Journal of Arid Environments xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Arid Environments

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

Desertification and ecosystem services supply: The case of the Arid Chaco of South America

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ARTICLE INFO

Keywords:
Precipitation use efficiency
Precipitation marginal response
RESTRENDS
Ecosystem services provision index
MODIS

ABSTRACT

New integrated perspectives are increasingly needed to bridge the gap between biophysical and ecosystem services' based assessments of desertification. For a vast area of the dry Chaco region we sought to: (1) assess the spatial extent of four syndromes of vegetation change, associated with human or climatic drivers and (2) estimate and compare the supply of ecosystem services among these syndromes. We used a remote sensing approach based on the growing season –October to March- normalized difference vegetation index from MODIS, and climatological datasets from 2003 to 2013 to estimate: i) precipitation use efficiency, ii) precipitation marginal response, iii) the temporal trends of the residuals from the normalized difference vegetation index - annual precipitation linear relationship, and iv) the ecosystem services provision index. We diagnosed vegetation syndromes based on the difference between actual and reference sites' precipitation use efficiency and precipitation marginal response. Negative residuals trends were interpreted as vegetation changes driven by inadequate human management. The ecosystem services provision index assumes that ecosystem services supply varies positively with primary production and a negatively with its seasonal variability. Our results showed that 9.1% of the observed area belonged to the vegetation improvement syndrome - positive Delta precipitation use efficiency and Delta precipitation marginal response - while 3.4% were classified as vegetation cover reduction -negative Delta precipitation use efficiency and Delta precipitation marginal response. In turn, 10.5% and 2% of the study area fell within the increment in herbaceous vegetation -negative Delta precipitation use efficiency and positive Delta precipitation marginal response - and woody encroachment syndromes - positive precipitation use efficiency and negative precipitation marginal response - respectively. Human management did not have a uniform impact as all 4 syndromes displayed positive and negative residuals trends. Contrary to our expectations, there was no apparent association between vegetation syndromes and the supply of ecosystem services as estimated by the ecosystem services provision index. This study serves as a prototype to remotely assess ecosystem properties indicative of different vegetation syndromes and the associated supply of ecosystem services in dryland regions.

1. Introduction

The study of desertification, land degradation in drylands, has been pervaded with debates concerning to its definition and measurements. In part, the ubiquitous lack of consensus in desertification studies is related to its historical context. The occurrence of extensive famines in sub-Saharan Africa during the late 1970s fostered conceptualizations focused mainly on biophysical aspects (Reed and Stringer, 2016). Emphasis was on variables characterizing soil or vegetation condition and change. Assessments were derived from different sources, ranging from informed opinion, field surveys and remote sensing. However, not all changes in the biophysical components have a direct and immediate effect on humans and neither of these can be straightforwardly interpreted as a loss or degradation (Reynolds et al., 2006).

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https://doi.org/10.1016/j.jaridenv.2017.11.001
Received 21 December 2016; Received in revised form 20 October 2017; Accepted 6 November 2017

More recently, desertification has been approached from a different conceptual framework, one that strengthens the link between nature and human welfare (Rock, 2006). Thus this conceptualization of desertification focuses primary on the assessment of ecosystems services, local communities' perception and economic indicators (Reed and Stringer, 2016). However, difficulties involved in the measurement of ecosystem services have limited its use (Kremen, 2005; Norgaard, 2010). Thus, two main definitions coexist: "desertification as land degradation in arid, semiarid and sub humid areas resulting from various factors including climatic variations and human activities" (United Nations, 1994), and "desertification as a persistent reduction in the capacity of ecosystems to supply services … over extended periods of time" (Rock, 2006).

Despite this apparent disconnection, integrated approaches combining biophysical and socioeconomic perspectives are being increasingly used (e.g. Reynolds et al., 2007, 2011; Chapin et al., 2009; Scholes, 2009; Verstraete et al., 2009, Bestelmeyer et al., 2015). These integrated frameworks are essential for local or regional decision making and policy development because they provide tools that help organize ideas, identify key system properties –i.e. slow variables, variables that strongly influence ecosystems but remain relatively constant over years to decades despite interannual variation in weather, grazing, and other factors (Chapin et al., 2009)- at its relevant scale, and anticipate impacts of different policy options. However, combined perspectives have not necessary translated into an improved operational monitoring of desertification at a global scale because the key slow socioeconomic and biophysical variables to monitor are system dependent.

However, recent advances in the quantitative estimation of desertification and ecosystem services suggest a way to bridge the gap between biophysical and ecosystem services' based assessments of desertification. Verón et al. (2006) and Kaptué et al. (2015) schematized 4 frequent vegetation syndromes based on the spatial or temporal comparison of two desertification indicators: the Precipitation Use Efficiency (PUE, Le Houérou, 1984; Prince et al., 1998) and the Precipitation Marginal Response (PMR, Verón et al., 2005). PUE, the ratio between aboveground net primary production (ANPP, the rate of net carbon accumulation by vegetation in above-ground organs) and precipitation (Le Houérou, 1984), provides information on the ability of a system to convert precipitation water into vegetation growth. PMR, the slope of the linear relationship between annual aboveground net primary production and precipitation (Verón et al., 2005), describes the sensitivity of vegetation to interannual changes in precipitation. Thus, the first syndrome identified by these authors is compatible with a reduction in plant cover, which should translate into a decrease in PUE and PMR as more precipitation would be lost to evaporation and runoff. The second syndrome, compatible with an increase in the abundance of herbaceous vegetation, should decrease PUE but increase PMR as forbs and grasses tend to respond faster to annual precipitation as the relative growth rate (growth rate per mass unit) is in general higher for grasses than for shrubs (Lambers et al., 1998). The third syndrome, compatible with woody encroachment, is frequently observed at grazed areas where fire is absent or suppressed and generally translates into a decrease in PMR but not necessary in PUE. We use woody encroachment in opposition to shrub encroachment to differentiate when the expansion of woody vegetation occurs as sites where shrubs are an important component of vegetation communities –as it is in the dry Chaco-than when shrubs are marginal. In Patagonia, Verón and Paruelo (2010) showed that the replacement of grass steppes by shrublands decreased PUE and PMR. Finally, the fourth syndrome is compatible with an increase in vegetation cover and should increase PUE and PMR as the fraction of precipitation lost to drainage, runoff or bare soil evaporation should decrease. Also, increased vegetation cover would allow for larger responses to wet years as potentially more water can be transpired with higher leaf areas.

In addition to the potential utility of PUE and PMR to track functional and structural changes in ecosystems, a methodology to assess desertification would benefit from the attribution of these changes to human or climatic causes. Herrmann and Hutchinson (2005) and Wessels et al. (2012) proposed a methodology based on the residual trends (RESTREND) to discriminate human from climate induced desertification. RESTREND, is calculated from the temporal trend in the residuals of the annual ANPP-PPT linear relationship. Therefore, a negative RESTREND implies that the ANPP not explained by precipitation decreased during the studied period. In general, the causes of this decrease are assumed to be human.

Recently, Paruelo et al. (2016) proposed and tested an integrative indicator of regulating ecosystem services. The ESPI (ecosystem services provision index) relates the supply of regulation ecosystem services related to biodiversity (avian biodiversity), C (soil organic C) and water dynamics (ground water recharge and evapotranspiration) to the mean active photosynthetic radiation absorbed by vegetation and its intra-annual variability. The hypothesis underlying the use of the ESPI is that ecosystem services increase with primary production and decrease with seasonal variability. This hypothesis is based on solid conceptual and empirical evidence that i) primary production determines the energy available for the rest of the trophic levels (excluding autotrophs) (McNaughton et al., 1989), ii) energy availability at ecosystem level determines ecosystem services supply (Richmond et al., 2007), iii) increases in season variability in primary production is tightly linked to land use changes (Paruelo et al., 2001a; Guerschman et al., 2003) and iv) temporal mismatches between resource pulses and resource pulse consumers decreases the overall energy use and ecosystem processes (Schwinning and Sala, 2004). Tested over forests and grasslands regions in the southern South America using field and modelling data on different ecosystems services (groundwater level regulation, soil C sequestration and hydrological yield), Paruelo et al. (2016) concluded that ESPI could be used as an aggregate indicator of the status and/or trends of ecosystem services over large areas.

The Arid Chaco is the driest portion of the Gran Chaco region. It is located on alluvial and aeolian plains on central South America (Fig. 1) and represents the transition zone between dry forest and shrublands. In the Arid Chaco, as in other arid and semiarid regions of the world, the spatial degradation patterns are quite heterogeneous in the region due to the irregular distribution of watering points (Lange, 1969; Blanco et al., 2008). Areas close to water sources lost most of the herbaceous cover –i.e. piospheres-while areas more than 8 km away from watering points show minimum signs of degradation (Blanco et al., 2008). Pickup and Chewings (1994) were the first who defined the term 'grazing gradient' as "spatial patterns in soil or vegetation characteristics resulting from grazing activities and which are symptomatic of land degradation". Domestic animals (sheep, goats, cattle, and horses) prefer to graze in vicinity to a watering point. When food is depleted in this area they move away from the source of water but return regularly for drinking. Consequently, higher number of individuals is frequently concentrated around the watering points. Then, animal density decreases gradually with increasing distance from water (Pickup et al., 1993; Friedel, 1997). Degradation patterns in the Arid Chaco are, then, mainly associated with the distribution of watering points.

Our objectives were twofold. First we assessed the spatial extent of desertification in the dry Chaco region by means of the spatial changes in PUE, PMR and RESTRENDS and identified vegetation syndromes. Second we estimated the supply of ecosystem services using the ESPI and compared it among vegetation syndromes. We focused on the dry Chaco region, an area that presents a broad gradient of both precipitation and degradation in a relatively flat landscape that minimize water redistribution. To address our objectives we used freely available remote sensing time series, global climatological datasets and local knowledge.