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A remote sensing protocol for identifying rangelands with degraded productive capacity

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ABSTRACT

Rangeland degradation is a growing problem throughout the world. An assessment process for comparing the trend and state of vegetation productivity to objectively derived reference conditions was developed. Vegetation productivity was estimated from 2000 to 2012 using annual maximum Normalized Difference Vegetation Index (NDVI) from the MODIS satellite platform. Each pixel was compared with reference conditions derived from surrounding pixels on similar sites with nearly identical potential species assemblages, vegetation structure and productivity. Trends in degradation were determined by comparison between the slopes of the linear trends in mean annual maximum NDVI at each pixel and reference conditions with a one-sample *t*-test. In contrast, the state or "status" of degradation at each pixel was evaluated by comparing the mean annual response of NDVI between 2000 and 2012 to that of reference conditions over the same time period using a one-sample *t*-test. These procedures to evaluate trends and status of rangelands were applied across northern and southern Great Plains of the United States. Trends in degradation were almost undetectable across the entire study area. In contrast the degradation status assessment revealed that 16% (7,330,625 ha) of the vegetation on the northern Great Plains and 9% (3,295,106 ha) of the southern Great Plains were significantly different ($p \leq 0.01$) from reference conditions. The amount of annual net primary reduction lost resulting from these degraded lands relative to reference conditions was estimated at 2.02 Tg C yr^{-1}, less than 1% of the total annual net primary production in the study area of 212 Tg C yr^{-1}.

1. Introduction

Rangelands are the most extensive kind of land cover, occupying nearly 33% of ice-free land globally (Ellis and Ramankutty, 2008) and supporting tens of millions of people (Papanastasis, 2009). These arid regions are characterized by relatively low productivity with a high proportion of bare ground, and therefore account for less than 15% of terrestrial net primary production (NPP) (Ellis and Ramankutty, 2008). Despite the relatively low productivity, a large suite of ecosystem goods and services derived from rangelands are becoming increasingly recognized especially as both tangible and intangible societal benefits are considered (Havstad et al., 2007). Rangelands, however, are relatively fragile ecosystems due to factors including aridity, thin soils and low productivity per unit area. The fragility of rangelands means that sustainability of NPP is relatively easy to compromise and therefore reduction of productive capacity threatens the maintenance of societal benefits. Indeed, land degradation is a growing environmental problem and is particularly severe in semi-arid landscapes (Middleton and Thomas, 1997).

Land degradation is an ambiguous term with multiple definitions usually relating to changes in vegetation and soil (Washington-Allen et al., 2006). The United Nations Convention to Combat Desertification (UNCCD) defines degradation as, "reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns..." and the changes are usually considered permanent (Abel and Blaikie, 1989). This definition suggests that degradation describes permanent changes in the capability of lands to support human activities (Abel and Blaikie, 1989), which is differentiated from short-term, reversible changes induced by climatic influences. While some forms of environmental changes can theoretically be reversed when sufficient restorative actions are applied, fiscal or social constraints may render the change permanent from a practical perspective (Reed et al., 2006, 2011).

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The majority of research aimed at characterizing degradation has been global or international in nature and often focuses on sub-Saharan Africa (Dean and MacDonald, 1994; Dougill et al., 1999; Eswaran et al., 2001; Lane, 1998). For example, the Land Degradation Assessment in Drylands (LADA) project develops tools and methods for evaluating the extent and magnitude of degradation in six countries and has moved toward developing replicable and codified procedures for degradation assessments. In a similar manner, the Desertification Mitigation and Remediation of Land (DESIRE) project http://www.desire-project.eu (accessed 23.07.13) was incepted to combat the pervasive and increasing extent of global degradation using contemporary conservation strategies.

Despite these efforts, much is still unknown about the extent and magnitude of rangeland degradation (Lund, 2007), partly because a variety of techniques are used to determine the scope of degradation. Whereas some techniques focus primarily on evaluating the reduction of productivity relative to the site potential, other programs view land degradation as, "a decrease in the capacity of the environment as managed to meet its user demands" (Kasperson et al., 1995), suggesting the extent and severity of land degradation will vary between different management goals (Reed et al., 2011). These differing paradigms make consistent assessment difficult and those considering social and economic components are usually required to engage local communities (Fraser et al., 2006; Reed et al., 2006, 2011) to collect data which is costly. The burdensome cost of field data collection and the need for a consistent methodology for quantifying the extent and magnitude of reductions in productive capacity suggest that a remote sensing approach is a reasonable solution.

Remote sensing systems have been used to quantify degradation but their application has been limited by three principle factors; availability of reliable ground-truth data (Tongway and Hindley, 2004), the high variability in precipitation that can mask land degradation (Wessels et al., 2007), and a lack of appropriate reference conditions that represent lands not degraded for comparison. A variety of methods have been developed to address these issues including the commonly employed Residual Trend Analysis (RESTREND) technique generally applied to remotely sensed estimates of primary production (Wessels et al., 2007, 2012). Another technique for evaluating degradation is local NPP scaling (Wessels et al., 2008; Prince et al., 2009). Other techniques involve remote sensing and climatological information, such as rainfall use efficiency, which is a measure of NPP per unit of precipitation and has been used for comparing the relative productive capacity of similar sites.

Bai et al. (2008) produced a global assessment of degradation using Normalized Difference Vegetation Index (NDVI) as a measure of production combined with annual rainfall to analyze areas with significantly reduced rainfall use efficiency. For a global analysis, this method of identifying degraded lands may be suitable where other types of data may be lacking. Patterns of degradation, however, often occur at much finer spatial resolutions than most gridded precipitation data, making the applicability (but not necessarily the theory) of the rainfall use efficiency approach less useful in some areas. In addition, many previous studies have relied upon field identification of degraded areas a priori. In many cases, it is difficult and costly to conduct field reconnaissance, especially in regions dominated by private land holdings where collecting data may be prohibited.

In recognition of these issues, the present work develops a process for detecting lands with statistically significant reductions in productive capacity (estimated with NDVI) compared with similar sites in close proximity. The process developed here focuses solely on the ecological components of degradation and does not address social or economic attributes. Therefore, this assessment falls short of a degradation assessment as defined by organizations such as the United Nations Environmental Program (UNEP). The process presented here does, however, objectively evaluate trends in degradation and indicate where the mean NDVI response is significantly different from reference conditions.

Development and application of the process for identifying lands exhibiting significantly reduced productive capacity was conducted with two objectives. The first was to develop an objective evaluation of productive capacity, relative to reference conditions, that avoids the subjective process of classifying land degradation in terms of management objectives. This was accomplished by analyzing statistical differences between both the trend and mean response (status), from 2000 to 2012, of NDVI from rangelands compared with reference conditions. The second objective was to test the protocol on the northern and southern Great Plains regions of the coterminous U.S.

2. Methods

2.1. Test area description

The northern and southern Great Plains were chosen as test area given their diversity of land ownership and unique history. Beginning in 1862, a series of Acts were passed which effectively encouraged expansion of settlement from the Eastern to the western U.S. Collectively, these Acts led to a 6-fold increase in cattle production resulting in roughly 27 million head by 1890 (Poling, 1991), while sheep numbers increased 20-fold peaking at 20 million head in 1890 (Stoddart and Smith, 1943). Most of these lands were largely unclaimed which fostered unrestricted use, leading to serious degradation of rangeland resources (Carpenter, 1981). Although this does not suggest that past management of lands from more than 100 years prior drives present landscape patterns, it is assumed that past management will influence the productive capacity of a site.

The northern and southern Great Plains, found in the central U.S., occupy 75 and 60 million ha respectively and are broad, relatively flat, regions whose natural vegetation is composed primarily of mixed and shortgrass prairie (Fig. 1). The study area contains about 96% non-federal ownership and, as a result, many different land management regimes are present. Annual precipitation across the entire region ranges from an estimated 223 to 1109 mm and generally increases from west to east (Fig. 1). Average NPP from 2000 to 2012 tends to follow a similar pattern (Fig. 1) and ranges from an estimated average of 32 to 815 g C m^2 yr^{-1}.

2.2. Landscape stratification

Stratification of rangelands across the study area was performed to identify similar sites exhibiting comparable climatic and vegetation production characteristics. Three datasets were needed to develop a rangeland stratification for reference conditions including the Biophysical Settings (BPS) from the Landfire Project (Rollins, 2009), Ecological Subsections (Bailey and Hogg, 1986), and rangeland extent from Reeves and Mitchell (2011) (Fig. 2). Biophysical Settings are delineated based on biotic and abiotic factors such as slope, aspect, elevation, soils, NPP, microclimate, and species composition. Ecological Subsections are derived from a hierarchical classification of ecological regions distinguished by factors such as macroclimate, ecological processes, physiognomy, and prominent landscape features. The Ecological Subsections chosen for this study reside within the northern and southern Great Plains (Fig. 2). These three datasets were spatially intersected rendering 5723 unique strata. Each time a BPS occurred in a different Ecological Subsection, it was considered to be a unique site and accounted for different climatic regimes from 2000 to 2012. This approach allowed