Potential feedback of recent vegetation changes on summer rainfall in the Sahel

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The Sahel region of Northern Africa is home to more than 50 million people for whom summer rainfall is a crucial water resource in terms of food security and societal stability. Using satellite-based Normalized Difference Vegetation Index (NDVI) and gridded observational precipitation records during 1982–2012, we detected a significant increase ($p$-value < 0.01) in both vegetation greenness and monsoon rainfall over the Sahel since the early 1980s. A significant positive association between NDVI and precipitation was observed for most of the Sahel during the boreal summer. In further efforts to examine the potential causal association behind the positive correlation, we found that summer vegetation greenness Granger-causes summer rainfall in the Sahel. Regarding the physical process behind this identified Granger causality, we inferred that significantly increasing latent heat flux and specific humidity resulted in increasing summer rainfall during the years of high NDVI in the Sahel. A significant increase in the percentage of land used for crops and pastures was a potential cause of the recent vegetation change. Our findings indicated that the positive effect of vegetation cover through agricultural activities on regional precipitation could lead to a positive feedback between the vegetation and climate in the water-limited Sahel region.

Keywords: vegetation index; precipitation; Granger causality; Sahel; climate; agricultural land use

Introduction

The Sahel region of Northern Africa is one of the most complex terrestrial ecosystems in the globe (Foley, Coe, Scheffer, & Wang, 2003). To the north is the Sahara desert, the largest hot desert on the planet. To the south, there is a sharp gradient of vegetation cover transitional to the monsoonal forests of West and Central Africa. In this study, the Sahel region is the area bounded between 15°W and 20°E longitude and 13°N and 20°N latitude (Figure 1), as suggested by Nicholson (1994). Being one of the poorest and most environmentally fragile places on Earth, this narrow semi-arid transition zone is home to more than 50 million people, and with a rapid growth rate, the population was projected to double by 2050 (Integrated Regional Information Networks [IRIN] 2008). The majority of the population in the region is engaged in, or dependent on, rain fed agriculture (Hatibu, Oweis, & Wani, 2007). Most rainfall in the Sahel occurs during the summer monsoon season – June, July, August, and September (hereafter, JJAS) when the growing season gets underway, while the rest of the year is very dry. This
means that monsoon rainfall is a crucial water resource for food security and societal stability in the Sahel region.

Monsoon in the Sahel is strongly driven by lower-level winds from the Atlantic Ocean to land due to the differential heating of the atmosphere over land and the surrounding water body. This land-ocean heating contrast is the fundamental basis of a well-developed monsoon climate (e.g. Webster, 1987). Based on the pioneering study of Charney (1975), the positive biogeophysical feedback associated with radiative aspects could help to perpetuate the dry (or wet) conditions in the Sahel. Regarding the ocean and atmosphere interactions in the Sahel monsoon climate, Lamb (1978a, 1978b, 1979) pointed out that sub-Saharan drought coincided with an equatorward displacement of near-equatorial atmospheric-oceanic features, including the sub-tropical high pressure belt and tropical easterly jet stream, at the tropical Atlantic. The roles of both land and ocean in controlling monsoon development and overall intensity are therefore important. The strength, timing, and spatial details of the heating contrast determine the annual and seasonal characteristics of monsoon rainfall and its impact on regional water resources. Monsoon rainfall in the Sahel, which is of high interannual and interdecadal variability over the twentieth century (Shanahan et al., 2009), has a profound influence on human lives. The last Sahelian drought, one of the worst on record, persisted for more than a whole decade from 1972 to 1984 (United Nations Environmental Program (UNEP), 2002). The drought was responsible for the death of over 100,000 people in the region, and rendered more than 750,000 people in Mali, Niger and Mauritania totally dependent on food aid in 1974 (Wijkman & Timberlake, 1984). The drought

Figure 1. Seasonal mean of the NDVI in Africa during the boreal summer (June–September) for 1982–2006, which was obtained from the AVHRR GIMMS NDVI. Very low values of NDVI (0.1 and below) correspond to barren areas or sand, like the Sahara Desert in Northern Africa and the Kalahari Desert in Southern Africa. Low values [0.2–0.3) represent shrub and grassland, followed by a moderate transition range [0.3–0.6) and high values [0.6–0.8) indicating temperate and tropical rainforests (Cai et al., 2014).
Note: The Sahel region was outlined in red.

Figure 1
also resulted in power shortages in Benin, Chad, Mali, and Nigeria because of hydro-
power failures at the Kainji Dam on the River Niger (IPCC, 1998). On the other hand,
severe flooding of August 2013 in drought-prone Niger killed at least 20 and left
around 48,000 homeless (GlobalPost, 2013).

Previous research has suggested significant changes in Sahel monsoon rainfall attri-
butable to the variance of heat and moisture over both the land (vegetation cover,
albedo, and soil moisture) and ocean (sea surface temperatures (SST)) surface (Lock-
wood, 1986). To define the moisture sources of the monsoon in the Sahel, many studies
have focused on the relationships between monsoon rainfall and SST in the Atlantic
Ocean (e.g. Lamb, 1978a, 1978b; Shanahan et al., 2009; Zheng & Eltahir, 1998). The
composite analyses (Lamb, 1978a) and case studies (Lamb, 1978b) using surface atmo-
spheric and oceanic observations in the tropical Atlantic suggested that distinctive SST
departure fields (maximum SST displaced to equatorward) accompanied the anomalous
tropical atmospheric circulation patterns, including the equatorward extension of the
North Atlantic subtropical high, which rendered the environment less favorable for the
occurrence of precipitation. Shanahan et al. (2009) linked severe drought in the Sahel
to natural variations in the Atlantic SST. Several observational and climate-modeling
studies have identified ocean variability as the primary force altering the monsoon in
West Africa (e.g. Shanahan et al., 2009) as well as other monsoon systems in India
(e.g. Kumar, Rajagopalan, & Cane, 1999) and East Asia (e.g. Wang, Wu, & Fu, 2000).
Some studies have examined the role of the land surface in monsoon rainfall over the
Sahel (e.g. Anthes, 1984; Charney, Quirk, Chow, & Kornfield, 1977; Nicholson, 1988,
2000; Taylor, Lambin, Stephenne, Harding, & Essery, 2002; Wang & Eltahir, 2000;
Wang, Eltahir, Foley, Pollard, & Levis, 2004; Xue, 1997; Xue, Boone, & Taylor, 2012;
Xue et al., 2004; Zheng & Eltahir, 1998). The positive biogeophysical feedback mechani-
sm linking vegetation, albedo and precipitation postulated by Charney (1975) had
been simulated by numerical modeling experiments over the semi-arid regions in
Africa, Asia, and North America (Charney et al., 1977). The simulated results sup-
ported that the increase of albedo causes a net decrease of radiative flux into the ground
and therefore a net decrease of convective cloud and precipitation. Xue (1997), in
desertification experiments, simulated increased surface air temperature and reduced
precipitation, runoff, and soil moisture over the Sahel region during July through
September, using a general circulation model (GCM). Taylor et al. (2002) also applied
a GCM to assess the impact of land-use change on Sahelian climate. They suggested
that recent historical land-use changes were not large enough to have been the principal
cause of the Sahel drought, while the climatic influence of land-use change in the Sahel
were likely to increase rapidly in the coming years. Wang et al. (2004) indicated that
vegetation dynamics, which govern the energy, mass (including water and carbon), and
momentum flux exchanges between land and the overlying atmosphere, act as a mecha-
nism for persistence of the Sahel climate, using an atmospheric GCM coupled with the
dynamic global vegetation model. Previous studies using GCMs have improved our
understanding of the effect of land use/land cover on monsoon rainfall in the Sahel.
However, empirical research using accurate historical records of regional vegetation
cover, essential to identify the association between vegetation and rainfall variations,
has received little attention.

Recently, changes in land use/land cover due to the expansion and intensification of
deforestation and agricultural practices have been observed across the world from the
tropics to the mid-latitudes (FAO, 2011; Foley et al., 2005). Since the 1960s, the Sahel
has experienced a devastating and prolonged drought and has been asserted to be a
region of irreversible desertification region (Dai et al., 2004; Lamprey, 1988). While rainfall conditions at some locations have improved considerably, drought persisted into 1998 for most of the West African Sahel (Tarhule & Tarhule-Lips, 2001). However, recent findings based on analysis of satellite images and rainfall measurements reported increasing rainfall and vegetation greenness over the Sahel since the mid-1980s (Eklundh & Olsson, 2003; Olsson & Hall-Beyer, 2008; Tucker & Nicholson, 1999). Most previous studies claimed that the increasing vegetation greenness over the Sahel was due to increasing rainfall (Haarsma, Selten, Weber, & Kliphuis, 2005; Herrmann, Anyamba, & Tucker, 2005; Olsson, Eklundh, & Ardö, 2005). Hickler et al. (2005) found that precipitation controls the vegetation greening trend over the Sahel. On the other hand, higher vegetation cover can transfer more moisture into the atmosphere through evapotranspiration, and vegetation’s lower albedo compared with bare ground increases solar radiation absorption and, in turn, might encourage rainfall (Van Noorden, 2006). Los et al. (2006) concluded that vegetation effects account for about 30% of annual rainfall variation in the Sahel. There seems to be no agreement on the recent change of Sahel rainfall and the feedback between increasing vegetation greenness and precipitation over the Sahel.

In this study, we examined the changes in recent land cover over the Sahel region during the pre-monsoon spring (March, April, and May; hereafter, MAM) and monsoon (JJAS) seasons and their associations with the regional monsoon rainfall using satellite-based vegetation data and atmospheric observations and reanalysis datasets through empirical analyses. Our objectives are fourfold: (1) to examine the temporal and spatial changes of vegetation cover and rainfall in the Sahel during the past three decades, (2) to determine the relationships between vegetation and rainfall variations, (3) to assess the potential causal associations between vegetation and summer rainfall, and (4) to infer the physical processes behind the identified statistical associations by examining land surface and atmospheric conditions.

**Data and methods**

**Data**

*Reconstructed 31-year vegetation data in the Sahel*

We used the Normalized Difference Vegetation Index (NDVI), the unitless difference between near-infrared and red spectral reflectance normalized by their sum, as a measure of vegetation and land cover (Tucker et al., 2005). Spectral vegetation indices are highly correlated with photosynthetically active biomass, chlorophyll abundance, and energy absorption (e.g. Myneni, Hall, Sellers, & Marshak, 1995), thus NDVI is used as a measure of vegetation greenness (see Figure 1). Additionally, NDVI could be a function of canopy density, leaf area index and surface moisture as resulting from antecedent precipitation, and also influenced by vegetation type and phenological stage (Geerken, Zaitchik, & Evans, 2005; Myneni et al., 1995). The NDVI data-set was derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the National Oceanic and Atmospheric Administration (NOAA) satellite series (Tucker et al., 2005). The data-set was acquired from the Global Inventory Modeling and Mapping Studies (GIMMS), Global Land Facility at the University of Maryland. The time span of this data-set (1981–2006) does not cover the entire study period (1982–2012). Moreover, the AVHRR sensors were not originally intended for vegetation study, and there are some shortcomings for vegetation trend
studies, such as post-launch degradation in sensor calibrations and drift in the satellite overpass times (e.g. Teillet, Staenz, & William, 1997; Van Leeuwen, Huete, & Laing, 1999). Thus, we also used NDVI from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the National Aeronautics and Space Administration (NASA) Earth Observing System-Terra platform (Huete et al., 2002). The MODIS sensor has been designed for vegetation monitoring and features more accurate geographic positioning, atmospheric correction, reduced geometric distortions, and improved radiometric sensitivity (Gobron, Pinty, Verstraete, & Widlowski, 2000; Sylvander, Henry, Bastien-Thiry, Meunier, & Fuster, 2000). However, the MODIS NDVI is only available from April 2000 to the present.

To create a consistent NDVI data-set for the study period of 1982–2012, we therefore combined the remotely sensed NDVIs from NOAA AVHRR (GIMMS NDVI) and NASA MODIS. Because the temporal resolutions for AVHRR GIMMS NDVI and MODIS NDVI were 15 and 16 days, respectively, temporal resampling methods were employed to calculate the monthly NDVI. Three different resampling methods, namely simple average (Brown, Lary, Vrieling, Stathakis, & Mussa, 2008), maximum value composite (Fensholt & Proud, 2012), and weighting average (Solano, Didan, Jacobson, & Huete, 2010) methods, were compared, and the simple average method was selected among the three as the best method for minimizing the differences between the two NDVI datasets in the Sahel region. We constructed a linear regression function between the two NDVI datasets during the overlapping period (see a linear regression graph in Supplementary Figure 1). A good fit ($R^2 = 0.85$) between the area-averaged monthly NDVI values over the Sahel during 2001–2006 was observed. Then, we used the area-averaged monthly NDVIs over the Sahel to construct a linear regression on the MODIS NDVI with AVHRR GIMMS NDVI data during the overlapping period (2001–2006). The calculated regression function was applied to obtain the reconstructed NDVI time-series for the period of 1982–2000.

In summary, we used monthly time-series of NDVI area averaged over the Sahel from the reconstructed NDVI for 1982–2000 and MODIS NDVI for 2001–2012. The continuous NDVI time-series for 1982–2012 were used in statistical analyses. Spatial resolutions of the AVHRR GIMMS NDVI (8 km by 8 km) and MODIS NDVI (250 m by 250 m) were re-gridded from their original resolutions to 0.5° by 0.5°, based on a linear interpolation, to be consistent with the spatial resolution of precipitation data.

Climate datasets

The monthly mean precipitation derived from the Climate Research Unit (CRU) was used to calculate the seasonal mean precipitation in the Sahel region. CRU precipitation is high-resolution gridded data obtained from meteorological stations over the global land surface (CRU TS 3.21) (Mitchell, Carter, Jones, Hulme, & New, 2004). The CRU TS 3.21 data-set was available for 1901–2012 at a 0.5° by 0.5° spatial resolution. For the comparisons with CRU precipitation data, we used Tropical Rainfall Measuring Mission (TRMM)-based precipitation (Huffman et al., 2007). TRMM multisatellite precipitation analysis provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gage analyses where feasible, at fine scales (0.25° by 0.25° spatial and 3-h temporal resolutions) from 1998-present. The comparison of CRU with TRMM precipitation during 1998–2012 confirmed that spatial and temporal patterns of Sahel rainfall from the datasets were consistent
(Supplementary Figure 2). The time-series of JJAS Sahel rainfall from the CRU were significantly correlated with those from the TRMM at the 1% level \((r = 0.9)\).

To infer the physical processes between vegetation change and monsoon rainfall, we used surface moisture variables of latent (LE) and sensible (H) heat fluxes and specific humidity at 2 m from the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP-II) monthly reanalysis (Kanamitsu et al., 2002). We also used atmospheric specific humidity at the lower-troposphere (850 hPa) obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996). For the validation of LE flux from the NCEP-DOE, we used LE flux from the FLUXNET-MTE (Jung, Reichstein, & Bondeau, 2009), with FLUXNET observations of carbon dioxide, water and energy fluxes upscaled to the global scale using the machine learning technique of Model Tree Ensembles (MTE) (Jung et al., 2011). MTE method was used to predict site-level gross primary productivity, terrestrial ecosystem respiration, net ecosystem exchange, latent and sensible heat based on remote sensing data, climate and meteorological data, and information on land use (Jung et al., 2011).

**Agricultural land-use data**

Recent studies have generated improved representations of regional and global agricultural systems by developing a global data-set of cropland and pasture land use using national and subnational level agricultural census statistics and satellite-derived land-cover data (Ramankutty, Evan, Monfreda, & Foley, 2008; Ramankutty & Foley, 1998, 1999). Historical changes in global croplands are available at 5-arc minute resolution, spanning the period of 1700–1992 (Ramankutty & Foley, 1999). Recently, the original historical data were updated to 2007, with the additional inclusion of pastures. We used the transient crop and pasture areas for the period of 1982–2007, which is provided at 0.5° resolution by EarthStat (http://www.earthstat.org/).

**Statistical methods**

**Linear regression and correlation analysis**

The spatial and temporal variability of vegetation cover and rainfall over the Sahel were first analyzed using linear regression models of NDVI and precipitation with respect to time:

\[
Y = a + bX + e,
\]

Parameters \(a\) and \(b\) are the regression coefficients, estimated by the ordinary least squares; \(e\) is the uncorrelated random error with zero mean and constant standard deviation (Freund, Wilson, & Sa, 2006). In this study, we were interested in \(b\), the slope of the regression line, to see how the dependent variable \((Y)\) has changed over time \((X)\). Two models were estimated with the seasonally averaged NDVIs and precipitation as the dependent variable, respectively. The linear regression analysis was also applied to examine the changes in pasture and cropland areas over time.

To determine the associations of vegetation and monsoon rainfall, we calculated the Pearson correlation coefficients \((r\) value; Pearson, 1895) of NDVI time series during the pre-monsoon and monsoon seasons with seasonally averaged precipitation for JJAS
at each grid cell over the Sahel region. Furthermore, significance tests for the linear regression and correlation coefficients were performed, and statistically significant regions at the 5% level were contoured on the map.

**Granger-causality test**

Because the correlation analysis does not necessarily imply a causal relationship between vegetation change and monsoon rainfall, we further assessed the causality between NDVI and precipitation using the Granger-causality test (Granger, 1969). A Granger-causal relationship is defined as follows: one time-series variable \( g_t \), \( t = 1, 2, \ldots, n \) Granger-causes another time-series variable \( h_t \) if knowledge of the past history of \( g_t \) is useful for explaining the future state of \( h_t \) over and above knowledge of the past history of \( h_t \). The test involves a comparison of two regression models, one being the regression of \( h_t \) on lagged values of \( h_t \) only, and the second the regression of \( h_t \) on both lagged values of \( h_t \) and \( g_t \). If the second one significantly improves upon the first, \( g_t \) is said to Granger-cause \( h_t \). The granger causality test has been applied in a variety of studies on the coupled climate systems including ocean and atmosphere interactions (e.g. Elsner, 2006, 2007) and land and atmosphere interactions (e.g. Meng, Long, Quiring, & Shen, 2014).

In this study, the two-way interactions between NDVI and precipitation were examined as follows:

**Precipitation**

\[
\text{Precip}_t = \sum_{i=1}^{p} \alpha_i \text{Precip}_{t-i} + \sum_{i=1}^{p} \beta_i \text{NDVI}_{t-i} + \epsilon_t, \quad (2)
\]

**NDVI**

\[
\text{NDVI}_t = \sum_{i=1}^{p} \gamma_i \text{NDVI}_{t-i} + \sum_{i=1}^{p} \delta_i \text{Precip}_{t-i} + \eta_t, \quad (3)
\]

where \( \alpha, \beta, \gamma, \) and \( \delta \) are regression coefficients, \( \epsilon \) and \( \eta \) are white noise errors, \( p \) is the lag length (\( p = 1 \) in this study). To test whether NDVI Granger-caused precipitation, we estimated a restricted form of Equation (2) by eliminating NDVI through restricting \( \beta \) in Equation (2) to zero (Equation (4)). Similarly, we tested whether precipitation Granger-caused NDVI by restricting \( \delta \) in Equation (3) to zero (Equation (5)).

**Restriction**

\[
\text{Precip}_t = \sum_{i=1}^{p} \alpha_i' \text{Precip}_{t-i} + \epsilon_t', \quad (4)
\]

\[
\text{NDVI}_t = \sum_{i=1}^{p} \gamma_i' \text{NDVI}_{t-i} + \eta_t', \quad (5)
\]

Next, to test whether the restricted estimates (Equations (4) and (5)) were statistically different from the unrestricted estimates (Equations (2) and (3)), the following \( F \)-test statistic (Elsner, 2006) was calculated:

\[
F_{\text{ndvi \precip}} = \frac{(\text{SSE}_R - \text{SSE}_U)/H}{\text{SSE}_U/(n-K)} \sim F_{H,n-K}, \quad (6)
\]

where \( \text{SSE}_R \) and \( \text{SSE}_U \) are the sum of squared errors of restricted and unrestricted versions, i.e. Equations (4) and (2), or Equations (5) and (3), respectively. The number of coefficients set to zero in the restricted version is \( H \), the number of predictors in the
unrestricted version is $K$, and $n$ is the number of observations. If $F_{\text{ndvi,precip}}$ was less than $F_{H,n-K}$, we concluded that NDVI did not Granger-cause precipitation, otherwise, it did. The same reasoning was applicable to the inverse Granger causal relationship. The two regression models in the Granger-causality test were used for quantifying the statistical difference between the models with and without the interesting variable (NDVI or precipitation in this study). Thus, a Granger-causal relationship does not necessarily imply a true (physical) causal association, which is admittedly very difficult to assess in an empirical setting.

Composite analysis

Potential physical processes behind the correlation and Granger-causality of vegetation greenness and monsoon rainfall were inferred by examining surface and atmospheric moisture variables. Composite analysis (Von Storch & Zwiers, 2001) was performed to determine whether changes in surface LE flux, specific humidity (2 m and 850 hPa), and precipitation were associated with vegetation change in the Sahel. The composite differences of the moisture variables between the five cases (years of 2003, 2005, 2007, 2010, and 2012) with highest JJAS NDVI (i.e. top 15% of the observation; $n = 31$, 1982–2012) and the five cases (years of 1983, 1984, 1985, 1986, and 1987) with lowest JJAS NDVI (i.e. bottom 15%) in the Sahel were calculated. To quantify the significant differences, we conducted a $t$-test for a two sample difference of means (Walpole, Myers, Myers, & Ye, 1993), with rejection of the zero difference null hypothesis at the 5% significant level.

Results

Changes in vegetation and precipitation in the Sahel

Seasonally averaged NDVIs (AVHRR GIMMS NDVIs) during the pre-monsoon (MAM) and monsoon (JJAS) seasons increased over the Sahel during the period of 1982–2006 (Figure 2(a) and (b)). JJAS NDVI significantly increased over the most parts of the Sahel at the 5% level, except for the southern Sahara Desert (Figure 2(b)). During the same period, monsoon rainfall over the Sahel increased as shown in the regression trends of JJAS precipitation (Figure 2(c)). Significant increasing precipitation was dominant in the northern Nigeria. In order to check the spatial consistency of linear regression trends between JJAS NDVI and JJAS precipitation in the Sahel region, we computed the correlation coefficient between Figure 2(b) and (c) on the basis of each grid point in the specified region (i.e. 15°W–20°E and 13°–20°N; 1152 data points). Using Moran’s Index (Moran, 1950), significant spatial autocorrelations ($p$-value < 0.01) were identified for the patterns in Figure 2(b) and (c). It is well known that the existence of such autocorrelation leads to spurious correlation, thus we applied the modified $t$-test (Clifford, Richardson, & Hemon, 1989) to take account of this issue. The correlation coefficient between the two patterns was 0.44 and significant at 1% level ($p$-value = 0.0021), with the modified $t$-test. This analysis indicated that spatial distributions of regression trend values for JJAS NDVI were significantly correlated with those for JJAS precipitation over the Sahel.

Seasonal means of area-averaged variables in the Sahel region were used to examine changes in time-series of the reconstructed NDVI and precipitation for 31 years
Figure 2. Spatial distributions of 1982–2006 estimated trend of seasonally averaged NDVIs (NDVI/decade) during (a) MAM (March-May) and (b) JJAS (June–September), and (c) precipitation (precipitation/year) during JJAS, based on linear regression. Note: Significant regions at the 5% level were contoured in green.
from 1982 to 2012. Vegetation cover, averaged over the entire Sahel during the pre-monsoon spring, has not significantly changed over the time period of 1982–2012 (Figure 3). However, during the monsoon season, both NDVI and precipitation significantly increased in the Sahel at the 1% level. In Figure 3, the interannual variation of Sahel summer rainfall coincides with that of summer vegetation index in the Sahel. A significant positive correlation between the time series of JJAS NDVI and JJAS precipitation area averaged in the Sahel was observed (p-value < 0.001). On the other hand, the time series of MAM NDVI were negatively related to those of JJAS precipitation, but this correlation was not statistically significant (p-value = 0.59).

**Correlations of vegetation greenness with summer rainfall in the Sahel**

The relationships of vegetation greenness during the pre-monsoon (MAM) and monsoon (JJAS) seasons with monsoon rainfall in the Sahel were examined by the correlation patterns of area-averaged NDVIs in the Sahel with precipitation in each grid cell in the Sahel and surrounding regions. Time series of MAM NDVI in the Sahel were positively associated with JJAS precipitation in the western (Mauritania) and eastern (eastern Niger) Sahel regions and they were negatively related to summer monsoon rainfall in the central Sahel regions (Figure 4(a)). For most of the Sahel, the correlation coefficients were statistically insignificant.

A significant positive association between JJAS vegetation greenness and JJAS monsoon rainfall was observed for most of the Sahel region (Figure 4(b)). In particular, strong positive correlations were characteristic of much of the 15°N latitude region in the Sahel (r > 0.6). Although the correlation analyses showed the strong relationship between NDVI and precipitation in JJAS, it did not necessarily imply potentially causal associations between NDVI and rainfall.

Figure 3. Time-series of JJAS precipitation and MAM and JJAS NDVIs area-averaged over the Sahel region.
Granger causality between vegetation and rainfall in the Sahel

Normality test

Classical regression models require the normal distribution of data. Non-normality of the data in a regression model may induce heteroscedasticity and non-normality of the residuals, which can result in the bias of forecasts and confidence intervals estimated by the statistical model (Walpole et al., 1993). Histograms and probability density functions (PDFs) of the variables (MAM NDVI, JJAS NDVI, and JJAS precipitation, which were area averaged over the Sahel, for 1982–2012) were used as the first visual inspection of the normality. All three variables used in the Granger causality test were close to normal distribution (Figure 5(a)). Quantile–quantile ($Q–Q$) plots, which illustrated the quantiles of the variables against the quantiles of a normal distribution (Walpole et al., 1993), provided a graphical representation of normality. The line

Figure 4. Correlation coefficients (Pearson) of area-averaged NDVIs in the Sahel for (a) MAM and (b) JJAS with JJAS precipitation at each grid during 1982–2012. Notes: Significant regions at the 5% level were contoured in green. The boxes indicate the Sahel region over which MAM and JJAS NDVIs were calculated.
passing through the first and third quartiles was added to Q–Q plots (Figure 5(b)). The distribution of all variables could be inferred to be normal, because the points of the variables generally fell on the line. To confirm the statistical significance of normality, we performed one sample Kolmogorov–Smirnov (K–S) test, which examined the fitting of observed cumulative distribution function (CDF) and expected CDF (Von Storch & Zwiers, 2001). The K–S test for all three variables failed to reject the null hypothesis that the expected CDF was not different from the observed CDF (p-values were 0.49, 0.81, and 0.97 for MAM NDVI, JJAS NDVI, and JJAS precipitation, respectively). Thus, the results of visual and statistical inspections supported the conclusion of normality of the three variables.

**Stationarity test**

The Granger causality test requires stationarity of the time-series data (Elsner, 2007; Granger, 1969). As shown in Figure 3, there were trends in the variables, particularly in NDVI and precipitation for JJAS. We performed a linear regression analysis to assess for trends over time. The t-statistics of slope coefficients for JJAS NDVI and JJAS precipitation were statistically significant (p-values < 0.01), while that for MAM NDVI was insignificant (p-value = 0.25). The significant trends in the two variables were detrended by removing the slope of the regression model. The trend in MAM NDVI time-series was also removed to be consistent with the other variables, although it was statistically insignificant. After the trends were removed, the t-statistics of slope coefficients for all three variables were statistically insignificant (p-values = 0.99, 0.91, and 0.80 for MAM NDVI, JJAS NDVI, and JJAS precipitation, respectively).
detrended time series of the variables appeared stationary (Supplementary Figure 3), and we used them in the subsequent Granger-causality analysis.

**Granger causality**

Table 1 shows the statistics of Granger causality test between JJAS NDVI and JJAS precipitation. In the Granger test for Equation (2) (Test 1 in Table 1), the \( F \)-statistic (18.46) suggested a rejection of the null hypothesis, which indicated that the unrestricted equation (Equation (2)) was significantly different from the restricted equation (Equation (4)) \( (p\text{-value} < 0.001) \). Thus, the eliminated variable from Equation (2) (JJAS NDVI) significantly improved the explanation of future values of JJAS precipitation, which suggested that JJAS NDVI did Granger-cause JJAS precipitation in the Sahel. With current JJAS NDVI as a dependent variable (Test 2 in Table 1), the \( p\text{-value} \) of \( F \)-statistic was larger than 0.05 but less than 0.1, which meant JJAS precipitation did not Granger-cause JJAS NDVI at the significance level of 5%, but did so at the significance level of 10%. We also examined the Granger causality of MAM NDVI to JJAS precipitation. The \( F \)-statistic (0.57) calculated from the unrestricted (including both MAM NDVI and JJAS precipitation) and restricted (including only JJAS precipitation) regression models did not reject the null hypothesis \( (p\text{-value} = 0.46) \), which indicated that MAM NDVI did not Granger-cause JJAS precipitation in the Sahel. The results of the Granger test using the detrended time series of the variables were consistent with those using their first-order differences (Elsner, 2007) which were also found to be stationary.

**Potential physical processes behind the Granger causality of vegetation to Sahel rainfall**

We explored the physical processes behind the strong Granger causality of JJAS NDVI to JJAS precipitation in the Sahel region by analyzing surface and atmospheric moisture variables. Figure 6 shows the differences of LE flux, specific humidity at 2 m and 850 hPa, and precipitation in JJAS between the composite 5 years of highest and of lowest NDVI area-averaged over the Sahel in JJAS. When higher vegetation greenness (as indicated by higher NDVI values) occurred in the Sahel during the boreal summer, stronger energy transfer from the surface to the atmosphere through latent heat process was found (Figure 6(a)). Significant positive differences were observed in the central and eastern Sahel regions, including northern Nigeria and southern Niger, where there was a difference of more than 20 W/m\(^2\) of LE flux during the years of high JJAS

| Model | Residual df | df | F-statistics | \( p\text{-value} \) |
|-------|------------|----|--------------|-------------------|
| Test 1: JJAS precipitation = JJAS precipitation + JJAS NDVI | 27 | | | |
| Unrestricted | 27 | | | |
| Restricted | 28 | 1 | 18.456 | 0.0002 |
| Test 2: JJAS NDVI = JJAS NDVI + JJAS precipitation | 27 | | | |
| Unrestricted | 27 | | | |
| Restricted | 28 | 1 | 3.9483 | 0.0572 |
NDVI, compared to the years of low JJAS NDVI. The composite analysis of LE flux from NCEP-DOE reanalysis was compared to that from FLUXNET-MTE observations, which was available from 1982 to 2008. LE flux from FLUXNET-MTE was significantly higher in the 15°N latitude regions over the Sahel during the three years of high JJAS NDVI (2003, 2005, and 2007), compared to the three low years (1983, 1984, and 1987) (Supplementary Figure 4). Spatial pattern of composite differences of LE flux from NCEP-DOE were generally consistent with that from FLUXNET-MTE.

Increased LE flux, which was associated with increased evapotranspiration from the enhanced vegetation activity, could result in increased water vapor in the atmosphere. We examined the composite patterns of specific humidity at the surface (2 m) from the NCEP-DOE, and at the 850 hPa level from the NCEP-NCAR reanalysis between the five high and five low years of JJAS NDVI. Significant positive differences of specific humidity at 2 m were observed in the most of the Sahel region (Figure 6(b)). A center of the positive difference was in southeastern Niger where there was more than 5 g/kg of increased specific humidity during the high years of JAS NDVI, compared to the low years. Increasing water vapor in the atmosphere related to increased vegetation activity was also shown in the lower-troposphere. The spatial pattern of composite differences of specific humidity at 850 hPa (Figure 6(c)) was consistent with that of specific humidity at 2 m. The center of the positive difference was slightly displaced to the northwest, in central Niger, compared to specific humidity at 2 m.

The increased water vapor in the lower troposphere through increased evapotranspiration during the years of high vegetation greenness in the Sahel could provide more favorable conditions for rainfall, especially in this moisture-limited region. During the years of high JJAS NDVI in the Sahel, significant positive differences of summer rainfall were shown over most of the Sahel region, compared to the years of low NDVI.
Along the borders between Burkina and Mali, northeastern Nigeria, and southern Chad, JJAS precipitation was higher by more than 70 mm/month during the high years of summer vegetation greenness compared to low vegetation greenness in the Sahel.

**Discussion and conclusions**

We found a steep increase in vegetation and summer rainfall in the Sahel during the last three decades, from the spatial and temporal trends of NDVI and precipitation records. Whereas many previous studies asserted that the Sahel has experienced a prolonged drought and an irreversible desertification since the 1960s (e.g. Dai et al., 2004; Lamprey, 1988; Nicholson, 1980; Shanahan et al., 2009; Yoshioka et al., 2007; Zeng, Neelin, Lau, & Tucker, 1999), our results showed increasing rainfall and vegetation greenness over the Sahel since the early 1980s, which agreed with other previous findings (e.g. Eklundh & Olsson, 2003; Olsson & Hall-Beyer, 2008; Tucker & Nicholson, 1999).

The associations of spring and summer vegetation greenness with summer rainfall in the Sahel were examined spatially using correlation analysis. Negative correlations of MAM NDVI with JJAS precipitation were observed in the Sahel, except for the northwestern and northeastern Sahel regions. Although the correlation patterns between MAM NDVI and JJAS precipitation were statistically insignificant for most of the Sahel, the negative association of vegetation greenness during the pre-monsoon season with monsoon rainfall was consistent with the findings in other monsoon regions in India (Lee et al., 2009) and East Asia (Lee, Barford, Kucharik, Felzer, & Foley, 2011). A strong association between summer vegetation and summer precipitation in the Sahel was shown. Statistically significant positive correlation values between NDVI and precipitation in JJAS were found in most of the Sahel, and in particular a strong positive association in the 15°N latitude region.

The recent trend of increasing vegetation over the Sahel, as indicated by summer NDVI values, is probably due to increasing rainfall (Haarsma et al., 2005; Herrmann et al., 2005; Hickler et al., 2005; Olsson et al., 2005), which is supported by the traditional understanding that the climate affects the terrestrial ecosystem. On the other hand, terrestrial ecosystems can also affect the climate by affecting net radiation and surface heat fluxes (e.g. Chase, Pielke, Kittel, Nemani, & Running, 2000; Foley et al., 2003; Lawrence & Chase, 2009; Mahmood et al., 2014; Pielke et al., 2002). We performed Granger-causality tests in seeking the potential feedback between increasing vegetation cover and monsoon rainfall. We confirmed the normality of the variables used in the causality test through the visual and statistical inspections of histograms, PDFs, Q–Q plot, and K–S test. Although the Granger-causality test requires stationary time-series data, environmental variables, especially climate data, are not always stationary over time (e.g. Kumar et al., 1999). We detrended the seasonal mean NDVIs and precipitation data used in the causality test by removing the slopes from the linear regression trend, because two variables (JJAS NDVI and JJAS precipitation) showed statistically significant trends. In the comparisons of the two regression models, which were unrestricted (including both precipitation and NDVI) and restricted (including only either precipitation or NDVI) models, we determined whether the past values of NDVI (precipitation) was significantly useful for explaining the future state of precipitation (NDVI), compared to the past values of precipitation (NDVI). The $F$-statistic calculated from the unrestricted and restricted regression models indicated that there was a
significant improvement in explaining JJAS precipitation by including the past history of JJAS NDVI. The explanation of JJAS NDVI was not significantly improved by adding the past JJAS precipitation, compared to the regression model using the past JJAS NDVI only, although the $F$-statistic was significant at the 10% level. The results of the causality test implied that increasing vegetation greenness might increase with Sahelian rainfall during the boreal summer.

As mentioned earlier in this paper, it is important to note that a Granger-causal relationship does not necessarily represent a true (physical) causal relationship. On the other hand, the Granger-causal relationship is subject to confounding factors. For example, if more than two variables, probably including SST, are involved in the NDVI and precipitation interactions, the consideration of only a pair of variables in such a framework could lead to errors. In this case, a vector autoregressive model (Enders, 2003) seems more appropriate. Therefore, caution should be used when interpreting the results generated by this type of test, and true causality should be confirmed from physical mechanisms.

We inferred the potential physical processes behind the Granger causal effect of vegetation changes on Sahel rainfall using the composite analysis of surface and atmospheric moisture variables for the years of high and low vegetation in the Sahel. During the years of high summer vegetation greenness in the Sahel, more surface energy was transferred to the atmosphere by latent heat fluxes than by sensible heat fluxes (Supplementary Figure 5). Increasing LE flux resulted in more moisture from the surface into atmosphere, which was supported by the significant positive composite differences of specific humidity at 2 m in the Sahel for the high JJAS NDVI years, compared to the low NDVI years. Significant positive differences of specific humidity were also identified in the lower troposphere over the Sahel. Increased atmospheric moisture due to enhanced evapotranspiration from more abundant vegetation could provide favorable conditions for precipitation in the moisture-limited Sahel. Significantly increasing summer rainfall in the Sahel during the high vegetation years may have supported a positive feedback in vegetation and rainfall interactions. Foley et al. (2003) suggested that a positive effect of vegetation cover on local precipitation may be involved in a feedback between vegetation and climate in dry areas of the world including Northern Africa. Los et al. (2006) indicated that a positive feedback between the land surface and atmosphere affects rainfall in the West African Sahel. Our identified Granger causality explained by the potential physical processes between vegetation and rainfall in the Sahel is thus supported by previous studies.

What might have caused the recent land-cover change in the Sahel other than climate? As in other regions (Ramankutty et al., 2008), croplands and pastures have become one of the largest land cover categories in the Sahel. Pasture, the major land cover in the Sahel (Figure 7(a)), saw significant expansion ($p$-value < 0.01) in southern Mali and southern Niger during 1982–2007 (Figure 7(c)). Croplands covered most of the land areas in the central Sahel and exceeded 90% of the total land area along the border between northern Nigeria and southern Niger (Figure 7(b)). Cropland coverage has significantly increased ($p$-value < 0.01) in most of the southern Sahel during 1982–2007 (Figure 7(d)). Some local areas in the southern Niger have experienced an increase in croplands by as much as 30% over the 26-year period. Interestingly, the cropland areas with very significant increase generally coincided with the areas of significantly increasing LE flux in the southern Niger during the years of high NDVI (see Figure 6(a)). This significant increase in percent of land used for crops has also been observed in previous studies (Paré, Söderberg, Sandewall, & Ouadba, 2008; Taylor
et al., 2002). The evidence of significantly increased areas of croplands and pastures indicated that the changing land cover in the Sahel was largely attributable to the more cultivated lands in recent years.

In summary, the Sahel has experienced a significant increase in both vegetation greenness and precipitation since the early 1980s. A strong positive association between vegetation greenness and Sahel rainfall was observed in the boreal summer, and further analysis revealed that vegetation change Granger-caused Sahel summer rainfall. Increased atmospheric moistures from the increasing vegetation activity were the likely physical process behind this Granger causality. As recent vegetation change in the Sahel was largely attributable to a significant increase in percent of land used for crops and pastures, the potential positive feedback of vegetation change on regional precipitation identified in this study implied that accelerating agricultural practices could play a role in re-greening the Sahel and thereby favor rainfall increase in this moisture-limited region. To this end, future research on land and atmosphere interactions for the Sahel region could benefit from the use of observational records of a longer temporal interval and higher spatial resolution, as well as numerical model experiments that include recent land use changes in the Sahel.

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