Remote Sensing of Environment 213 (2018) 129–143

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Use of remote sensing indicators to assess effects of drought and human-induced land degradation on ecosystem health in Northeastern Brazil

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ARTICLE INFO

Keywords:
Desertification
Land degradation
Drought
Evapotranspiration
Impulse-response analysis
Granger causality
MODIS
LAI
Albedo
Anthropization
Caatinga
Drylands

ABSTRACT

Land degradation (LD) is one of the most catastrophic outcomes of long-lasting drought events and anthropogenic activities. Assessing climate and human-induced impacts on land can provide information for decision makers to mitigate the effects of these phenomena. The Northeastern region of Brazil (NEB) is the most populous dryland on the planet, making it a highly vulnerable ecosystem especially when considering the lingering drought that started in 2012. The present work consisted of detecting trends in biomass [leaf area index (LAI)] anomalies as indicators of LD in NEB. We also assessed how the loss of vegetation impacts the LD cycle, by measuring trends in albedo and evapotranspiration (ET). LAI, albedo and ET data were derived from MODIS sensors at 8-day temporal and 500 m spatial resolutions. For precipitation anomalies, we relied on CHIRPS-v2 10-day temporal at 5 km spatial resolution data. For detecting trends, we applied the Theil-Sen slope analysis on time series of MODIS LAI, albedo and ET images. Trend analysis was performed for the periods ranging from 2002–2012 (no severe droughts) to 2002–2016 (including the last drought). LAI trends were more pronounced and had a stronger signal than ET and albedo, therefore, LAI was our choice for mapping LD. The first analysis highlighted the human-induced LD prone areas whereas the last detected drought-induced LD prone areas. Considering only the trending areas, which was about 23.4% of the total, 4.5% of this area has undergone human-induced degradation whereas drought was responsible for 73%, although, not mutually exclusive. As reported in the literature and official data, grazing intensification might be a factor driving human-induced degradation. We noticed that the range of variation of LAI is narrow and even narrower for albedo, which demonstrates that land surface response is more influenced by soil reflectivity rather than the characteristic sparse vegetation coverage (LAI ranging from 0.04 to 0.4 in the Caatinga biome), which can barely alter albedo. Finally, the effects of LD on ET anomalies were assessed by Granger causality and impulse-response analyses as means to link land surface feature changes to the hydrological cycle. Albedo had a slightly weaker impulse than LAI on ET whereas precipitation played a major role. These relations are site-specific and, land surface features (biomass and albedo) showed to have a more substantial influence on ET in severely degraded areas. We concluded that drought led to trends indicating LD prone areas in NEB and the degradation cycle has positive feedback derived from ET reduction resulting in an increased net moisture deficit, although the latter statement has yet to be further investigated. The study warns of the desertification risk that NEB is facing and the need for the authorities to take action to mitigate degradation and drought effects on both traditionally surveyed (desertification nuclei) and newfound LD prone areas. We also highlight the limitation of confirming LD, as to date there is no post-drought data available and, lessons learned from the Sahel case make us cautious about claiming that an area is in fact degraded.

1. Introduction

Desertification is defined by the United Nations Convention to Combat Desertification as *"land degradation in arid, semiarid, and dry subhumid areas resulting from various factors, including climatic variations and human activities"*, within this context, land degradation (LD) is therefore defined as *"the reduction or loss of biological or economic productivity"* (UN, 1994). This interdisciplinarity definition leads the

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https://doi.org/10.1016/j.rse.2018.04.048
Received 13 September 2017; Received in revised form 18 April 2018; Accepted 27 April 2018
0034-4257/

scientific community to take more integrative approaches to address the problem, considering both climate change and sustainable development, as discussed in a review by Reynolds et al. (2007), drawing special attention to drylands, which typically have low fertility and sparse vegetation coverage characterizing a fragile ecosystem. In a comprehensive work of simulations, Huang et al. (2015) argue that enhanced warming, population growth, and higher aridity will likely increase the risk of LD and, to an extreme extent, desertification. Further, the drylands in developing countries are more sensitive to climate change due to anthropogenic pressure and dependence on local natural resources – poverty is likely to increase, therefore feedbacking pressure on drylands leading to soil erosion, and eventually, desertification (Jiang and Hardee, 2011; Reynolds et al., 2011).

All the factors mentioned above are present in the Northeastern region of Brazil (NEB), the most populous dryland region in the world, with more than 53 million inhabitants and a population density of about 34 inhabitants per km^2 (Marengo et al., 2017). It is highly vulnerable to both environmental and anthropogenic LD, as observed (Oyama and Nobre, 2004). More than 10% of the area experienced intense environmental degradation processes, showing the vulnerability of the Caatinga – the local predominant xeromorphic biome – to climate hazards, and more specifically to drought. During the period of 2011–2016, a severe, long-lasting drought has taken place in NEB, drawing the scenario for high degrees of LD (Gutiérrez et al., 2014; Marengo and Bernasconi, 2015). Simulations for climate change scenarios of global warming show that the future of the NEB may be compromised, which draws attention to the LD problem and its apparent irrevocability (Huang et al., 2017; Marengo et al., 2016).

Privette et al. (2002) and Fensholt et al. (2004) validated MODIS Leaf Area Index (LAI) with *in situ* measurements in semiarid regions of Southern Africa Kalahari and the Sahelian zone of Senegal finding strong linear relation with Normalized Difference Vegetation Index (NDVI) and characterizing phenological variability; considering the regions where the studies were carried out, LAI is potentially a good indicator for biomass loss and, therefore, LD assessment. Surface albedo as an indicator of soil exposure is often used to assess LD on arid regions. The study carried out by Oyama and Nobre (2004) relied on integrating albedo and vegetation cover fraction trends to simulate LD effects leading to precipitation reduction. A comprehensive and prominent approach was taken by Pan and Li (2013) on desertification detection by coupling NDVI and albedo information based on Landsat data, in which they could assess degradation and its intensity levels. Samain et al. (2008) thoroughly investigated albedo variability to associate it with degrees of desertification in the Sahel, supporting the fact that increased albedo may affect drought occurrence and leverage LD.

Assessing LD over large areas is an issue commonly addressed by trend analysis of long term biomass-related and environmental remote sensing based data. Vicente-Serrano (2007) analyzed 13 years of high-frequency coarse resolution imagery along with precipitation anomalies to assess drought impacts on vegetation in the Mediterranean semiarid region. They concluded that drought occurrence is the primary driver of interannual vegetation variability based on the aridity of the region. Dubovyk et al. (2013) analyzed time-series of NDVI data to detect negative trends as an indicator of degradation in Uzbekistanian irrigated croplands. Eckert et al. (2015) mapped not only LD but grass regeneration, urban expansion, and other land use changes in Mongolia using trend analysis of MODIS NDVI and precipitation. They were able to detect changes even in small-scale areas, which is an important feature to address in smallholder agriculture that characterizes some of the regions covered in this study. One concern about RS-based time-series analysis to detect LD is the strength that the signal has to have to produce significant negative slope and map these trends; moreover, decoupling vegetation persistent changes from interannual variations due to anomalies in precipitation and anthropogenic activities may require ancillary data (Wessels et al., 2012).

Once biomass changes are decoupled from environmental anomalies (mostly precipitation), human-induced LD can be assessed; nevertheless, it is not easily approachable (Evans and Geerken, 2004). Although no long-term remote sensed data exist to depict human-induced land changes, trend analysis based methods have the potential to provide a general idea of such occurrences. For both cases of drought and human-induced LD, no post-drought data are existent for NEB, considering the year of 2017, which makes the LD confirmation unfeasible, as like in the case of Sahel, which is still drawing controversy related to LD and desertification processes, as reported by Prince et al. (2007). There are recent studies showing a re-greening behavior in parts of Sahel due to both anthropogenic and climatic reasons, which may weaken the claims of desertification (popularly thought as an irreversible phenomenon) (Brandt et al., 2014; Dardel et al., 2014; Herrmann et al., 2005; Tong et al., 2017) . This draws us a limitation to the extent one can assess LD; however, LD prone areas based on trends of albedo, biomass and ecosystem health indicators are still identifiable.

Finally, albedo and LAI also play a significant role in the surface energy balance which in turn, is a key driver of evapotranspiration (ET) on partitioning sensible and latent heat fluxes. Charney et al. (1977) simulated albedo changes over semiarid areas to investigate its effect on ET and precipitation; the authors support a link between albedo, vegetation, ET and precipitation as a partial cause for recurrent drought in semiarid regions, which intensifies the effects of degradation. Li et al. (2016) studied the changing global net primary production (NPP) effects on ET, showing a complementary relationship between NPP and ET in arid regions rather than a proportional relationship in humid areas. A review on desertification described 2 cycles of degradation with losses of vegetation as their starting point (D'Odorico et al., 2013). The first cycle follows increases in albedo and ET; this depends on the regional characteristics of ET contributions to large fractions of total precipitation. The second cycle is simply described by an increase in soil erosion and a reduction in its fertility. In both cases, there are positive feedbacks aggravating vegetation condition, a key trigger for desertification. Nicholson et al. (1998), however, reported that the albedo increase may not be as pronounced as observed by Charney et al. (1977) for the Sahel, because the albedo dynamic is driven by vegetation and precipitation, meaning that loss of biomass not necessarily will lead to higher albedo due to precipitation effects on the surface brightness.

The overarching objective of this study is to develop a solid basis for understanding LD trends in the NEB region for the period spanning from 2002 to 2016. The specific objectives are: (1) to analyze precipitation variation through the study period and highlight drought occurrences, (2) to detect the hotspots of LD prone areas, (3) to detect areas of human-induced degradation, and (4) analyze how LD impacts ET. This study enables us not just to locate hotspots of LD prone areas, but also determine whether human activities are catalyzing these trends and how degradation can potentially contribute to the drought feedback.

2. Spatio-temporal domain

The study area is the NEB, which consists of the states of Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Sergipe (SE), Alagoas (AL), and Bahia (BA). The NEB comprises the most populous semiarid region in the world (Marengo et al., 2016). The predominant biome (52.5% of the NEB) is the Caatinga [from *tupi* language: *ka'a* (forest) + *tinga* (white)], which is characterized by xeromorphic vegetation, mostly small semi-deciduous trees, shrubs, and low profile grass. The vegetation is highly responsive to climate variations and adapted to various degrees of aridity. The remaining biomes are savanna (Cerrado - 29.4%), Atlantic Forest (10.7%), and Amazon (7.4%) (da Silva et al., 2017). Our study focuses on Caatinga and Cerrado biomes. Agriculture in the region is mostly for subsistence consisting mainly of beans, cassava, potatoes and pasture (natural vegetation), with low levels of technology and input.