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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}.

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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

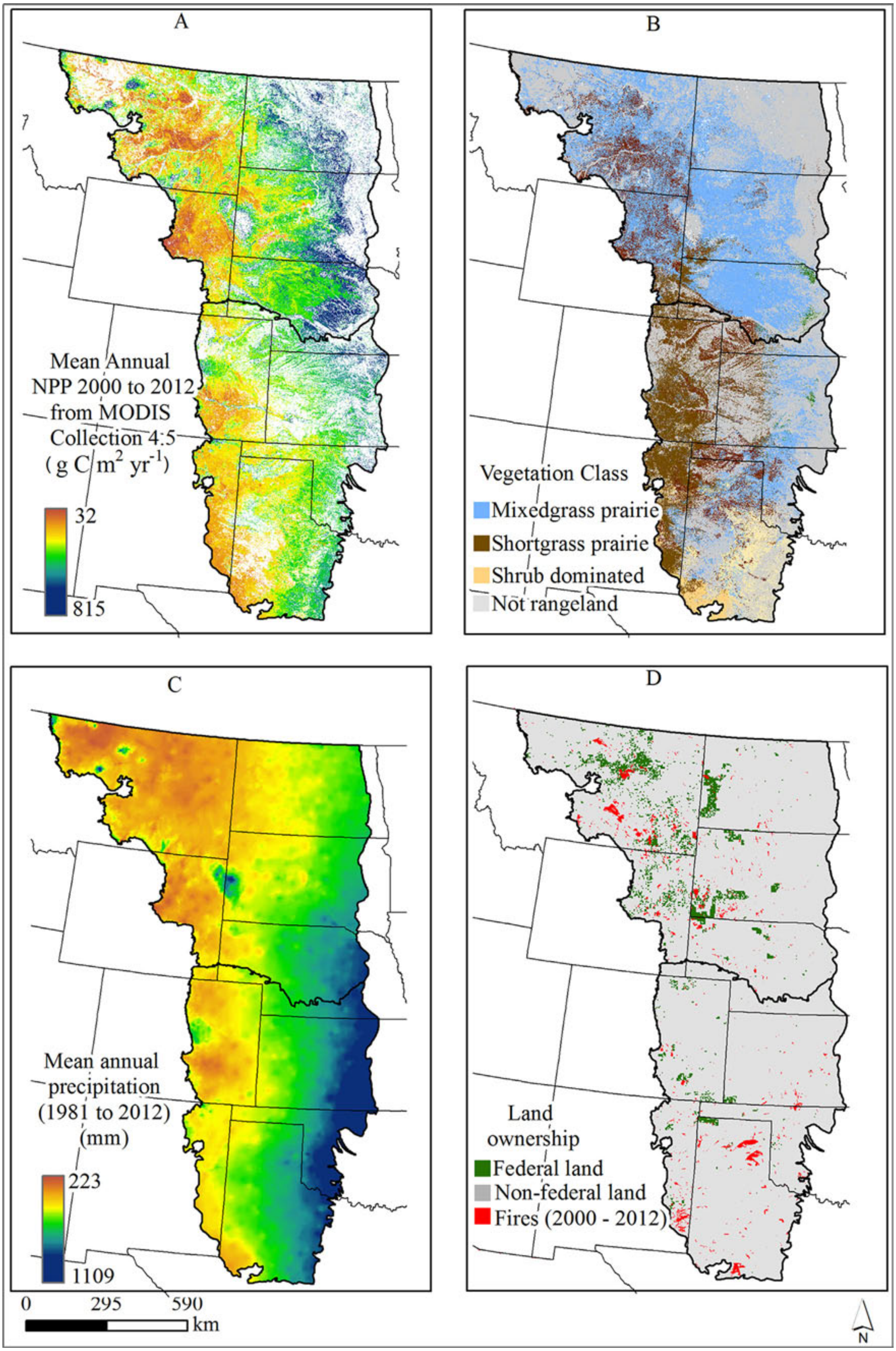

Fig. 1. Panels A and B represent mean annual net primary production (NPP) and existing vegetation type (or class) for the northern and southern Great Plains respectively. Net primary production data come from the MODIS Collection 4.5 NPP data product (Running et al., 2004) from 2000 to 2012. The vegetation types were adapted from the LANDFIRE Existing Vegetation Type (EVT product) (Rollins, 2009). Panels C and D represent mean annual precipitation derived from PRISM data averaged from 1981 to 2012 (Daly et al., 2001) and private land ownership from the Protected Areas Database of the United States (PAD-US) (The Conservation Biology Institute, 2010). Panel D also depicts the estimated fire perimeters from 2000 to 2012.

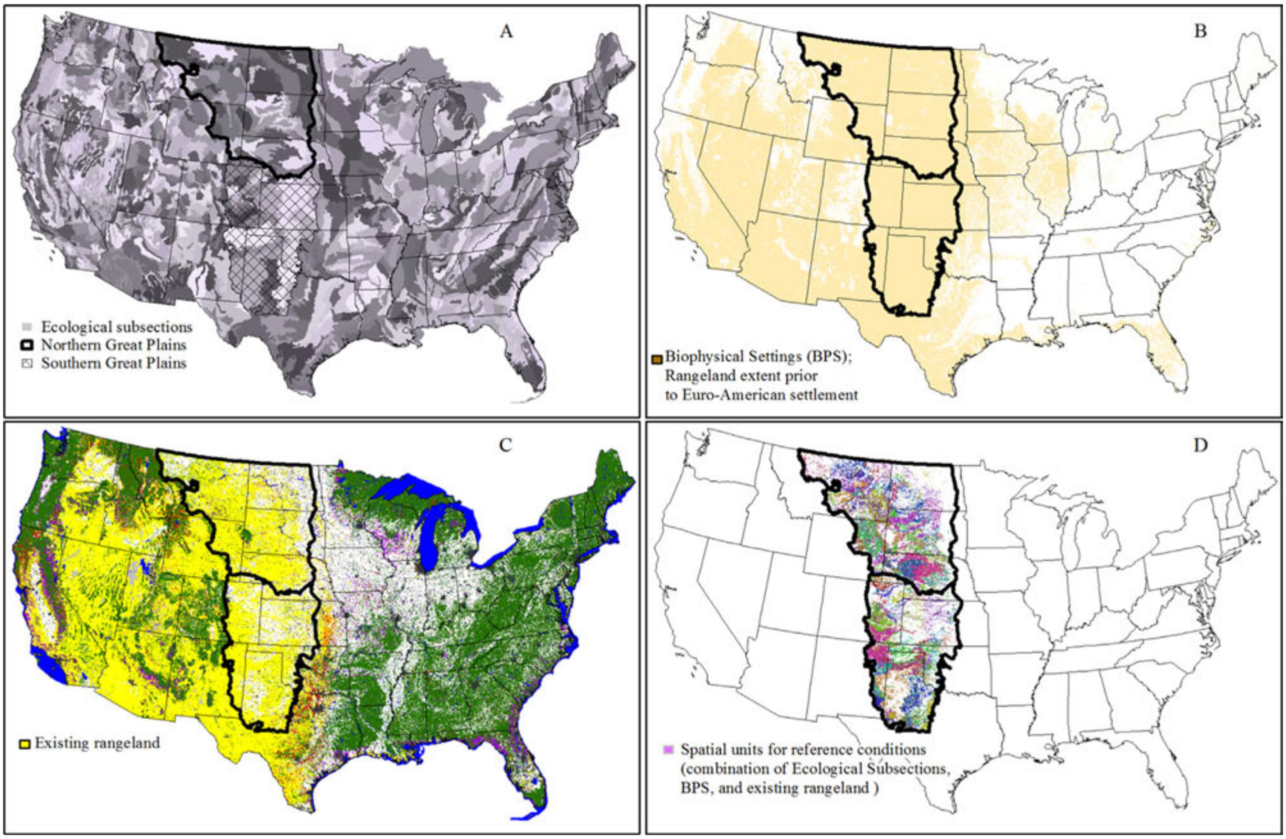

Fig. 2. (A) Ecological Subsections (Bailey and Hogg, 1986), (B) Biophysical Settings (Rollins, 2009), (C) Existing Rangelands (Reeves and Mitchell, 2011) of the coterminous U.S. and (D) Intersection of these data resulting in 5723 unique strata for developing reference conditions enabling analysis of extent and magnitude of degraded productive capacity.

comparison of sites with nearly identical biophysical and climatic conditions against one another but not similar sites existing in different climatic regimes. Comparison of similar sites capable of producing nearly identical species composition, structure and production of vegetation reduced the chance of falsely detecting degradation (Washington-Allen et al., 2006). The resulting strata are somewhat similar in concept to land capability units (LCUs) used in Prince et al. (2009) or Wessels et al. (2007).

2.3. Processing MODIS data

Normalized Difference Vegetation Index data at 250 m spatial resolution (Mod13Q1.005) were obtained in 15 MODIS tiles of the HDF-EOS format for the years between 2000 and 2012 as an indicator of above-ground primary productivity (Hicke et al., 2002; Bai et al., 2008; Wessels et al., 2008; Gu et al., 2012). These data were subsequently mosaicked into seamless images covering the coterminous U.S. In addition to the NDVI data, a quality assurance layer (the pixel reliability summary) associated with each bi-weekly NDVI period was mosaicked in a similar manner as with NDVI. For each year of MODIS data collection there were 23 periods which were filtered using the pixel reliability summary such that only the best quality (quality flag of 0 or 1) pixels were retained for further analysis. From these MODIS data, a maximum NDVI value was chosen from the 23 periods (maximum value compositing) and served as an indicator of vegetation production (Bai et al., 2008; Gu et al., 2012).

Following the maximum value compositing routine, an analysis mask representing the current distribution of coterminous U.S. rangelands (Fig. 2, panel C) was used to spatially subset the quality screened NDVI data. The analysis mask was developed by converting the distribution of coterminous U.S. rangelands (Reeves and Mitchell, 2011) from 30 m to 250 m to match the resolution of the MODIS NDVI. To be considered a "rangeland" pixel, the 250 m area had to be covered by at least 70% of 30 m pixels (tantamount to 49 pixels representing about 4.375 ha). Application of the analysis mask to spatially subset the NDVI reduced contamination from pixels dominated by non-rangeland vegetation.

2.4. Reference conditions and statistical analysis

Reference conditions were needed for evaluating the status, computed as the mean annual maximum NDVI, from 2000 to 2012 at a pixel. In addition, reference conditions were needed for evaluating the trend of maximum value composite NDVI from 2000 to 2012. All areas within estimated fire perimeters (Fig. 1, panel D) were removed from the calculation of reference conditions and from the degraded land area estimates.

Evaluating the status of each pixel was accomplished in an iterative manner. For each iteration, all pixels, except the target (Fig. 3, panel C) belonging to a particular BPS in the same Ecological Subsection (Bailey and Hogg, 1986) (Fig. 3, panels A and B), were pooled and the mean annual maximum NDVI response from 2000 to 2012 was computed. To demonstrate, consider a BPS in an Ecological Subsection occupying 62,500 ha (10,000 pixels). When analyzing the first pixel in this group, the mean maximum NDVI response between 2000 and 2012 was computed on 9999 pixels because the subject pixel was withheld. This method of holding out each pixel was iterated across all 10,000 pixels. This evaluation of the mean response of all pixels in the stratum, where the target pixel was iteratively withheld, formed the reference conditions (Fig. 3, point E) to compare with the target pixel (Fig. 3, point F). The

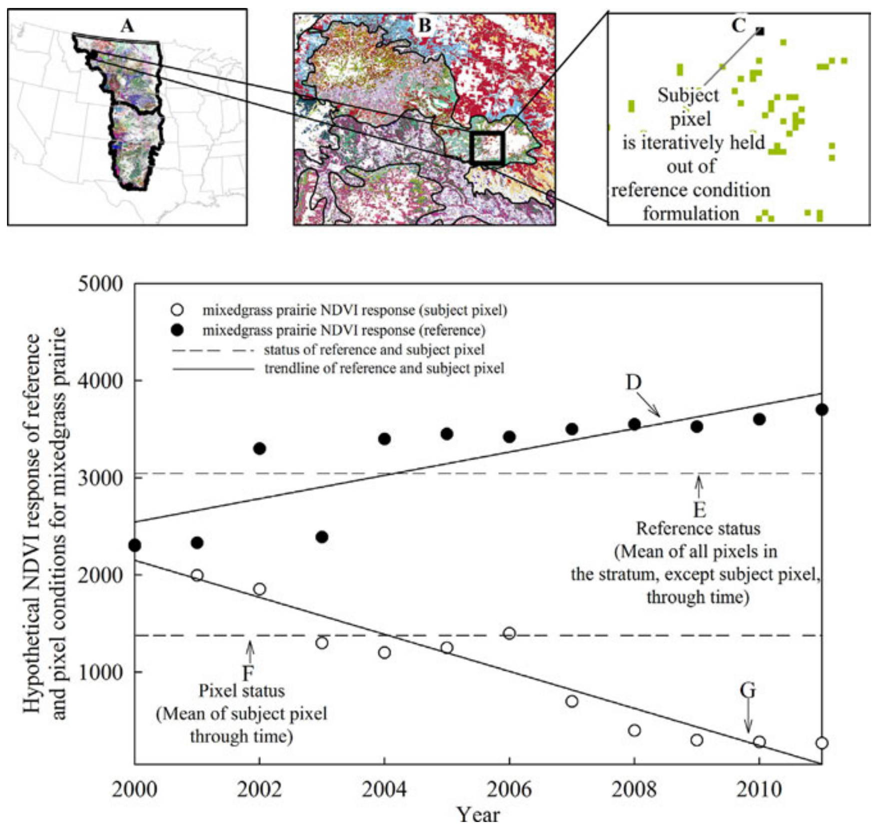

Fig. 3. Panel A represents configuration of strata across the extent of the study area. Panel B depicts strata configuration around one of the Ecological Subsections in the study area while panel C demonstrates how a particular site within an Ecological Subsections forms a single strata (in this case mixedgrass prairie). The graph representing points D, E, F and G refer to the stratum pixels represented in panel C. Point D represents the trend of the reference pixels (all pixels in panel C except the subject pixel). Point E represents the status of reference pixels (mean of all pixels from 2000 to 2012 withholding the subject pixel). Point F represents the status of the subject pixel (mean of the subject pixel from 2000 to 2012). Point G represents the trend of the subject pixel (mean of all pixels from 2000 to 2012 withholding the subject pixel).

response of each pixel was compared to the appropriate reference conditions using a one-sample *t*-test. At this stage, temporal autocorrelation was a concern since the vegetation response of a pixel can influence the following years. Thus, standard error bias induced by temporal autocorrelation was addressed by including a first order autoregressive (AR(1)) term in the error variance–covariance structure of the mean tests. Analysis of the status or mean response was necessary because many sites (represented as pixels) were degraded prior to the year 2000 (first year in the time series).

The trend analysis used a similar process to derive trend reference conditions. For each pixel, the population estimate of slope was computed from a simple linear regression of annual maximum NDVI on year using NDVI from the aggregate neighborhood, but excluding the target pixel (Fig. 3, panel C and point D). The target pixels' slope was then derived using a simple linear regression of NDVI (Fig. 3, point G) on year and compared to the corresponding population parameter of slope from the appropriate stratum using a one-sample *t*-test. As with the status assessment, standard error bias induced by temporal autocorrelation in the trend analysis was addressed by including a first order autoregressive term in the error variance–covariance structure of the linear regressions. This process was repeated for each pixel until all pixels in the strata were evaluated. The corresponding p-values were adjusted for multiplicity using the modified false discovery rate method described in Ventura et al. (2004). This technique was also needed because spatial autocorrelation is often encountered when comparing two near or adjacent pixels. This modified false discovery rate method protects against false rejections of the null hypothesis that may be induced by spatial auto-correlation. The *p*-values assess the difference between the pixel being compared and the associated population of pixels or reference conditions. This is true for both the status (mean) and trend (slope) comparisons. All analyses for both the trend and status evaluation were completed using R package nlme (Pinheiro et al., 2013) and function fdr.R available at http://www.stat.berkeley.edu/~paciorek/code/fdr/fdr.R (accessed 23.07.13). Results for the trend and status of degradation were reported for three significance values including $\alpha \leq 0.01$, 0.001, and 0.0001. Pixels exhibiting a negative *t* score and p-value ≤ 0.01 were considered in degraded status, relative to reference conditions, since the NDVI was significantly different from identical sites in neighboring areas.

The correlation between NDVI and precipitation from 2000 to 2012 was also explored for the study area. The precipitation data from 2000 to 2012 used for relating with NDVI from the same time period were derived from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) project (Daly et al., 2001).

2.5. Efficacy assessment

Although a true accuracy assessment of degradation is not practically possible, testing the utility of the process for detecting areas that are obviously impaired in terms of their annual production compared to similar sites is possible. Evaluation of the usefulness or efficacy of the process developed here was accomplished by randomly locating 500 points and visually determining the general vegetation conditions using color composite aerial imagery from the National Aerial Imaging Program (NAIP) at 1 m spatial resolution (http://www.fsa.usda.gov/Internet/FSA_File/naip_2009_info_final.pdf) (accessed 23.07.13). Three categories were used to determine the overall

Table 1
Estimated extent of status and trends of degradation for the study area across three significance levels.

Significance level	Northern Great Plains			Southern Great Plains		
	Status (ha)	Trend (ha)	Proportional area (%)	Status (ha)	Trend (ha)	Proportional area (%)
0.01	7,330,625	300	16.1	3,295,106	53	9.1
0.001	4,210,050	0	9.2	1,753,681	0	4.8
0.0001	2,346,056	0	5.1	966,450	0	2.6

utility of the process for identifying lands in degraded condition. These categories included (a) site is obviously less productive than surrounding, like-kind vegetation, (b) site is not obviously different from surrounding, like-kind vegetation and (c) vegetation conditions undeterminable due to clouds, shadows, or unclear imagery.

2.6. Estimating lost productivity

Quantifying vegetation productivity lost due to degraded lands was accomplished by deriving an approximation of NPP, hereafter referred to as approximated NPP, and subsequently quantifying the difference between non-degraded sites and degraded sites within each stratum. The process was achieved in five steps and occurred after the degraded pixels had been identified. First, an analysis mask was made by selecting pixels that were identified as degraded during both the trend and status analyses. These pixels were then overlain with the 5723 landscape strata. Second, the mean annual maximum of MODIS 250 m NDVI was quantified for non-degraded pixels from 2000 to 2012 across each of the 5723 landscape strata. Third, spatially explicit estimates (spatial resolution of 1 km) of annual NPP derived from the MODIS sensor (Running et al., 2004) were obtained and spatially subset to include only rangeland pixels. The spatial subsetting of MODIS-derived NPP was accomplished by aggregating the 250 m analysis mask described above to 1 km. The aggregation process consisted of computing the number of 250 m pixels within the 1 km domain. To be retained during the subsetting process, a 1 km NPP pixel had to be covered by at least 11 of the 250 m rangeland pixels (tantamount to 70% coverage or 70 ha). Fourth, the relationship between mean annual NPP and mean annual maximum NDVI was established using linear regression. Different equations were developed for the northern and southern Great Plains and approximated NPP was developed at a spatial resolution of 250 m using these equations. Finally, annual average approximated NPP lost from degradation was quantified by computing the difference between degraded pixels and on non-degraded pixels at each stratum. Since each stratum represents identical sites, this technique is similar to comparing expected NPP to observed NPP used in previous works such as Prince et al. (2009).

3. Results

3.1. Regional vegetation patterns

Vegetation trends observed using the NDVI record between 2000 and 2012 varied considerably between the northern and southern Great Plains (Fig. 4). From a broad perspective, vegetation production on the northern Great Plains increased over the time period examined while the southern Great Plains exhibited slightly decreasing production. The northern Great Plains, however, exhibited a greater correlation (r^2 = 0.79) than the southern Great Plains (r^2 = 0.51). Some areas within the northern and southern Great Plains revealed approximated NPP patterns that were markedly different from their respective regional averages (Fig. 4).

3.2. Status and trends of degradation

During the trend analysis, 353 ha exhibited significantly decreased ($\alpha \leq 0.01$) NDVI response from 2000 to 2012 across the study area (Table 1). Determination of the status of degradation did not require a trend analysis but did result in a *t*-test which compared the 12 year pixel mean annual maximum NDVI response with the 12 year response of the stratum to which a given pixel belongs (Fig. 5, panels B and D). An analysis of extent and magnitude of degradation from the status assessment across the study areas was conducted using varying significance thresholds of $\alpha \leq 0.01$, 0.001 and 0.0001 (Table 1). Both the southern and northern Great Plains exhibited degraded areas. An estimated 7,330,625 ha (approximately 16%) of the northern Great Plains exhibited significantly ($\alpha = 0.01$) lower NDVI response compared with only 3,295,106 (approximately 9%) on the southern Great Plains ($\alpha = 0.01$) (Table 1). The degraded area estimates depend on the significance level chosen for analysis (Table 1) so it is inappropriate to report a single estimate of lands with reduced capacity.

3.3. Efficacy assessment

The results of the 500 point comparison are shown in Table 2. Using this rudimentary assessment, 82% of the degraded areas appeared visibly different and less productive than similar vegetation in close proximity. At 20 of these visual comparison plots, vegetation conditions could not be visually determined. During the assessment of 500 points, three general categories of land use usually appeared to be responsible for reducing productive capacity including oil and gas development, livestock (usually sacrifice areas; e.g. areas of water), and colonies developed by burrowing rodents of the genus *Cynomys* (prairie dog).

3.4. Estimating lost productivity

The relationships between MODIS 250 m NDVI and MODIS-derived NPP were estimated for both the northern and southern

Table 2
Results of visual analysis comparing areas estimated to be degraded with 1 m aerial imagery. This table forms the basis for an efficacy assessment.

Classification totals		Reference totals			
		1	2	3	Total
Site is obviously less productive than surrounding, like-kind vegetation	1	381	6	12	399
Site is not obviously different from surrounding, like-kind vegetation	2	53	28	8	89
Vegetation conditions not determined	3	12	0	0	12
Total		446	34	20	500

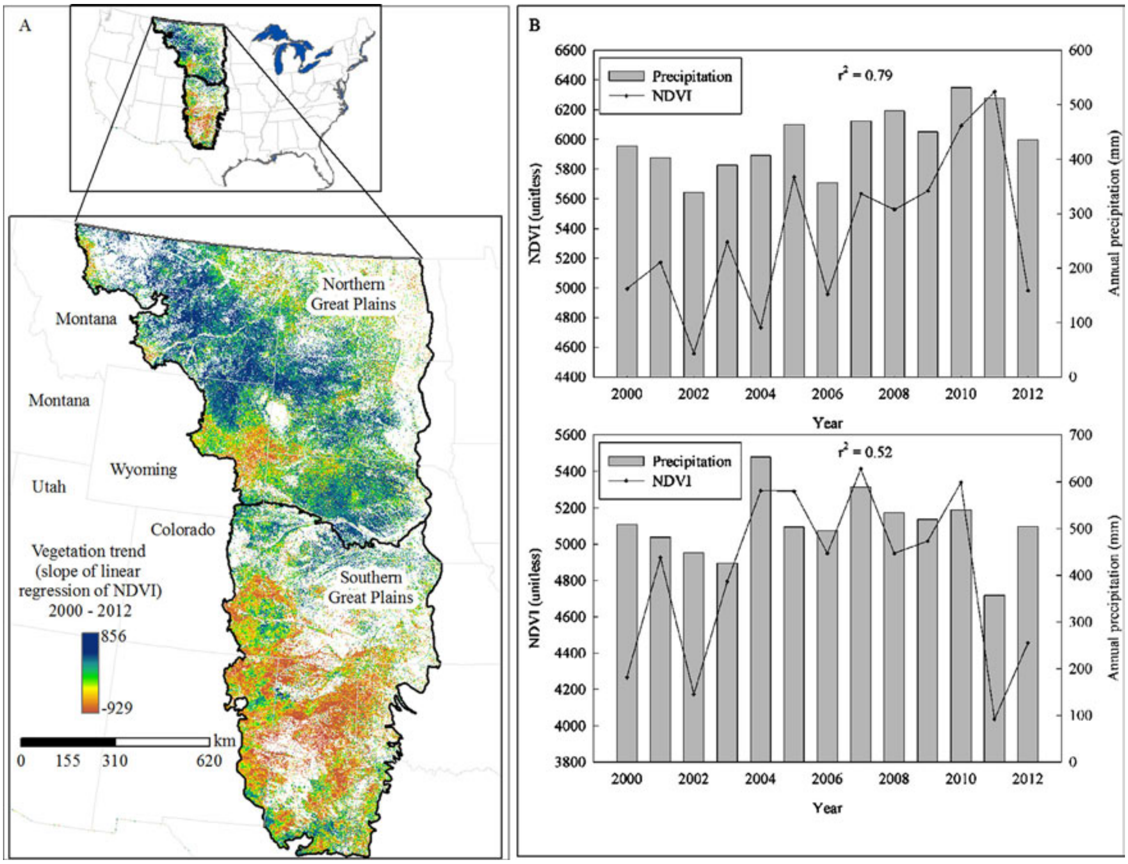

Fig. 4. Panel A is the spatially explicit NDVI response (slope of linear regression) in the study area from 2000 to 2012 and panel B shows the temporal trajectory of the NDVI response in relation to the annual precipitation for the study area.

Table 3
Linear regression between mean annual maximum NDVI and mean annual NPP from 2000 to 2012 shown with r^2, standard error of regression (SE), bias and mean absolute error (MAE). SE, bias and MAE are shown in units of kg C m^2 yr^{-1}. $NDVI_{annmax}$ is the annual maximum NDVI value. Both NDVI and NPP data were averaged across each of the 5723 strata. NPP_{approx}. is approximated NPP.

	Northern Great Plains	Southern Great Plains
Linear regression	$NPP_{approx.}$ = 0.072 ($NDVI_{annmax}$) − 82.09	$NPP_{approx.}$ = 0.049 ($NDVI_{annmax}$) − 0.38
r^2	0.82	0.61
SE	0.03	0.04
Bias	−0.23	−3.7
MAE	31	37

Great Plains (Table 3). The evaluation of how much approximated NPP was lost or reduced due to degradation was only performed on the degraded lands identified during the status assessment since the trend analysis revealed very little degradation. Loss of approximated NPP due to degradation of rangelands for the study area was estimated as 0.62, 1.21, and 2.02 Tg C yr^{-1} corresponding to p-values ≤ 0.0001, 0.001, and 0.01 respectively. These values represent the difference between approximated NPP of degraded sites relative to the reference areas they belong to. While these losses are significant, they represent less than 1% of the total annual average approximated NPP of non-degraded rangelands in the study area, which was estimated at 212 Tg C yr^{-1} from 2000 to 2012. The average reduction in approximated NPP for degraded pixels relative to the reference areas was estimated as 33, 29 and 25% corresponding to p-values ≤ 0.0001, 0.001, and 0.01 respectively.

4. Discussion

4.1. Trends of degradation

The small amount of degraded area revealed during the trend analysis was surprising, even though a much greater proportion of rangeland degradation related to the status assessment was expected, based on the assumption that past land management influences observed site productivity. There were, undeniably, many areas experiencing declining trends in NDVI response relative to reference conditions and, although not statistically significant, these areas may be compromised in terms of productive capacity (Fig. 5).

Visual inspection of NAIP imagery indicated that areas with significantly decreased trends in productivity generally coincided with extreme changes in land use such as oil and gas exploration. Given the recent increase in oil and gas production in the western U.S. (Behrens and Glover, 2011), however, a greater amount of area experiencing declining trends in vegetation productivity was expected but that supposition was apparently incorrect. This does not indicate that oil and gas development do not have an impact on the landscape, but it does suggest that, relative to the 250 m (6.25 ha) pixel size of MODIS NDVI, the footprint of oil and gas infrastructure is relatively small. The surprising lack of detection of more significant degradation trends from 2000 to 2012 could be due to at least five reasons:

- There were few significant trends to detect.
- If degradation has been occurring since 2000, it manifests in focused areas with small areal coverage (subpixel resolution ≤6.25 ha or 250 m). Field reconnaissance could help but would

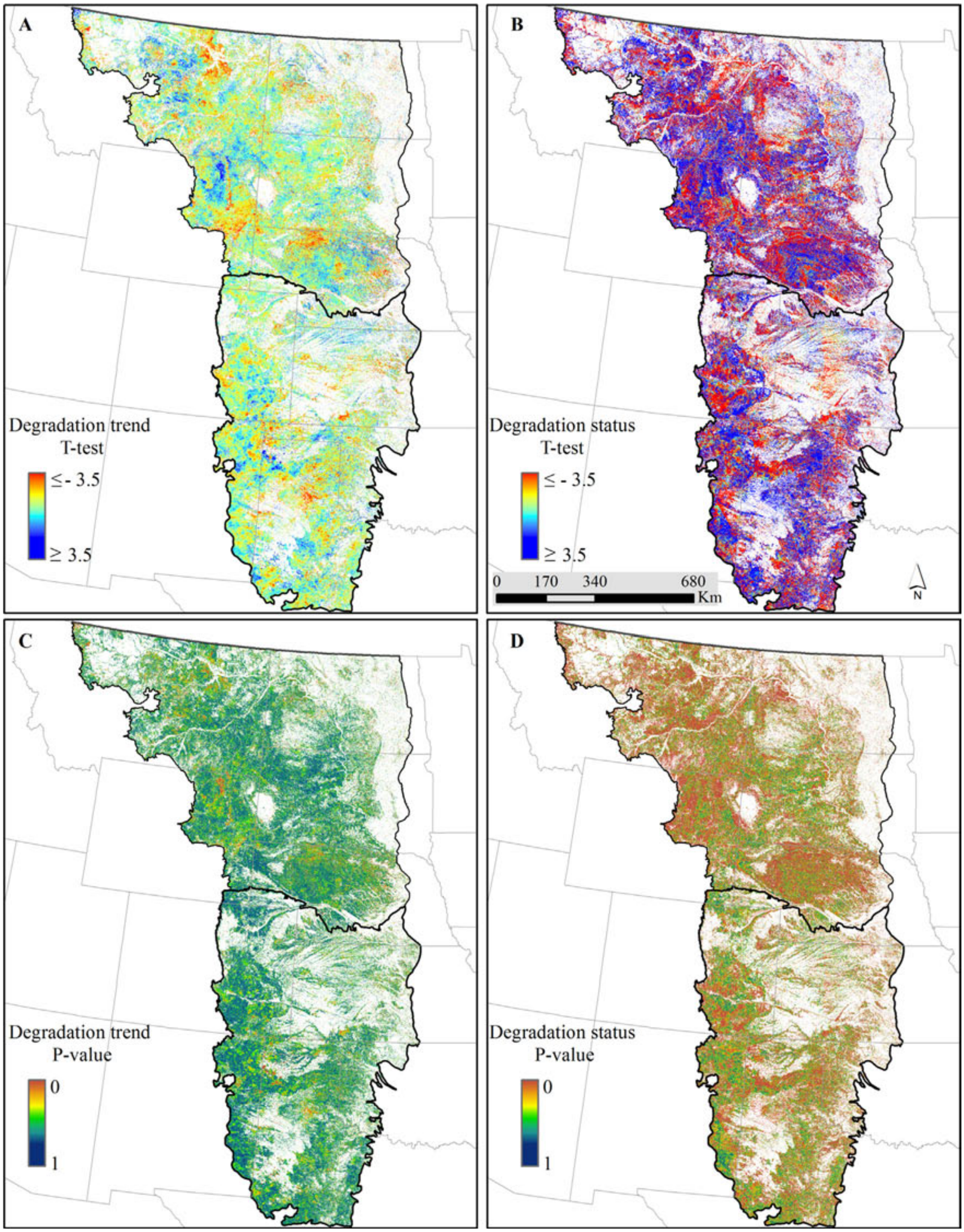

Fig. 5. Panels A and C represent the *t*-test and associated *p*-values between the slopes of each pixel and reference conditions. This process represents an analysis of the trends in degradation. Panels B and D represent the *t*-test and associated *p*-values between the mean responses of each pixel and reference conditions. This process represents an analysis of the status of productive capacity.

require repeated monitoring to determine if land degradation began since or prior to the year 2000.

- The land cover classification used to identify rangeland vegetation is generally incorrect.
- The reference conditions are inappropriate.
- The magnitude of degradation is not significant enough or the time period for evaluating degradation is too short.

Many concerns regarding land degradation in the U.S. are site specific and often relate to intensive use by livestock in riparian areas (Bear et al., 2012; Dalldorf et al., 2013; Lucas et al., 2004) or off-highway vehicle use (Lovich and Bainbridge, 1999). This sort of site specific degradation resulting from intensive use should be differentiated from extensive (i.e. degradation occurring over large areas) use resulting in widespread degradation. Degradation in riparian areas is a concern throughout the study area, but different methodology is needed to detect degradation at these smaller scales. Overstocking (or overuse) of livestock in riparian areas contributes to degradation (Bear et al., 2012; Dalldorf et al., 2013; Lucas et al., 2004) because forage utilization is strongly associated with water availability (Ganskopp, 2001; Holechek et al., 1989). Heavier utilization generally occurs in proximity to water (Pinchak et al., 1991; DelCurto et al., 2005), which effectively incases stocking rate in these areas. Riparian areas of the western U.S. occupy less than 1% of the rangeland area but can occur for long linear distances (Braun, 1986). When scaling the rangeland extent from Reeves and Mitchell (2011) (30 m) to the resolution of MODIS 250 m NDVI, most of the riparian areas were filtered out due to their small areal coverage relative to the MODIS pixel. Therefore, most riparian areas were not evaluated. To address this problem, other schemes have been enabled which rely on higher resolution data for evaluating temporal trends in spectral trends to determine degradation for smaller areas more appropriate to evaluating riparian areas. For example, Maynard et al. (2007) used tasseled cap transforms from ETM+ data to identify anomalous spectral responses at a series of ecological sites as a proxy for determining degradation in the state of Montana. In a similar fashion, Washington-Allen et al. (2006) suggested development of ecological indicators related to the Soil Adjusted Vegetation Index from Landsat satellite data and analyzing the indicators through time compared to benchmark conditions. It is conceivable that higher spatial resolution imagery might offer improvements for degradation assessment but spatial and temporal coverage would be more limited.

Another factor, which may limit the ability of the assessment developed here to identify significant trends in degradation, may also be an artifact of the reference conditions developed to compare a given pixel to. The reference conditions were based on the BPS data product (Rollins, 2009) and Ecological Subsections (Bailey and Hogg, 1986). If a BPS pixel was mischaracterized as a shortgrass prairie, when, in fact, it is a wooded draw supporting a greater amount of annual production, the shortgrass prairie pixels might appear degraded due to lower production relative to the misclassified woody draw. Conversely, if relatively unproductive sites, such as those found on sandy or sodic soils, are incorrectly classified as productive tallgrass prairie sites, then the estimated overall vegetation response for the tallgrass prairie type will be reduced. This situation would make it more difficult to detect significant decreasing trends in vegetation productivity through time. Furthermore, the patch size over which reference conditions are developed will influence results to some degree. For the reference conditions developed here, the distribution of patch sizes was highly variable and skewed with a median size of 4 ha but a mean of 155 ± 1185 ha (standard deviation). In a similar manner, more trends might have been detected if the rainfall use efficiency degradation approach (Bai et al., 2008) was used. The pixel size of most gridded precipitation data, however, is much larger than the 250 m which would produce some false analyses. The final reason why very few significant trends in degradation were detected could be due to the relatively small differences of degraded areas relative to similar sites. The average production of degraded areas relative to their reference conditions were only 25, 29 and 33% depending on significance level chosen. These are, on average, below the threshold of 30–40% which Wessels et al. (2007) found was required to successfully detect trends in degradation. In addition, the timing of degradation can also influence detection using time-series but this problem is common to all trend analyses that are based on a limited time-series (Wessels et al., 2007).

4.2. Status of degradation

As expected, the evaluation of the status of degradation revealed a significant amount of rangeland area with reduced productive capacity indicating that historical events may have had greater impact on vegetation production than present land management practices. This is somewhat different than the global situation where present land use practices are having significant impacts on trends in production (Bai et al., 2008; Prince et al., 2009; Wessels et al., 2008).

The causes of rangeland degradation in developing countries typically include overgrazing and unsustainable fuel wood uses which are usually associated with depressed socio-economic factors, and climatic stressors such as drought (Bedunah and Angerer, 2012). These conditions result in widespread degradation across large areas which are ideal for degradation assessments from coarse scale remote sensing techniques such as the rainfall use efficiency metric employed by Bai et al. (2008) (e.g. the pixel size representing precipitation was 0.5°, approximately 156 times greater than the pixel size used in the present study). These factors contributing to spatial coverage of degradation in regions of developing countries are not markedly different from those in the U.S. in the latter stages of the 20th century. For example, rangelands in Mongolia and some Central Asian states have become largely unregulated as a result of the collapse of the Soviet Union (Bedunah and Schmidt, 2004; Humphrey and Sneath, 1999; Mearns, 1996) mirroring the former situation of public lands in the U.S.

Results of the status assessment suggest that many of the sites where past intensive use has occurred in the study area have recovered to a more productive state because they are not significantly different than reference conditions. The status assessment, however, also indicates that not all areas have fully recovered from a previously degraded state. While degraded land area estimates found here vary depending on the significance level chosen to report, they do not seem entirely unreasonable given the relative agreement (82%) with the ground conditions estimated from the efficacy assessment and a comparison with officially reported U.S. land statistics in Herrick et al. (2010).

Herrick et al. (2010) revealed that $21.3 \pm 1.3\%$ of the 158,786,000 ha of rangelands analyzed exhibited at least moderate departure from reference conditions associated with one of three metrics examined including biotic integrity, hydrologic function and soil and site stability (Pyke et al., 2002). While this study was unique and comprehensive for non-federal rangelands, rangeland health evaluations do not necessarily depict degradation as it is usually defined. Issues such as changes in species composition can decrease rangeland health but they do not constitute changes in the ability of a site to maintain productive capacity. For example, many rangelands now host a variety of exotic species such as *Bromus inermus* (smooth brome). As relative cover of smooth brome increases on a site, the estimated biological integrity, and thus rangeland health, decreases but the site may indeed be producing herbage within an appropriate range considering site and climate characteristics. As a result, rangeland health studies cannot be relied upon to verify degradation estimates such as those derived in the present work. The assessment developed here can be used to monitor vegetation conditions in the future as long as the MODIS 250 NDVI data stream remains available. The protocol may be hindered, however, by ambiguous interpretation of what the degradation estimates really mean.

Reed et al. (2011) suggested degradation analyses should include a social and economic analysis involving the appropriate stakeholders. Reed et al. (2011) outline an extensive process for choosing indicators of sustainability where stakeholders are engaged through workshops. Additionally, the degradation concept outlined by the United Nations Environmental Programme interprets degradation as, “lowering of the productive capacity of land as a result of human activities”, or, “a decrease in the capacity of the environment as managed to meet its user demands”. Including goals and sustainability criteria from stakeholders, however, can lead to disagreements and may direct the assessment away from analysis of the biophysical situation. For these reasons, the present study focused entirely on evaluating the productive capacity of rangelands thereby eliminating potential bias arising from social considerations. As an example, some areas within the study area exhibit degraded productive capacity resulting from colonies of prairie dogs. So, from an NPP perspective, the areas are degraded but may be considered to be in appropriate condition if the goal were to sustain prairie dog populations or to maintain habitat for species preferring more bare ground such as *Haradrius montanus* (mountain plover) or *Ammodramus henslowii* (Henslow's sparrow) (Fuhlendorf et al., 2006; Knopf and Miller, 1994).

5. Conclusions

The process developed here is an objective method for quantifying both the status and trend of rangeland productive capacity relative to reference conditions. The resulting analyses focus on productive capacity because if a land degradation assessment is performed with respect to social or managerial objectives, it will be a subjective evaluation that can change with differing viewpoints. Our supposition that most of the degradation found on rangelands within the study area happened prior to 2000 seems reasonable given the lack of significant current down trends. Indeed, rangelands within the study area do not exhibit widespread decreasing trends in decreased productive capacity. The remote sensing approach used here suggests that, overall, the land management policies and techniques in the study area are probably not furthering the extent of degraded lands. Determining the extent to which land use policies are aiding broad-scale recovery of degraded lands may not be best accomplished with use of 250 m MODIS NDVI data where significant differences exist between small paddocks in the study area with differing management styles or so called "fence line contrasts". Additionally, use of reference conditions to develop standards or benchmarks, against which pixels can be compared, may potentially limit application to areas where reference landscapes are well studied. If spatially explicit data describing site potential (e.g. BPS), with suitable resolution and accuracy do not exist, then the approach developed here will not provide reliable results. Therefore, a hybrid strategy which uses reference areas or conditions combined with rainfall use efficiency measures may be more effective for detecting trends in degraded productive capacity.

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