1970s to images collected more recently (Tappan and McGahuey 2007; Polgreen 2007). These longitudinal studies often aim to demonstrate the impact at community level of improved techniques in natural resources management based on local knowledge, whether with or without external support. To these lines of research we can add a third, more recent approach, which broadly seeks to ground truth one type of evidence with the other, by comparing remotely sensed observations to the few local, long-term inventories of vegetation cover in the region, at times augmented by surveys of local perceptions of environmental change (Herrmann and Tappan 2013; Dardel et al. 2014; Brandt et al. 2015).

The analyses of historical trends in NDVI (Tucker et al. 1991), while often critiqued, cannot be dismissed completely. The fact that the record is stitched together from a variety of satellites with different life span has in the past raised concerns about its homogeneity. However, Eklundh and Olsson (2003) conclude that the time series ending in 1999 does not express significant spurious trends that could be associated with change in the zenith angle through time, and Fensholt and Proud (2012) conclude that the long Global Inventory Modeling and Mapping Studies (GIMMS) NDVI time series based on retrievals from the Advanced Very High Resolution Radiometer (AVHRR) does not deviate significantly in its quantification of trends in semiarid regions when compared with the more recent and improved algorithm used on Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals over the overlapping period from 2000 to 2011. Since we are ultimately interested in discerning the long-term outcomes of physical and human influence on the environment at the subcontinental scale, we have no alternative to using the GIMMS NDVI record, because it is the only one available that is long enough to quantify vegetation change on climatic time scales in a region like the Sahel that is characterized by large interannual and interdecadal fluctuations in precipitation.

d. *Objectives of this study*

This study is inspired by Herrmann et al.'s (2005) attribution of the trend in residual NDVI—that is, the regreening trend that remains once the linear influence of precipitation is accounted for—to human intervention. Herrmann et al. (2005) point to this qualitative correspondence in a few locations, which are well known from case study literature to be the loci of successful interventions to combat land degradation. Seeking a middle ground between the three lines of research described above, which operate at vastly different spatial scales, we attempt to systematize the comparison between NDVI trend, whether independent of precipitation or not, and the spatial distribution of development interventions, while maintaining a subcontinental-scale perspective. This study therefore spans the four larger Francophone countries of the western Sahel, namely, Burkina Faso, Mali, Niger, and Senegal, which are recognized sites of intense international development work from the 1970s to present. This region was also the subject of the seminal "Etude Sahel" (Botoni and Reij 2009) as well as more recent work on the impact of conservation agriculture (Bayala et al. 2012). Its temporal horizon, the decades of the 1980s and 1990s, is bookended by the inception date of the continuous GIMMS NDVI record from AVHRR retrievals, which is July 1981, and transition from persistent drought to partial recovery of rainfall, which occurred in the mid-1990s (Agrhymet 2010).

In section 2, we present the measures of human and climatic influence that we use to explain environmental change. In section 3, we situate the characterization of environmental change based on the relation between greenness and precipitation in the space of human influence. The synthesis of our analysis given in section 3 distinguishes three categories of environmental outcome in this bidimensional space of human influence. In the conclusions section, we exploit our examination of the impact of efforts to rejuvenate rural Sahelian livelihoods in the aftermath of the environmental disasters of the 1970s and 1980s against the backdrop of a varying climate in order to frame the transition from desertification to regreening discourses in the context of adaptation to climate change (Batterbury and Mortimore 2013).

2. Method: Data and approach to quantify development intervention, people, and environmental outcome

We use three variables to portray the interactions between development interventions, people, and the environment: in section 2a, development intervention, a measure of ‘‘active’’ human influence, is quantified by a count of donor-funded environmental projects; in section 2b, local population pressure, a measure of ‘‘passive’’ human influence, is quantified by population density; and in section 2c, the relationship between rainfall and vegetation cover is quantified by measures of trend and correlation of NDVI and rainfall.

Our period of interest spans the decades of the 1980s and 1990s, focusing on the response to the environmental and humanitarian crisis that began with the first round of persistent drought years in the early 1970s and was further exacerbated in the early 1980s. The continuous NDVI record does not reach further back in time, and the positive trend in rainfall termed ‘‘partial recovery,’’ in relation to the anomalously wet epoch of the 1950s and 1960s that preceded persistent drought, is most obvious from the very dry early 1980s to the mid-1990s (Ali and Lebel 2009; Agrhymet 2010; Alhassane et al. 2013). Since then, rainfall has exhibited significant year-to-year variability but no trend in either direction. We assemble information on development interventions (section 2a) during the period 1979–2001, and NDVI (section 2c) during the period 1982–2003, with the understanding that the impact of interventions may take 2–3 years to manifest. We take population density (section 2b) at the midpoint of our period of interest, in 1990.

Our aim is to construct a regional map that exemplifies the diversity of possible relations among climate, human influence, and environmental outcome on the large scale. For this reason we favor the aggregation of information with widely varying original resolution—from 8 km in the case of NDVI, to 2.5° in longitude/latitude in the case of precipitation, and anywhere in between in the case of development projects—to a relatively coarse resolution, the scale of the first subnational administrative boundary, called *région* in these West African Francophone countries, as the unit of analysis. As will be further discussed in the subsections that follow, a coarse resolution is inevitable given the intent to integrate over a long climatic time scale and subcontinental spatial scale of impact.

a. A project database of development interventions

The first dimension of our analysis is the count of development projects by *région*, the French term referring to the first administrative unit below country level, which we will use throughout the manuscript to reduce confusion with the general use of the word ‘‘region’’ referring to the West African Sahel. As a measure, project count offers a coarse but consistent way of spatially and temporally locating donor attention toward environmental concerns. We collected information about 309 donor-funded interventions into our own independently constructed database.[1] Tables 1 and 2 summarize the breakdown of per country number of projects by donor and by project purpose, respectively. Since the four countries of the western Sahel object of this study are relatively large, they not only comprise the larger fraction of the Sahelian political space constituted in the CILSS, but are also representative of the ecological variation within the Sahel.

Our database includes information about agricultural projects sponsored by international aid organizations during 1979–2001. While we do not intend to marginalize the role of non-aid-sponsored environmental regeneration, the spatial scope of this analysis sought a suite of measures that could be consistently gathered at the subcontinental scale of this study. Non-aid-sponsored environmental regeneration has been documented (Reij and Smaling 2008; West et al. 2008), but primarily on a case-by-case basis and not yet consistently throughout the entire study region.

We started the assembly of our database with a literature review to gain insight into the trends of

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[1] Available at http://iridl.ldeo.columbia.edu/SOURCES/.IRI/.Projects.

TABLE 1. Number of projects in the four countries that are the object of this study, by donor country or organization.

Primary financier (country/donor organization)	Burkina Faso ($n = 94$)	Mali ($n = 88$)	Niger ($n = 56$)	Senegal ($n = 71$)
AfDF (African Development Fund)	7	13	5	5
Austria	10			4
BADEA (Arab Bank for Economic Development in Africa)	3	5	3	6
Belgium	6	5	7	5
Canada	1		2	4
Denmark			2	
EC (European Commission)	7	1	5	2
France	5	6	2	2
Germany	4	4		3
IDA (International Development Association)		10	8	5
IFAD	25	4	5	6
ISDB (Islamic Development Bank)	3	3	1	5
Italy	5	3	6	2
Japan			1	
Kuwait		7		4
Luxembourg	1			
Monaco		1		
Netherlands		3	1	
Norway		2		
OPEC (Organization of Petroleum Exporting Countries)	2	15	4	5
Saudi Arabia		4		5
Spain		1		
Sweden			1	
Switzerland		1	1	
United Arab Emirates				1
USAID	15		2	7

environmental aid to drought-prone countries in sub-Saharan Africa. We combined this broad strategy with increasingly more specific levels of analysis, creating a multipronged search strategy that addressed the diverse forums and media in which information about Sahelian agricultural interventions is presented and published. Donor countries to the OECD, Bretton Woods institutions, and UN agencies were included in the search. As work progressed, we found sufficient indication of a sustained involvement of Middle Eastern and North African countries to warrant their inclusion. The reporting practices of these organizations vary considerably in terms of format and detail. Overall, reporting practices of all aid organizations appear to have increased in consistency, availability, and transparency over time. While many donor organizations have historically published comprehensive project reports, other organizations that have contributed considerably to agricultural development efforts in Sahelian countries since the 1970s present project information in less standardized forms. As a result, we systematically researched project/program reports, conference proceedings and publications, annual donor reports, scientific and academic journals, news articles, and books to compile information, cross-check data, and generate a comprehensive database of development projects.

For each project the database entry contains name, purpose, description, donor, country, *région*, and *région* locator coded to correspond to the "second administrative level boundary" (SALB) geometries implemented in the International Research Institute for Climate and Society (IRI) Data Library to enable mapping.

We limited our consideration to agricultural projects whose direct ecological aims were explicit and included the following scopes: 1) soil and water conservation and wells, 2) irrigation schemes, 3) sustainable livestock, 4) general agriculture, and 5) reforestation. Agricultural projects aimed at large-scale infrastructure, general socioeconomic development, emergency food aid, veterinary services, and farmer training were excluded on the grounds of being inconsistent with the focus on vegetation/land cover that was established in the scope of this study. We cross-checked the project information collected independently against a dataset generated by the online portal AidData,[2] a public database of information

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[2] http://www.aiddata.org/

TABLE 2. Total number of projects across the four countries of this study and breakdown by purpose. SWC stands for ''soil and water conservation.''

Country	Reforest	General agriculture	Irrigation	Livestock	Wells/SWC	Total
Burkina Faso	6	56	6	1	25	94
Mali	6	46	24	8	4	88
Niger	4	35	6	2	3	56
Senegal	5	46	14	5	1	71

on development projects undertaken by multilateral and bilateral foreign donors. We found sufficient overlap as well as an addition of development projects and project details to consider our exploration to have satisfactorily spanned the space of reported-on projects that would offer a novel contribution to a more comprehensive picture of aid activity in the Sahel.

The measure we chose to quantify active engagement is donor project count per *région*, displayed in Fig. 2a. Various ideal measures of project impact could be conceived, for example, project cost, extent of spatial footprint, or a measure related to project evaluation. Data limitations excluded all three. Information on project cost was not always detailed, and if it was provided, the amount dedicated to direct versus indirect costs was not consistently provided. Even if specific project-related information on spatial extent had been present, it would have been impossible to distinguish outcomes in areas directly targeted by a project versus in surrounding areas affected through diffusion of solutions. Information on project evaluation, even when final project reports are in the public domain, is not consistently measured across donor agencies. While we realize that project count is a woefully inadequate measure of the human and societal constraints that intervene in explaining a project's success or failure, it is a homogeneous measure that, with 309 projects scattered across 41 *régions*, is sufficiently well sampled and can be conveniently mapped against measures of regreening.

In plotting project count per administrative region, in Fig. 2a, we note the difference in size of the *régions* in the four countries. To some extent *région* size is proportional to country size: the larger countries, Mali and Niger, are made up of a smaller number of larger *régions*, 8 and 7, respectively (excluding the small administrative units around the capital cities of Bamako and Niamey), compared to Burkina Faso and Senegal, which are made up of larger numbers, 13 and 11, respectively, of smaller *régions*. Therefore, we also used project density, the ratio of project count to the *région*'s area to quantify human impact in our final summary plots in Fig. 6. Project counts are more homogeneously distributed in Mali and Niger than in Burkina Faso and Senegal, perhaps an artifact of *région* size. The majority of projects in Senegal are concentrated in the east, along the valley of the Senegal River, which flows from the highlands of Guinea and forms the border with Mali and Mauritania, though the *région* with the most projects is Kolda, in the south. The majority of projects in Burkina Faso are concentrated to the west and north of the capital, which lies at the center of the country, though the *région* with the most projects is the southwest (PERN-PRIPODE 2007). Project purpose shows interesting variation among countries, with irrigation schemes most prevalent in Mali and Senegal, and soil and water conservation schemes in Burkina Faso (Table 2), while the ''general agriculture'' category provides a catch-all in the absence of a sufficiently detailed purpose.

b. *Population density*

The second dimension of our analysis is population density. Estimates for 1990, the midpoint of the period covered by our search on development projects (1979–2001), were extracted from version 3 of the Gridded Population of the World (GPW v3: CIESIN/CIAT 2005). The original gridded data are displayed in Fig. 1b. The well-known heterogeneous pattern of population distribution across West Africa (Raynaut et al. 1997; Club du Sahel 1998) is clear: high population densities characterize the coastal *régions* of Senegal (a pole of attraction not just for its immediate inland hinterland), the Central Plateau of Burkina Faso, the cotton-growing *régions* south and east of the Niger River in Mali, and the southern Nigerian peanut basin. They are contrasted by the low densities of eastern Senegal and western Mali, and eastern Burkina Faso, and by the very high densities of northern Nigeria, immediately to the south of our study region.

Since we are ultimately interested in explaining nonurban environmental change, we avoided introducing a bias in population counts due to the presence of urban areas by excluding grid cells where population density exceeded 500 people per square km from administrative regions. We masked these grid cells both in the population density data discussed here and in the NDVI data that go into generating the classification of environmental outcomes that is discussed in the next

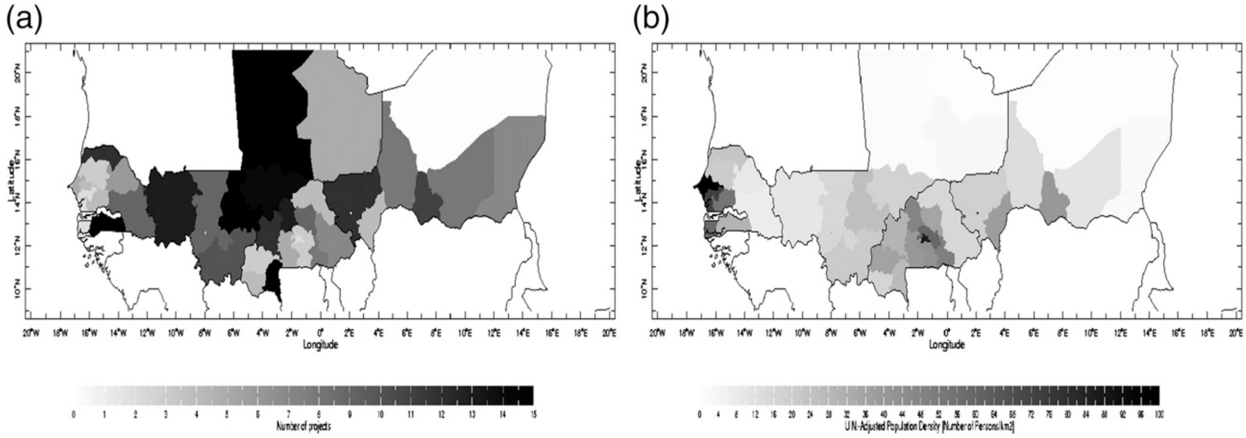

FIG. 2. (a) Total number of projects by administrative region. (b) Population density averaged by administrative region.

subsection, summarized in Fig. 5. Results of the regional averaging of population density are shown in Fig. 2b, which displays the same heterogeneous pattern of population density distribution, albeit at a coarser scale.

c. Characterization of environmental outcomes based on correlation of satellite estimates of greenness and precipitation

The third dimension in our analysis is environmental outcome. To characterize it, we took an approach complementary to the analysis of Herrmann et al. (2005), where trends in residual NDVI, that is, in the signal that remains after correlation with precipitation is accounted for, are highlighted to identify potentially nonclimatic components in regreening.

Acknowledging that both precipitation [Global Precipitation Climatology Project (GPCP); Adler et al. 2003] and NDVI (Tucker 1979; Rouse et al. 1974; Tucker et al. 1985; Myneni et al. 1995) display significant trends over the period and region of interest (summarized in the online supplemental material), we made use of correlation to distinguish between interannual and longer time scales in the spatial relation between greenness and precipitation. As in Fensholt et al. (2012), we used annual averages in both NDVI and precipitation. In the case of NDVI, annual averages are constructed in two steps: from 16-day composites to monthly means, and from monthly means to 12-month (January–December) averages. In the case of precipitation, the data come in monthly time steps, which are averaged over the 12-month, January–December calendar year. Annual averages integrate the influence of rainfall on vegetation mediated by hydrology, that is, through varying soil moisture, runoff, and water table recharge conditions, and provide an estimate of the net primary productivity (NPP; e.g., Eklundh and Olsson 2003; Prince et al. 2007). A positive trend in annual mean NDVI could be explained by an increase in maximum NDVI, that is, an increase in vegetation cover, or an increase in the length of the growing period, for example, as a consequence of significant variation in the processes that favor soil moisture retention.

We considered the local, that is, grid point by grid point, correlation between annual averages of precipitation and NDVI.[3] The spatial resolution of these two datasets is dramatically different. As in Herrmann et al. (2005), we used GPCP merged satellite–gauge precipitation, which has a 2.5° resolution, roughly equivalent to 250-km spacing, compared to 8-km spacing for NDVI. In computing the correlation, we matched the coarser dataset to the resolution of the finer dataset using weighted-area averaging, but the "boxy" nature of the pattern imparted by the coarser resolution is still apparent in places. Given the presence of linear trends in both variables (Figs. S.1, S.2, and S.3 in the supplemental material), we were concerned that trends may inflate correlation values. Therefore, we compared the correlation between precipitation and NDVI computed in two ways. We first computed the correlation at each grid point using the annual average time series of precipitation and NDVI over 1982–2003 (Fig. 3a). We then repeated the correlation calculation after having linearly

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[3] Correlation maps using maximum annual NDVI and July–September average precipitation are included for comparison in the supplemental material. We note in passing that computing the correlation on annual means simplifies the calculation in two ways. First, there is no need to define a lag at which vegetation responds most strongly to precipitation. Second, there is no need to exercise the care required when considering monthly values, in removing each month's climatology, to avoid artificially inflating the correlation value by neglecting to remove the seasonal cycle.

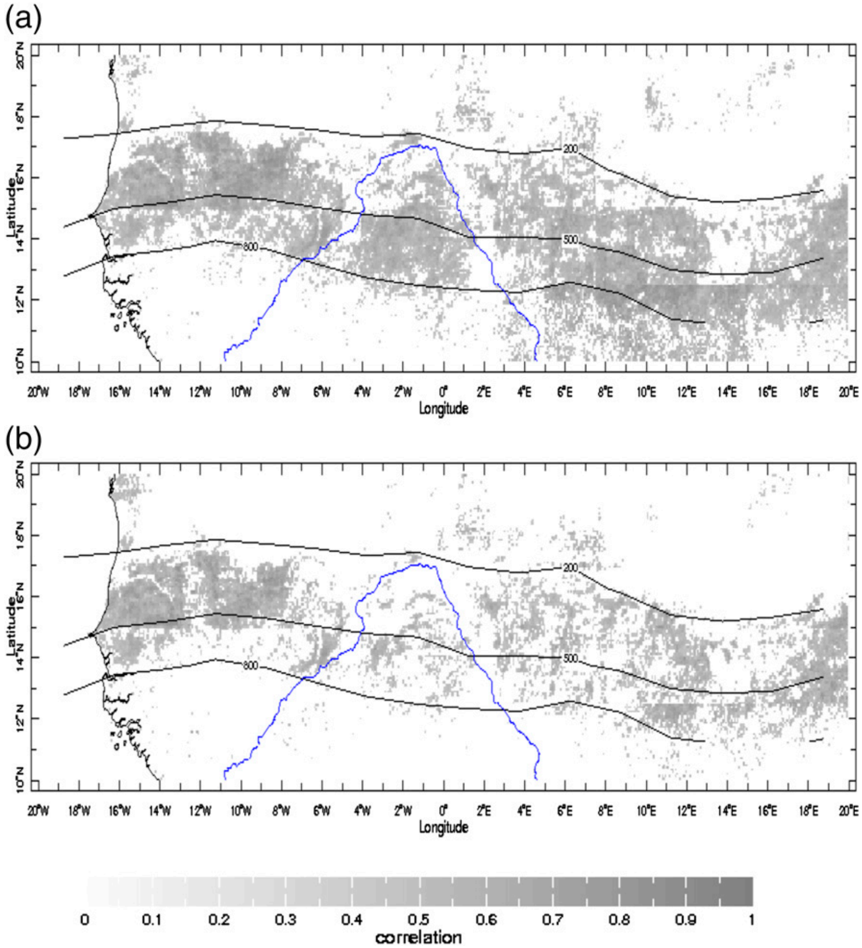

FIG. 3. (a) Correlation between annual mean values of NDVI and precipitation. (b) Correlation between linearly detrended values of annual mean NDVI and precipitation. Values not significant at 95% level are masked, as are the sparse negative values. As in Fig. 1, contour lines represent annual mean precipitation (computed over the period of study, i.e., 1982–2003) equal to 200, 500, and 800 mm.

detrended both time series, that is, after having subtracted the linear trend in each grid point's time series (Fig. 3b).

Correlation of the full time series (Fig. 3a) is significant at Sahelian latitudes in our domain, whether the less densely populated pixels spanned by the grassland/shrubland land cover type or the more densely populated pixels spanned by the cropland/pasture land cover type. Correlation is not significant in the southern savanna edge of our domain. When we compared the full (Fig. 3a) and detrended (Fig. 3b) correlations, we were interested in the places that display significant widespread positive correlation in the former: how does the correlation between precipitation and NDVI change once we have detrended both time series?

There is no marked difference between the two correlation maps across the northwestern tier of our domain of interest, in northern Senegal and southern Mauritania, between the 200- and 500-mm isohyets. These are places where the grassland/shrubland land cover type, our northern land cover class, dominates in Fig. 1a. They are also places where the linear trends in precipitation, and to a lesser degree in NDVI (see the online supplemental material for details), are not significant. Therefore, we inferred that for these pixels the interannual time scale dominates all variations and explains both correlation maps: the grasses' year-to-year variation is largely accounted for by variation in rainfall. Though we were tempted to conclude that where grasses dominate, there is no long-term trend to account for, because grasses do not accumulate from year to year (Kaptué et al. 2015), Dardel et al.'s (2014) finding of an increase in herbaceous cover in the Malian Gourma cautions against making sweeping generalizations.

In contrast, we noted a change in the correlation maps in a majority of pixels where both precipitation and NDVI exhibit significant positive trends, that is, in the center of our domain, in northern Burkina Faso, and in the east, in south-central Niger at the border with Nigeria, between the 500- and 800-mm isohyets. In these places the correlation using the full values (Fig. 3a) is significant, but the detrended correlation (Fig. 3b) is not. Only in a minority of pixels characterized by significant trend in NDVI (not shown) does correlation remain significant even after detrending. Where precipitation and NDVI are not correlated significantly on a year-to-year time scale, that is, when the time series are detrended, but they are at longer time scales, it seems plausible to infer that the long-term trends in the two variables may be due to independent factors. While alternative interpretations are possible, such as changes in fallow cycling or rural exodus (Olsson et al. 2005), in line with Heumann et al. (2007), Brandt et al. (2015), and Kaptué et al. (2015), we interpreted the positive vegetation trend as an increase in tree cover, rather than grass, whether natural regeneration of forest cover (an integration of rainfall recovery over time), or ''farmer-managed'' natural regeneration, that is, the tending of trees by farmers on agroforestry plots. It is in these places where matching the biophysical evidence with human agency becomes fundamental in trying to sort out causation.

Finally, we noted that places where correlation is not significant in either case tend to coincide with the southern tier of our region of interest, across southern Senegal, Mali, and Burkina Faso, which are places that belong to the southern, savanna land cover class. These are climatologically wet areas, not stereotypically ''Sahelian.'' Therefore, absence of significance in correlation is consistent with understanding that tree cover here does not vary on a year-to-year basis (PERN-PRIPODE 2007) or that NDVI values ''saturate'' or are contaminated by the more frequent presence of clouds.

To summarize our analysis of the relation between NDVI and precipitation, we characterize three categories of change in vegetation cover in Fig. 4 and match them to the ''climatological'' land cover types in Fig. 1:

- Category A (Fig. 4a): overlapping with the grasslands/shrubland land cover class in Fig. 1a, in the northern part of our study region; no significant trend in NDVI, significant (interannual) correlation between NDVI and precipitation.
- Category B (Fig. 4b): overlapping with the cropland/woodland mosaic in Fig. 1a, sporadic throughout the central portion of our study region; significant trend in NDVI, significant correlation with precipitation at longer time scales, but not in year-to-year variation.
- Category C (Fig. 4c): overlapping with the wetter savanna land cover class in Fig. 1a, in the southern portion of our study region; significant trend in NDVI, but no correlation between NDVI and precipitation, neither at interannual nor at longer time scale.

3. Synthesis and interpretation

Before we overlay consideration of environmental outcome, we compare the spatial distributions of project count and population density at *région* level. At first glance, there appears to be no relationship between these two variables, depicted in Figs. 2a and 2b, respectively. In Senegal the majority of projects are located in the eastern *régions*, characterized by lower population densities. Where population densities are higher, as in the historical peanut basin in the center of the country, there are fewer projects (Mbow et al. 2008; Herrmann et al. 2014). Conversely, in eastern Mali and adjacent northwestern Burkina Faso high project count and high population densities coexist. Quantitatively, however, total number of projects and total population by *région* are significantly correlated: the Spearman (rank) correlation over all *régions* in the four countries is 0.50 (Fig. 6a). Project density and population density by *région* are also correlated at 0.61 (Fig. 6b). This means that the more populated *régions* were the beneficiaries of more intense donor-funded intervention. This relationship is a premise of the driving question of this paper: How did these more densely populated *régions* that were the target of focused intervention do in terms of environmental outcome? Were they able to stave off the environmental degradation predicted by a Malthusian model and instead put themselves on a Boserupian trajectory of increased population density, intensification of agricultural land use, and improved soil fertility (Boserup 1965; de Sherbinin et al. 2007) thanks to intervention? Did interventions result in measurable environmental outcomes when controlling for population and rainfall?

Coming back to environmental outcome, in Fig. 5 we aggregate pixel values of trend and correlation in NDVI and precipitation into *région* averages. Out of a total of 41 *régions* across the four countries, 11 fall into category A, 4 fall into category B, and 10 into category C, while for the remaining 16 neither trend nor correlation is statistically significant at the 95% level. Categories A and C project onto the two ''natural'' agroecological zones in Fig. 1a—shrubland/grassland in northern *régions*, characterized by significant interannual variability, and savanna in southern *régions*, where variations

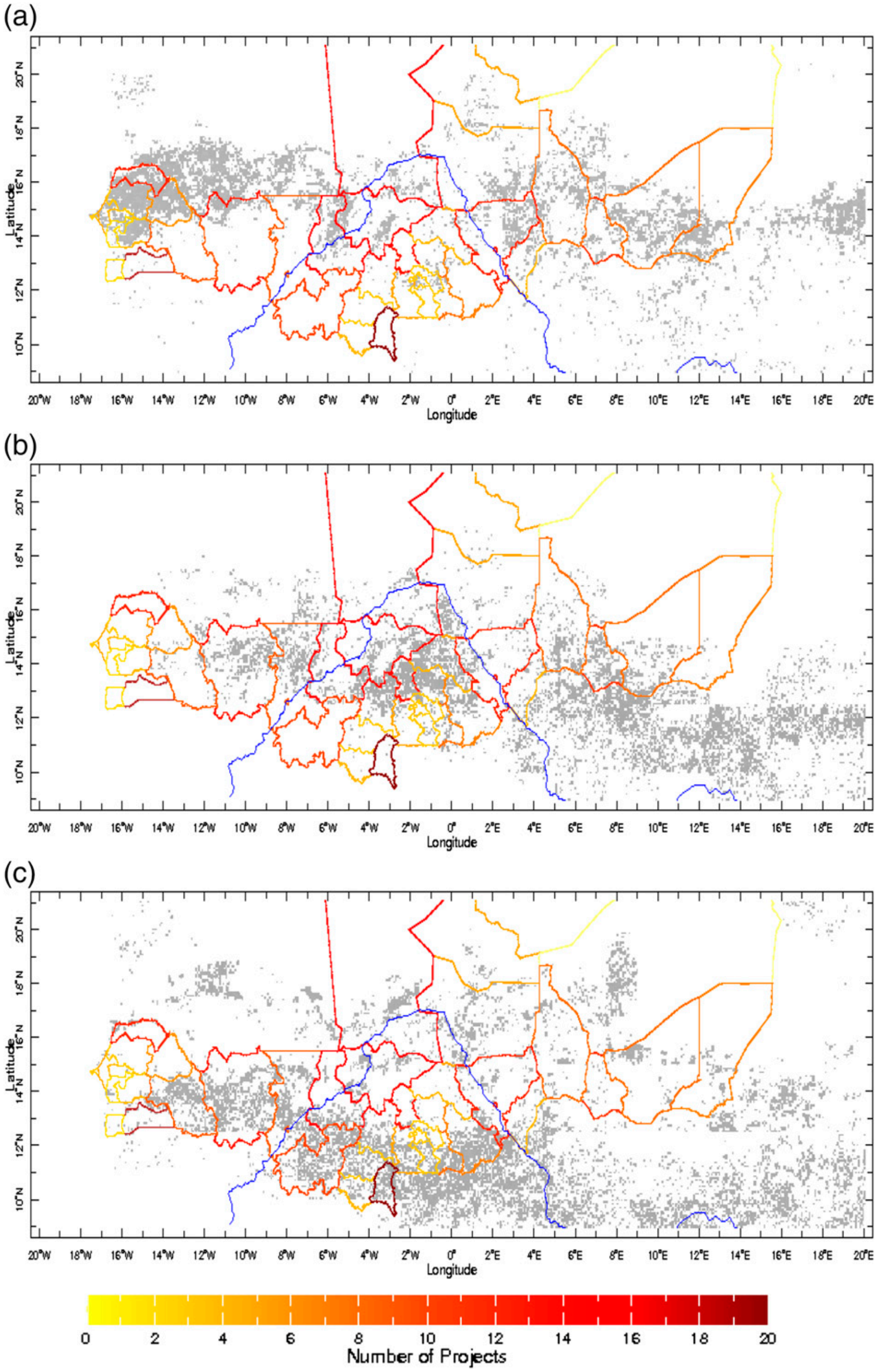

FIG. 4. Pixelwise categories based on the statistical significance (at 95% level) of NDVI trend, and of correlation between annual mean NDVI and precipitation. Shading represents the values of the t statistic of the linear trend in NDVI. Note that the spatial resolution is that of the higher-resolution NDVI dataset. (a) Shaded grid points exhibit significant positive correlation between NDVI and precipitation, but insignificant trend in NDVI (category A). (b) Shaded grid points exhibit significant trend in NDVI, but the correlation between NDVI and precipitation becomes insignificant when time series are linearly detrended (category B). (c) Shaded grid points exhibit significant positive trend in NDVI, but insignificant correlation between NDVI and precipitation (category C). In all panels, the subcountry contours shaded in yellow, orange, and red represent project count as displayed in Fig. 2a.

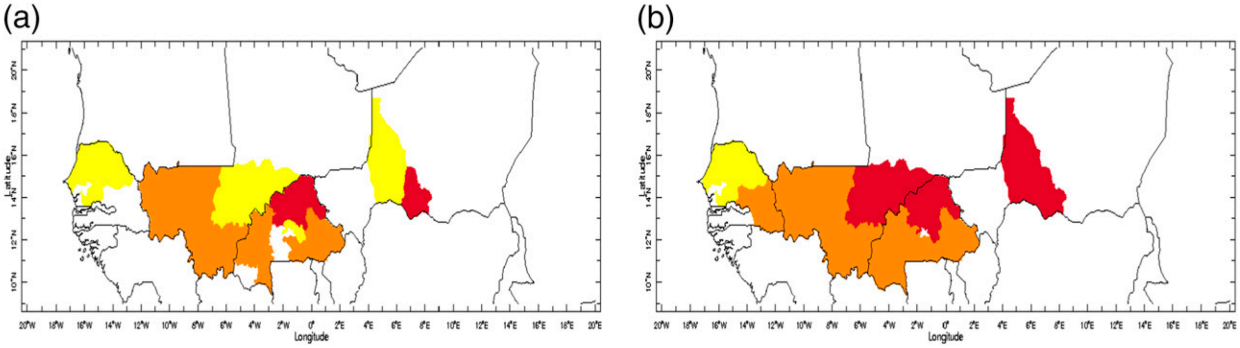

FIG. 5. *Région* classification based on the significance of NDVI trend, and of the correlation between NDVI and precipitation (a) in the regionally averaged NDVI trend is assessed at 95% significance level and (b) at the 90% level. *Régions* in yellow belong to category A, in orange to category C, in red to category B. Note that no *région* belongs to the category complementary to B, that is, significant trend and significant correlation whether detrended or not. Therefore, all *régions* left in white in the four countries studied are characterized by statistically not significant (at 95% level) trend in NDVI and correlation between annual mean NDVI and precipitation.

in land cover are independent of climate. Category B covers intermediate latitudes and captures *régions* in between, notably in northern Burkina Faso and in southern Niger, that are well known for the widespread implementation of efforts to combat land degradation. In Fig. 5, we plot the same three categories based on 95% significance of the region average of linear trend in NDVI and correlation with precipitation, that is, the same measures used to classify pixelwise in Fig. 4. (To gauge the sensitivity of our classification to the threshold chosen to assess significance of trend and correlation, in Fig. 5b we relax the threshold used for NDVI trend to 90%, which increases the number of *régions* falling into categories B and C.)

We are now ready to compare Figs. 2 and 5, which display all the information that we wish to synthesize—a characterization of the spatial distribution of regreening trend in relation to precipitation, project count, and population density, all aggregated at *région* level. In Table 3, we report statistics on median, mean, and standard deviation for the three variables of interest across the three categories of environmental change identified in section 2c. We noted earlier in this section that project count and population, whether the actual counts or their densities, are significantly and positively correlated. It is a valid null hypothesis to assume that projects will be implemented preferentially in relatively more densely populated rural areas. These areas correspond to categories B and C in our domain, rather than A, the drier desert fringe. The question then remains, what effect, if any, did these projects have?

We make the following observations based on the median values reported in Table 3. By construct, the NDVI trends are significant for all *régions* in categories B and C, but for no *région* in category A. Therefore, the median NDVI trend *t* value is significant for categories B and C, but not for category A. Median project count and population density are smaller in category A than in categories B and C. As we associated high project count with high population, we can also qualitatively associate significant trends in NDVI with higher project counts and population densities.

We summarize these relationships in the scatterplots in Fig. 6. In Fig. 6a, the horizontal axis represents project count, while the vertical axis represents population density. In Fig. 6b, we transform project count into project density on the horizontal axis by dividing project count by the *région*'s area. To situate environmental outcome in the two-dimensional space of human influence, we overlay in color membership in categories A (yellow), B (red), and C (orange), following the color scheme used in Fig. 5. Recall that the two categories characterized by significant NDVI trend are categories B and C, in red and orange, respectively. The 16 unclassified *régions*, those for which neither trend in NDVI nor correlation with precipitation were significant, which were left blank/white in Fig. 5, are colored in cyan.

The very low values in population density primarily represent the desert *régions* in northern Mali (identified by square markers in Fig. 6) and Niger (diamond markers), which display no significant environmental outcome, in cyan. Some of these *régions* are characterized by relatively high project count (Fig. 6a), likely concentrated geographically within the *région*: the case of Lac Faguibine, in the Timbuktu *région* of Mali, comes to mind (Brockhaus et al. 2013; Mann 2014). As population density increases, that is, moving up on the vertical axis, with a preponderance of *régions* in Burkina Faso (identified by the circle markers in Fig. 6) and Senegal (triangle markers), one transitions through the space of population densities between 30 and 50 people per square kilometer where regreening is

TABLE 3. Mean, median, and standard deviation in project count and population density and in the *t* statistic of the trend in NDVI for the three categories of change in vegetation cover described in section 2c.

		Median	Mean	SD
Category A (*n* = 11): Grasslands/shrubland in the northern part of our study region; no significant trend in NDVI, significant correlation between NDVI and precipitation (Fig. 4a).	Project count	5	6.9	4.5
	Pop. density	25	52	43
	t-val NDVI trend	1.57	1.53	0.42
Category B (*n* = 4): Cropland/woodland mosaic sporadic throughout central portion of our study region; significant trend in NDVI, significant correlation at longer time scales, but not in year-to-year variation (detrended correlation not significant; Fig. 4b).	Project count	10	9.3	3.3
	Pop. density	38	35	12
	t-val NDVI trend	2.56	2.58	0.24
Category C (*n* = 10): Wetter savannas in the southern portion of our study region; significant trend in NDVI, but no correlation between NDVI and precipitation, neither at interannual nor at longer time scale (Fig. 4c).	Project count	8.5	8.6	5.4
	Pop. density	28	28	12
	t-val NDVI trend	2.34	2.39	0.19

maximized. *Régions* in orange, which generally belong to the wetter tier of our domain, are matched in significance of regreening by *régions* in red, which belong to the intermediate, relatively dry center of our domain. Here, the four red markers representing the *régions* in category B stand out. They define an ''asymptotic trajectory,'' whereby increasing population densities, when matched by a corresponding increase in intervention, result in sustained positive environmental outcomes, as represented by a significant regreening trend. A case in point is the comparison between the two more densely populated *régions* in Niger, in the map in Fig. 2b: Dosso in the southwest and Maradi in the center. These two *régions* are represented by the diamond markers around 40 people per square kilometer in Fig. 6. While the former is known for the prevalence of land degradation, the latter, a red diamond marker in Fig. 6, is known to have been the focus of intervention, especially in agroforestry: trees that are allowed to grow on cultivated fields not only provide for nutrition in times of drought (Mousseau and Mittal 2006), but also help replenish the soil with nutrients (Tougiani et al. 2009; Larwanou and Saadou 2011; Sendzimir et al. 2011). The other red markers, circles, at comparable population densities correspond to the *régions* that are most widely discussed in the literature as the epicenters of the regreening phenomenon, located in northwestern Burkina Faso. Here regreening has been attributed to innovation in soil and water conservation practices based on local knowledge, such as zaï pits to focus the water and organic fertilizer close to plant roots, and stone contours to reduce runoff and increase infiltration (Reij et al. 2005, 2009a). Since *régions* in category B are representative of Sahelian population densities, but few in number, it is reasonable to infer that the human and societal context matters to project success or failure. While plausible to suggest that regreening may be physically sustained across other regions with comparable climate/physical characteristics and population densities, the exact social contexts and configurations that appear to have positively influenced regreening should not be underestimated, since variation in the structure of local communities and development projects likely affected outcomes.

4. Conclusions

We presented an interdisciplinary, subcontinental-scale analysis seeking to collocate physical and human influences on the environment in the West African Sahel, with a view to assessing whether interventions aimed at combating land degradation may be effective strategies in adaptation to climate change.

In acknowledging variation in the spatial distribution of development interventions and their relation to environmental outcome, our analysis lends partial, quantitative support to interpretations of the regreening of the Sahel that emphasize human agency. Even at the coarse resolution of analysis implemented, which we plan to refine in subsequent research, we were able to objectively identify *régions*, the first-level administrative boundaries below country in Francophone West Africa, where population density and regreening are higher than average in the presence of donor intervention. While few, these are places where significant long-term trends in precipitation and in NDVI ''decouple'' at interannual time scale, meaning that at interannual time scale precipitation variation is not the dominant explanation for variation in vegetation cover. These *régions* in Burkina Faso and in Niger coincide with locations that are well known from case study literature to be the foci of efforts to combat land degradation (Reij et al. 2009a,b), including but not limited to the development projects in this analysis. It seems plausible to infer that such interventions may have enabled exploitation of the

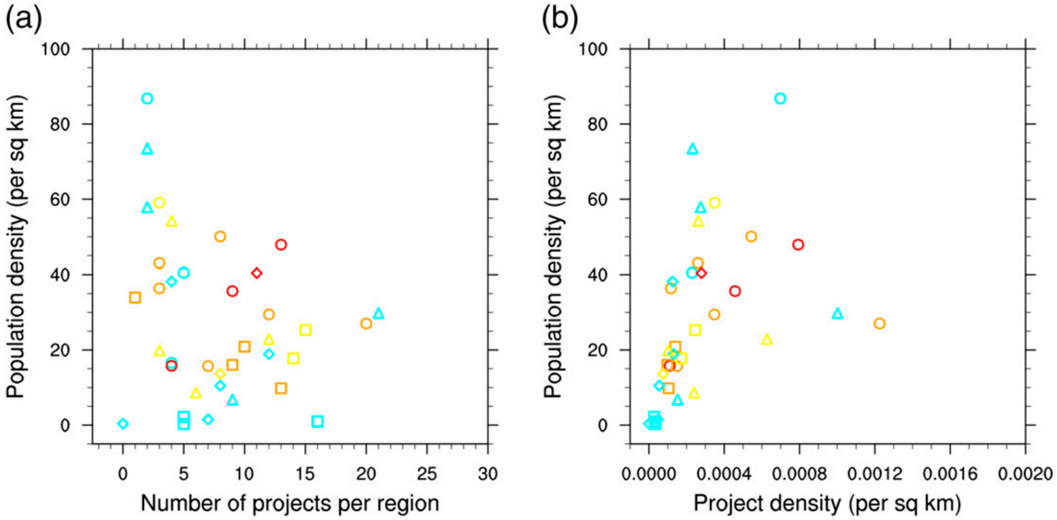

FIG. 6. Environmental outcome as a function of (a) project number or (b) project density (ratio of the number of projects in the *région* to the *région*'s area, in km^2) on the x axis and population density on the y axis. Category A *régions* in yellow, B in red, and C in orange, with *régions* not belonging to any category in cyan. Burkina Faso *régions* are represented by circles, Mali *régions* by squares, Niger *régions* by diamonds, and Senegal *régions* by triangles.

recovery of the rains in a way that reduces vulnerability to year-to-year variations. Such efforts should be further evaluated with the intent to better understand the physical constraints and societal context that may impede or favor their expansion into other Sahelian regions with similar, relatively high population densities.

This finding is relevant to the climate change adaptation discourse, because the recent shift in paradigm explaining the persistence of drought in the Sahel and subsequent partial recovery as a global-scale climate phenomenon, independent of local natural resources management practice, demands that we move away from the dominant crisis narrative linking local anthropogenic activity to land degradation and drought causation, which persists in the global discourse on desertification (Millennium Ecosystem Assessment 2005). The desertification discourse posited that the expansion of agriculture in marginal areas, overgrazing, and unsustainable wood cutting were the primary cause of drought. This discourse has been challenged by demonstration that oceanic change global in scale is sufficient to explain the historical evolution of precipitation in the Sahel. In responding to persistent drought, Sahelian communities have already adapted to some climate change. Consideration of efforts to combat land degradation in the context of climate change projections requires that we broaden our attention accordingly, to evaluate sustainable agricultural practices such as agroforestry and soil and water conservation as adaptation strategies in the face of projections for a more variable climate—with alternation of years of drought and above-normal rainfall and intensification of dry spells and flooding events within each rainy season (West et al. 2008; Giannini et al. 2013; Zougmoré et al. 2014).

In our compilation of a comprehensive database of project activity throughout the subcontinental-scale, West African Sahelian region, we qualitatively assessed that trends in aid do exist, such as particular types of projects being popular at particular times and peaks in the amount of donor dollars and interest. For instance, agroforestry solutions increased in the 1980s. These trends may relate to factors such as the magnitude of environmental crisis, awareness of need in sub-Saharan Africa, and environmental, scientific, and technological developments. These types of relationships merit further exploration along with local, traditional, and non-aid-driven activities toward land regeneration. More detailed information regarding project aims and evaluation, particularly the social and technical aspects, are especially important to explain uptake and sustainability. Social factors such as relationships between development projects and local communities, kinship and social networks, leadership across various spheres, and the resilience of indigenous environmental knowledge should also be considered in future analyses that explore the complicated suite of factors that have influenced regreening.

The evidence synthesized here supports the interpretation of regreening that in specific places occurred with donor support for interventions based in local knowledge of sustainable land management.

Future aid projects could build upon these efforts to ensure that a larger share of the population is engaged. As reporting on population dynamics and aid-sponsored and locally sponsored interventions becomes more transparent, more refined, including finer spatial scale, monitoring and assessment should be conducted in order to evaluate the effect of different types of agricultural projects, project duration, and spatial coverage, and population thresholds that maximize resilience in semiarid environments.

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REFERENCES

Adler, R. F., and Coauthors, 2003: The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeor.*, **4**, 1147–1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2.

Agrhymet, 2010: Le Sahel face aux changements climatiques. Bulletin mensuel, Numéro Spécial, 42 pp.[Available online at http://www.agrhymet.ne/PDF/BM2010/specialChC.pdf.]

Alhassane, A., S. Salack, M. Ly, I. Lona, S. B. Traoré, and B. Sarr, 2013: Evolution des risques agroclimatiques associés aux tendances récentes du régime pluviometrique en Afrique de l'Ouest soudano-sahélienne. *Secheresse*, **24**, 282–293, doi:10.1684/sec.2013.0400.

Ali, A., and T. Lebel, 2009: The Sahelian standardized rainfall index revisited. *Int. J. Climatol.*, **29**, 1705–1714, doi:10.1002/joc.1832.

Anyamba, A., and C. J. Tucker, 2005: Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *J. Arid Environ.*, **63**, 596–614, doi:10.1016/j.jaridenv.2005.03.007.

Batterbury, S. P. J., 1998: Shifting sands: The Sahel. *Geogr. Mag.*, **70** (5), 40–45.

——, and A. Warren, 2001: The African Sahel 25 years after the great drought: Assessing progress and moving towards new agendas and approaches. *Global Environ. Change*, **11**, 1–8, doi:10.1016/S0959-3780(00)00040-6.

——, and M. J. Mortimore, 2013: Adapting to drought in the West African Sahel. *Natural Disasters and Adaptation to Climate Change*, S. Boulter et al., Eds., Cambridge University Press, 149–157.

Bayala, J., G. W. Sileshi, R. Coe, A. Kalinganire, Z. Tchoundjeu, F. Sinclair, and D. Garrity, 2012: Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis. *J. Arid Environ.*, **78**, 13–25, doi:10.1016/j.jaridenv.2011.10.011.

Biasutti, M., and A. Giannini, 2006: Robust Sahel drying in response to late 20th century forcings. *Geophys. Res. Lett.*, **33**, L11706, doi:10.1029/2006GL026067.

Boserup, E., 1965: *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. Allen and Unwin, 124 pp.

Botoni, E., and C. Reij, 2009: La transformation silencieuse de l'environnement et des systèmes de production au Sahel: Impacts des investissements publics et privés dans la gestion des ressources naturelles. Tech. Rep., Centre for International Cooperation/Comité Permanent Inter-États de Lutte contre la Sécheresse au Sahel, 61 pp.

Brandt, M., C. Mbow, A. A. Diouf, A. Verger, C. S. Amimi, and R. Fensholt, 2015: Ground- and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. *Global Change Biol.*, **21**, 1610–1620, doi:10.1111/gcb.12807.

Brockhaus, M., H. Djoudi, and B. Locatelli, 2013: Envisioning the future and learning from the past: Adapting to a changing environment in northern Mali. *Environ. Sci. Policy*, **25**, 94–106, doi:10.1016/j.envsci.2012.08.008.

Chang, C.-Y., J. C. H. Chiang, M. F. Wehner, A. Friedman, and R. Ruedy, 2011: Sulfate aerosol control of tropical Atlantic climate over the 20th century. *J. Climate*, **24**, 2540–2555, doi:10.1175/2010JCLI4065.1.

Charney, J. G., 1975: Drought in the Sahara: A biogeophysical feedback mechanism. *Science*, **187**, 434–435, doi:10.1126/science.187.4175.434.

CIESIN/CIAT, 2005: Gridded Population of the World, Version 3 (GPWv3): Population density grid. NASA Socioeconomic Data and Applications Center, accessed 15 Jan 2016, doi:10.7927/H4XK8CG2.

Club du Sahel, 1998: Preparing for the future: A vision of West Africa in the year 2020—West Africa long-term perspective study. Tech. Doc., OECD/OCDE, 153 pp. [Available online at http://www.oecd.org/swac/publications/38512525.pdf.]

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. *Remote Sens. Environ.*, **140**, 350–364, doi:10.1016/j.rse.2013.09.011.

de Sherbinin, A., D. Carr, S. Cassels, and L. Jiang, 2007: Population and environment. *Annu. Rev. Environ. Resour.*, **32**, 345–373, doi:10.1146/annurev.energy.32.041306.100243.

Eklundh, L., and L. Olsson, 2003: Vegetation index trends for the African Sahel 1982–1999. *Geophys. Res. Lett.*, **30**, 1430, doi:10.1029/2002GL016772.

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 Sens. Environ.*, **119**, 131–147, doi:10.1016/j.rse.2011.12.015.

——, and Coauthors, 2012: Greenness in semi-arid areas across the globe 1981–2007—An Earth Observing Satellite based analysis of trends and drivers. *Remote Sens. Environ.*, **121**, 144–158, doi:10.1016/j.rse.2012.01.017.

Folland, C. K., T. N. Palmer, and D. E. Parker, 1986: Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature*, **320**, 602–607, doi:10.1038/320602a0.

Fraser, E. D. G., A. J. Dougill, K. Hubacek, C. H. Quinn, J. Sendzimir, and M. Termansen, 2011: Assessing vulnerability to climate change in dryland livelihood systems: Conceptual challenges and interdisciplinary solutions. *Ecol. Soc.*, **16** (3), 3, doi:10.5751/ES-03402-160303.

Giannini, A., R. Saravanan, and P. Chang, 2003: Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, **302**, 1027–1030, doi:10.1126/science.1089357.

——, S. Salack, T. Lodoun, A. Ali, A. T. Gaye, and O. Ndiaye, 2013: A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environ. Res. Lett.*, **8**, 024010, doi:10.1088/1748-9326/8/2/024010.

Giri, J., 1983: *Le Sahel Demain: Catastrophe ou Renaissance?* Karthala, 336 pp.

Glantz, M. H., 1977: Nine fallacies of natural disaster: The case of the Sahel. *Climatic Change*, **1**, 69–84, doi:10.1007/BF00162778.

Greene, A. M., A. Giannini, and S. E. Zebiak, 2009: Drought return times in the Sahel: A question of attribution. *Geophys. Res. Lett.*, **36**, L12701, doi:10.1029/2009GL038868.

Held, I. M., T. L. Delworth, J. Lu, K. Findell, and T. R. Knutson, 2005: Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Natl. Acad. Sci. USA*, **102**, 17 891–17 896, doi:10.1073/pnas.0509057102.

Helldén, U., 1991: Desertification—Time for an assessment? *Ambio*, **20**, 372–383.

Herrmann, S. M., and C. F. Hutchinson, 2005: The changing contexts of the desertification debate. *J. Arid Environ.*, **63**, 538–555, doi:10.1016/j.jaridenv.2005.03.003.

——, and G. G. Tappan, 2013: Vegetation impoverishment despite greening: A case study from central Senegal. *J. Arid Environ.*, **90**, 55–66, doi:10.1016/j.jaridenv.2012.10.020.

——, A. Anyamba, and C. J. Tucker, 2005: Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environ. Change*, **15**, 394–404, doi:10.1016/j.gloenvcha.2005.08.004.

——, I. Sall, and O. Sy, 2014: People and pixels in the Sahel: A study linking coarse-resolution remote sensing observations to land users' perceptions of their changing environment in Senegal. *Ecol. Soc.*, **19**, 29, doi:10.5751/ES-06710-190329.

Heumann, B. W., J. W. Seaquist, L. Eklundh, and P. Jönsson, 2007: AVHRR derived phonological change in the Sahel and Soudan, Africa, 1982–2005. *Remote Sens. Environ.*, **108**, 385–392, doi:10.1016/j.rse.2006.11.025.

Hulme, M., 2001: Climatic perspectives on Sahelian dessication: 1973–1998. *Global Environ. Change*, **11**, 19–29, doi:10.1016/S0959-3780(00)00042-X.

Kandji, S. T., L. Verchot, and J. Mackensen, 2006: Climate change and variability in the Sahel region: Impacts and adaptation strategies in the agricultural sector. Tech. Rep., UNEP/ICRAF, 48 pp. [Available online at http://www.unep.org/ecosystemmanagement/Portals/7/Documents/ClimateChangeSahelCombine.pdf.]

Kaptué, A. T., L. Prihodko, and N. P. Hanan, 2015: On regreening and degradation in Sahelian watersheds. *Proc. Natl. Acad. Sci. USA*, **112**, 12 133–12 138, doi:10.1073/pnas.1509645112.

Larwanou, M., and M. Saadou, 2011: The role of human interventions in tree dynamics and environmental rehabilitation in the Sahel zone of Niger. *J. Arid Environ.*, **75**, 194–200.

Loveland, T. R., B. C. Reed, J. F. Brown, D. O. Ohlen, J. Zhu, L. Yang, and J. W. Merchant, 2000: Development of a global land cover characteristics database and IGBP DISCover from 1-km AVHRR data. *Int. J. Remote Sens.*, **21**, 1303–1330, doi:10.1080/014311600210191.

Mann, G., 2014: *From Empires to NGOs in the West African Sahel: The Road to Nongovernmentality.* African Studies Series, No. 129, Cambridge University Press, 300 pp.

Mbow, C., O. Mertz, A. Diouf, K. Rasmussen, and A. Reenberg, 2008: The history of environmental change and adaptation in the eastern Saloum–Senegal—Driving forces and perceptions. *Global Planet. Change*, **64**, 210–221, doi:10.1016/j.gloplacha.2008.09.008.

McMillan, D. E., 1995: *Sahel Visions: Planned Settlement and River Blindness Control in Burkina Faso.* University of Arizona Press, 223 pp.

Mertz, O., and A. Reenberg, 1999: Building on diversity: Pathways to agricultural intensification in Burkina Faso. *Geograf. Tidsskrift*, **2**, 125–138.

Millennium Ecosystem Assessment, 2005: Ecosystems and human well-being: Desertification synthesis. Tech. Rep., World Resources Institute, 26 pp. [Available online at http://www.millenniumassessment.org/documents/document.355.aspx.pdf.]

Mortimore, M., 2010: Adapting to drought in the Sahel: Lessons for climate change. *Wiley Interdiscip. Rev.: Climate Change*, **1**, 134–143, doi:10.1002/wcc.25.

Mousseau, F., and A. Mittal, 2006: Sahel: A prisoner of starvation? A case study of the 2005 food crisis in Niger. Tech. Rep., Oakland Institute, 56 pp. [Available online at http://www.oaklandinstitute.org/sites/oaklandinstitute.org/files/sahel_0.pdf.]

Myneni, R. B., F. G. Hall, P. J. Sellers, and A. L. Marshak, 1995: The interpretation of spectral vegetation indices. *IEEE Trans. Geosci. Remote Sens.*, **33**, 481–486, doi:10.1109/36.377948.

Nicholson, S. E., 2000: The nature of rainfall variability over Africa on time scales of decades to millennia. *Global Planet. Change*, **26**, 137–158, doi:10.1016/S0921-8181(00)00040-0.

——, 2005: On the question of the "recovery" of the rains in the West African Sahel. *J. Arid Environ.*, **63**, 615–641, doi:10.1016/j.jaridenv.2005.03.004.

Olsson, L., L. Eklundh, and J. Ardö, 2005: A recent greening of the Sahel—Trends, patterns and potential causes. *J. Arid Environ.*, **63**, 556–566, doi:10.1016/j.jaridenv.2005.03.008.

Painter, T. M., 1993: Getting it right: Linking concepts and action for improving the use of natural resources in Sahelian West Africa. Drylands Network Issues Paper 40, International Institute for Environment & Development, 39 pp. [Available online at http://pubs.iied.org/7289IIED.html?r=p.]

PERN-PRIPODE, 2007: PERN-PRIPODE Cyberseminar on Population-Development-Environment linkages in the Sudano-Sahelian zone of West Africa. Accessed 29 December 2015. [Available online at https://www.populationenvironmentresearch.org/cyberseminars/1450.]

Polgreen, L., 2007: In Niger, trees and crops turn back the desert. *New York Times*, 11 February, New York ed., A1. [Available online at http://www.nytimes.com/2007/02/11/world/africa/11niger.html?_r=0.]

Prince, S. D., K. J. Wessels, C. J. Tucker, and S. E. Nicholson, 2007: Desertification in the Sahel: A reinterpretation of a reinterpretation. *Global Planet. Change*, **13**, 1308–1313, doi:10.1111/j.1365-2486.2007.01356.x.

Rasmussen, K., B. Fog, and J. E. Madsen, 2001: Desertification in reverse? Observations from northern Burkina Faso. *Global Environ. Change*, **11**, 271–282, doi:10.1016/S0959-3780(01)00005-X.

Raynaut, C., E. Grégoire, P. Janin, J. Koechlin, and P. L. Delville, 1997: *Societies and Nature in the Sahel.* Routledge, 351 pp.

Reij, C. P., and E. M. A. Smaling, 2008: Analyzing successes in agriculture and land management in sub-Saharan Africa: Is macro-level gloom obscuring positive micro-level change? *Land Use Policy*, **25**, 410–420, doi:10.1016/j.landusepol.2007.10.001.

——, I. Scoones, and C. Toulmin, 1996: *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa.* Earthscan Publications, 260 pp.

——, G. Tappan, and A. Belemvire, 2005: Changing land management practices and vegetation on the central plateau of Burkina Faso (1968–2002). *J. Arid Environ.*, **63**, 642–659, doi:10.1016/j.jaridenv.2005.03.010.

——, ——, and M. Smale, 2009a: Re-greening the Sahel: Farmer-led innovation in Burkina Faso and Niger. *Millions Fed: Proven Successes in Agricultural Development*, D. J. Spielman and R. Pandya-Lorch, Eds., International Food Policy Research Institute, 53–58.

——, ——, and ——, 2009b: Agroenvironmental transformation in the Sahel: Another kind of "Green Revolution." IFPRI Discussion Paper 00914, 43 pp. [Available online at http://www.ifpri.org/publication/agroenvironmental-transformation-sahel.]

Rotstayn, L., and U. Lohmann, 2002: Tropical rainfall trends and the indirect aerosol effect. *J. Climate*, **15**, 2103–2116, doi:10.1175/1520-0442(2002)015<2103:TRTATI>2.0.CO;2.

Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering, 1974: Monitoring vegetation systems in the Great Plains with ERTS. *Third Earth Resources Technology Satellite-1 Symposium*, Vol. 1A, NASA, 309–317.

Sanders, J. H., B. I. Shapiro, and S. Ramaswamy, 1996: *The Economics of Agricultural Technology in Semi-Arid Sub-Saharan Africa.* Johns Hopkins University Press, 328 pp.

Sendzimir, J., C. P. Reij, and P. Magnuszewski, 2011: Rebuilding resilience in the Sahel: Regreening in the Maradi and Zinder regions of Niger. *Ecol. Soc.*, **16**, 1, doi:10.5751/ES-04198-160301.

Skinner, E. P., 1980: *Sahelian Social Development*. Regional Economic Development Services Office, USAID, 720 pp.

Tappan, G., and M. McGahuey, 2007: Tracking environmental dynamics and agricultural intensification in southern Mali. *Agric. Syst.*, **94**, 38–51, doi:10.1016/j.agsy.2005.07.011.

Ting, M., Y. Kushnir, R. Seager, and C. Li, 2009: Forced and internal 20th century SST trends in the North Atlantic. *J. Climate*, **22**, 1469–1481, doi:10.1175/2008JCLI2561.1.

Tougiani, A., C. Guero, and T. Rinaudo, 2009: Community mobilization for improved livelihoods through tree crop management in Niger. *GeoJournal*, **74**, 377–389, doi:10.1007/s10708-008-9228-7.

Trenberth, K., and Coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 235–336.

Tucker, C. J., 1979: Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ.*, **8**, 127–150, doi:10.1016/0034-4257(79)90013-0.

——, J. R. G. Townshend, and T. E. Goff, 1985: African land-cover classification using satellite data. *Science*, **227**, 369–375, doi:10.1126/science.227.4685.369.

——, H. E. Dregne, and W. W. Newcomb, 1991: Expansion and contraction of the Sahara desert from 1980 to 1990. *Science*, **253**, 299–301, doi:10.1126/science.253.5017.299.

United Nations, 1994: Convention to Combat Desertification. Accessed 29 December 2015. [Available online at http://www.unccd.int/en/about-the-convention/Pages/Text-overview.aspx.]

Watts, M. J., 1983: *Silent Violence: Food, Famine and Peasantry in Northern Nigeria.* University of California Press, 687 pp.

West, C. T., C. Roncoli, and F. Ouattara, 2008: Local perceptions and regional climate trends of the Central Plateau of Burkina Faso. *Land Degrad. Dev.*, **19**, 289–30, doi:10.1002/ldr.842.

Zougmoré, R., A. Jalloh, and A. Tioro, 2014: Climate-smart soil water and nutrient management options in semi-arid West Africa: A review of evidence and analysis of stone bunds and *zaï* techniques. *Agric. Food Secur.*, **3**, 16, doi:10.1186/2048-7010-3-16.