Long-term Cross-scale Assessment of Woody Cover Stability in Drylands

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Abstract – Grasslands and savannas characterize much of the world's dryland ecosystems. Various lines of evidence indicate the grass/shrub balance in these systems has de-stabilized in the recent decades. Here, we link long-term field and remote sensing observations to quantify woody plant dynamics at a site in the southwestern USA where *Prosopis velutina* has proliferated in semi-desert grassland. Field records revealed that the overall trend can be dissected into three phases: Rapid expansion (1957-1991), abrupt decline (1991-1997) and stabilization (1997-2006). The contributions of land histories and topo-edaphic factors to the trend were complex. Remote sensing observations indicated net declines in woody cover since 1984. Some of these occurred at sites with recent fires, whereas others may reflect density dependent dynamics. Notable exceptions occurred at low elevations where cacti proliferated. This study confirms that temporal and spatial dynamics of woody cover change are not unidirectional and are influenced by complex combinations of factors.

Keywords: Arid environments; cacti, carbon sequestration; Landsat; *Prosopis velutina*; spectral mixture analysis, succulents, tree-grass interactions

1. INTRODUCTION

Ecological stability can be generally defined as a system maintaining a dynamic equilibrium through time (Holling 1973). Stability is often used to describe fluctuation in ecosystem structure and function in response to stress, disturbance or environmental variability. When ecosystems are de-stabilized, directional changes in structure and function occur and new steady-state configurations may result (Folke et al. 2004). Grasslands and savanna ecosystems characterizing many of the world's drylands appear to have de-stabilized in recent history and transformed into deserts, shrublands or woodlands, Widely known as "shrub encroachment" (Van Auken 2000), this type-conversion is mediated by topo-edaphic properties (e.g. soil texture, depth; slope aspect, inclination) and can change primary production and related ecosystem process (House et al. 2003, Knapp et al. 2008). The rates, dynamics and extent of shrub encroachment have not been widely quantified. Disturbances in the form of drought, land use or fire (Huang et al. 2007, Fensham et al. 2009) may arrest or reverse increases in woody cover and influence subsequent rates and patterns of increase (Fensham et al. 2005). Although woody plant proliferation is on-going in some areas, Browning et al. (2008) note that the process may have gone to completion in others, with shrub cover stabilizing at a new steady-state. The fact that landscapes within a region are a mosaic of sites at various stages of woody plant encroachment and recovery from disturbance, challenges our ability to make robust generalizations.

Although the dynamics of dryland woody vegetation is recognized as having potentially important impacts on terrestrial carbon pools, the lack of information on the trends of shrub abundance is a major source of uncertainty. Projecting future consequences of woody cover change on ecosystem function will require knowledge of where shrub cover in present-day landscapes lies relative to the potential maximum within a bioclimatic region (e.g., Sankaran et al. 2005). Within a bioclimatic region, the point at which shrub communities developing on grasslands will stabilize in terms of cover, density and biomass will be depending on disturbance, land use, topography and substrate properties. Presently we know neither the extent to which shrub communities developing on grasslands have reached developmental potential; nor what that potential may be for a given topo-edaphic setting.

Our understanding of how fundamental ecosystem processes such as primary production are altered with state-changes is limited, for reasons outlined by House et al. (2003). A key constraint is the lack of information on woody plant abundance across environmental gradients over large spatial extents through time. Field data from long-term plots or transects provide local insights, but their limited replication and spatial extent make it difficult to generalize across large areas. Advances in remote sensing have the potential to redress this constraint; and it is now feasible to quantify the spatial pattern and extent of woody plant cover at landscape scales with space- and airborne multi- and hyperspectral data (e.g., Asner and Heidebrecht 2005, Huang et al. 2007). However, ground based information is critical to interpreting, evaluating, and confirming output from time-series satellite imagery.

In this study, we combine long-term quantitative field data and time-series satellite remote sensing data to assess broad-scale patterns of woody plant cover and stability in a semi-desert grassland known to have undergone a state-change to shrubland since ca. 1900 (McClaran et al. 2010). Definitions of "stability" in ecology are varied and highly dependent on the structural attributes or functional processes of interest and spatial/temporal scales (Grimm and Wissel 1997). For our purposes, stability in the context of a grassland-to-shrubland state-change is defined as the persistence of a set amount of woody cover for a sustained period of time.

2. METHODS

2.1 Site Description

The Santa Rita Experimental Range (SRER) (31.83° N, 110.85° W) situated along the western edge of the semi-desert grassland region of the Sonoran Desert in southeastern Arizona was selected for this study (Figure 1). Established in 1903, the 200 km^2 SRER is the oldest experimental range in the US (McClaran et al. 2010). Annual precipitation in the region is bimodal with a pronounced peak in summer (July-September monsoon) and a lesser peak in spring (March-April) (Sheppard et al. 2002). Mean annual precipitation (MAP) is positively associated with elevation, ranging from 305mm (900m a.s.l.) to 489 mm (1500 m a.s.l.), and MAP is highly variable. Mean annual temperature (MAT) is 17.9°C at 1310 m. Physiognomy ranges from *Larrea tridentata* desert scrub at the lowest elevations to *Quercus* woodlands at the highest. *Prosopis velutina* is the dominant shrub at 990-1200 m elevation. SRER records document the proliferation of *P. velutina* from drainage arroyos into upland grasslands since 1903 (Glendening 1952, McClaran et al. 2010).

Fire is the most destructive disturbance in drylands. There were two major fire events occurred in SRER in the past two decades (Huang et al. 2007) (Figure 1a). Studies assessing the impacts of one event on *P. velutina* revealed that approximately 90% of the plants were severely impacted (Gottfried et al. 2003). SRER was subjected to managed yearlong (YL) grazing since 1915 until 1957 when several rest strategies were applied (Ruyle 2003). A grazing system, known as the Santa Rita Grazing System (RG), has been continuously implemented since 1972 (Figure 1a). The schedules of grazing and rest for a set of three pastures was based upon three seasons (November-February, March-June, July-October); and each pasture is grazed for 1-2 consecutive seasons following by a full year of rest (Martin 1978). Martin and Severson (1988) indicated that RG may enhance recovery of pastures in poor condition. Since 1972, YL and RG have been consistently applied in one (1855 ha) and four (3988 ha) designated pastures. Because of the contrasting fire regimes and grazing rotations, large sizes, the availability of detailed information of topography and geomorphic landforms, and close proximity with similar climatic conditions (Figure 1), these settings afforded unique opportunities to study the effects of anthropogenic perturbations and physical environments on woody plant stability at a large scale.
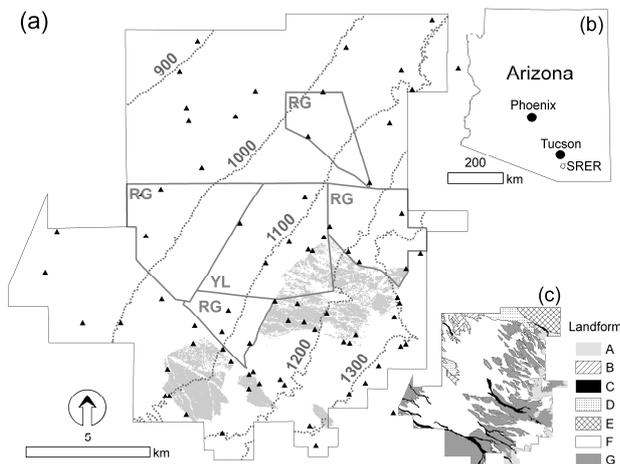

Figure. 1   (a) Locations of pastures in different grazing rotations (YL vs. RG) since 1972 and areas with recent fire history (light colored pixels) in SRER. The irregular dashed lines and triangles are elevation contour lines and rain stations, respectively. (b) The location of SRER and major cities within Arizona. (c) The landform pattern of SRER.

2.2 Long-term Field Records

There were 132 - 30.5 m (100 ft) permanent line transects installed at the SRER between 1953 and 1975, and these represent a wide range of topo-edaphic settings. Measures of projected woody canopy (entire live crown intercept excluding conspicuous openings or areas of dead crown for *P. velutina* and other shrubs, sub-shrubs and cacti) and basal herbaceous cover have been made at 1 to 7 y intervals through 2006. In this study, we only used the information of projected woody canopy cover (hereafter "woody cover"), which was recorded as the entire live crown intercept excluding conspicuous openings or areas of dead crown. In order to match remotely sensed data collection period, only transects with measures continuously made since 1984 were selected (n = 81) for analysis. Note that no transect had experienced recent fire disturbance. Long-term MAP records for summer (April-September) and winter (from previous October to current March) from 75 gauges (Figure 1a) widely spreading at SRER were also obtained from the SRER

website[1]; MAT data for summer and winter were acquired from six meteorological stations nearby SRER from the National Climate Data Center[2]. The data collection of MAP and MAT initiated as early as 1922 and 1956, respectively. However, we only used records from 1957 to 2006 in corresponding with the field woody cover measurement period. Deviations ΔMAP and ΔMAT, which are the differences to the mean MAP and MAT from 1957-2006, for observing regional climatic trends were also computed for summer and winter seasons for each year.

2.3 Remote Sensing

Eighteen sets of pre-summer (May, June) Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) images with minimum cloud contamination and spanning the 1984 and 2005 time-period were utilized. In southern Arizona, semi-arid environments generally exhibit the least amount of herbaceous green biomass during this time period; green vegetation signals derived from satellite data are almost exclusively from woody plants. Landsat TM and ETM+ are multi-spectral sensors that contain six 30m visible, near infrared (NIR) and shortwave infrared (SWIR) bands, and one thermal band. The historical data was available for the TM sensor beginning in 1984; and for the ETM+ sensor from 1999 onward. Both sensors are still active.

Image pre-processing entailed radiometric calibration, including geometric rectification and the removal of atmospheric effects. All images were ortho-rectified based upon a pre-registered Landsat image and a Digital Elevation Model (DEM). The root mean square error of ortho-rectification was controlled to less than half of a pixel (< 15 m) for each image. In addition, a second-degree polynomial geometric model and nearest-neighbor re-sampling were applied during ortho-rectification to minimize distortion of spectral properties during image registration. Atmospheric correction utilized the cosine of the solar zenith angle correction (COST) model (Chavez 1996). The absolute surface reflectance of an invariant target will differ even with identical atmospheric and illumination conditions due to sensor degradation (Schott et al. 1988, Hall et al. 1991). The impact of sensor degradation is not pronounced if the time between scenes is short. However, the time extent of this study was more than two decades, and we used a Landsat image acquired on year 2000 as the reference image and calibrated other images to this one.

2.4 Woody Cover Abundance and Dynamics

We used a probabilistic spectral mixture analysis approach (Asner and Lobell 2000) to unmix fractional woody vegetation cover from long-term pre-monsoon Landsat images. Specific settings of for this study have been described in Huang et al. (2007). After deriving the long-term fractional woody vegetation cover, we calibrated it to field measured woody cover by referring to Huang et al. (2007). For each pixel, we computed the mean and coefficient of variation CV (%) [(standard deviation (sd)/mean) × 100] through time. Additionally, we applied a trend analysis on each pixel to compute the rate of woody change per year using woody cover and year as the dependent and independent variables, respectively. In order to reduce the signals of noisy pixels, a correction procedure was applied on the trend map by multiplying (1-uncertainty), where uncertainty is inversely related to the fitness (r^2) of a trend line to each pixel.

2.5 Physical Environments /Anthropogenic Perturbations

Elevation was obtained from a US Geological Survey DEM[3]. Physiographic patterns (e.g., slope inclination and aspect) were homogeneous and excluded from the analysis. The spatial layer of geomorphic landforms was obtained from the SRER website (Figure 1c). The substrate data were originally in a vector format, and we converted them to 30 m grids using a Geographic Information System to match the Landsat images.The spatial layers of fire histories and pastures under YL and RG were acquired from Huang et al. (2007) and the SRER website, respectively.

2.6 Woody Cover Stability
Owing to the large number of data points generated by the satellite imageries (n ≈ 264,000 for the entire SRER) and most of these data were spatially correlated, we randomly selected 400 pixels from a large data pool to control the uncertainty < 5% (Yamane 1967); the random procedure should minimize spatial autocorrelation resulting biases and justify the use of a standard statistical analysis (Brus and DeGruijter 1993).

3. RESULTS

3.1 Field Woody Cover and Climate Trends
Increase of woody cover was tardy (0.1% yr^{-1}) by solely comparing the starting (1957) and end (2006) years of the field observation period (Figure 2a). However, the trend can be dissected into three periods: Fast growth (1957-1991, 0.6% yr^{-1}), abrupt decline (1991-1997, 2.3% yr^{-1}) and stabilization (1997-2006). In addition, variation (standard error, se) was quite similar through years (mean se = 1.7% ranging 1.2-2.4%). Mean summer and winter MAPs from 1957 to 2006 were 230.7 mm and 153.3 mm, respectively; MATs were 22.2°C and 11.2°C, respectively, respectively (Figure 2b and 2c). There were 10 out of 14 summer ΔMAPs and 9 out of 11 winter ΔMAPs below the long-term averages in the recent years; the increases of ΔMATs were pronounced in both summer and winter especially after 1995.

3.2 Regional Analysis of Woody Cover Dynamics
Regional estimates of recent (1984-2005) mean woody cover (± sd) and CV (± sd) of SRER derived from dry season Landsat images were 26.5 ± 3.4 % and 11.7 ± 1.2 %, respectively. Overall, woody cover at SRER decreased (mean trend ± sd = -0.8 ± 0.7 % yr^{-1}); the mean tendency (decrease) did not change after taking the model significance into account (Figure 3).

3.3 Topo-edaphic factors
There was a significant (r^2 = 0.28, p < 0.01) positive linear relationship between elevation and remote sensing estimated mean woody cover; a weak but significant (r^2 = 0.06, p < 0.01 for the intercept and coefficients) quadratic relationship was found between elevation and woody CV. However, elevation failed to explain the variations of mean woody cover and CV based upon field observations. The majority of surface soils in SRER had high proportions of sand (≥ 66%), medium silt (19-23%) and low clay (10-11%) contents, respectively. We found that in terms of model fitness, these soil texture attributes did not delineate the variations of mean woody cover and CV regardless of field or remote sensing estimates (r^2 ≤ 0.03). According to remote sensing observations, the areas with positive trends (woody cover increase) were mainly located at lower elevation approximately from 910-1050 m. The increase of woody cover in low elevation can be related to the growth of

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[3] http://seamless.usgs.gov/

cactus (mainly *Opuntia engelmannii*) populations according to the field validation (Figure 4).
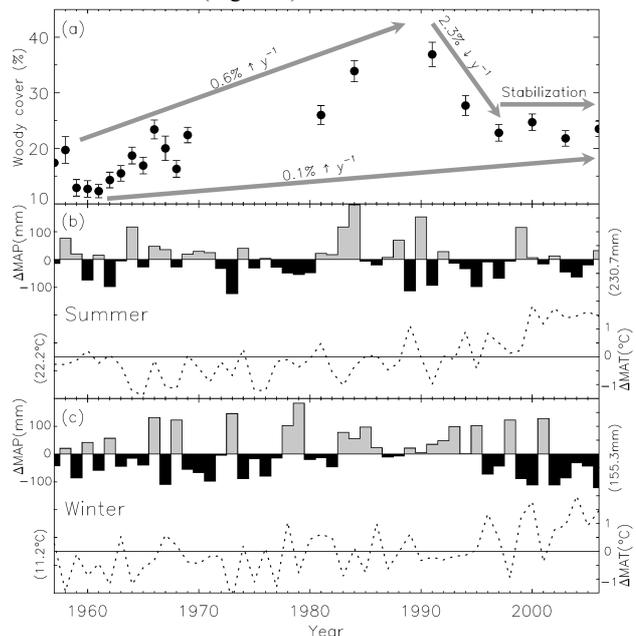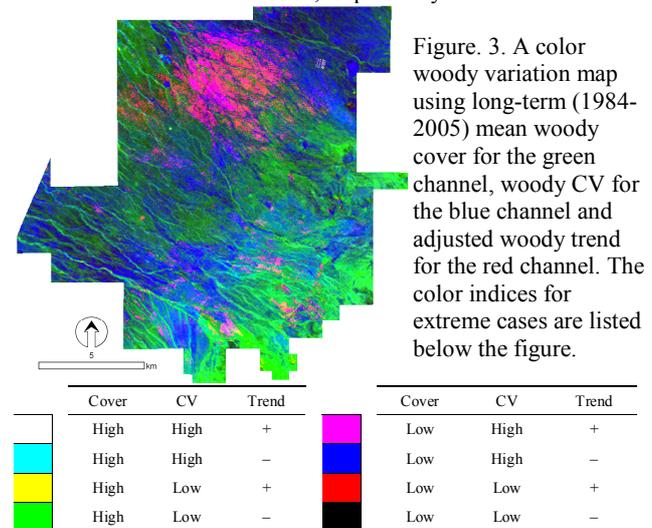

Figure 2. (a) Long-term (1957-2006) trends of field measured woody cover in SRER with error bars indicating one standard error from the mean. Deviations of (b) summer (April-September) and (c) winter (from previous October to current March) ΔMAP and ΔMAT relative to the MAP and MAT are shown as bars and dashed lines, respectively.

Figure. 3. A color woody variation map using long-term (1984-2005) mean woody cover for the green channel, woody CV for the blue channel and adjusted woody trend for the red channel. The color indices for extreme cases are listed below the figure.

Cover	CV	Trend		Cover	CV	Trend
High	High	+		Low	High	+
High	High	−		Low	High	−
High	Low	+		Low	Low	+
High	Low	−		Low	Low	−

3.4 Wildfire and managed grazing
The elevation range (mean ± sd) of areas with recent fire histories (1169.9 ± 64.3 m) was slightly higher than the rest of the range unburned areas (1066.0 ± 128.9 m). However, there was no difference in remote sensing woody cover for these two groups (one-way ANOVA, p = 0.31). In contrast, high woody CV of burned area can be clearly differentiated from unburned area (burned = 36.9 ± 0.5%, unburned = 28.6 ± 0.1%). Areas with recent fire histories (Figure 1a), and a medium-sized patch located at the east side of the low altitude woody cover increase area can be clearly discerned in the adjusted trend map (Figure 3). The mean elevation of YL pastures (1001.8 ± 95.2 m) was similar to those under RG management (1085.8 ± 108.1 m); there was no difference (p ≥ 0.66) of mean woody cover observed from field and remote sensing. The woody CV difference of these two types of pastures was discernible in

remote sensing ($p < 0.01$) but not from field data ($p = 0.72$). No clear trend of woody abundance among different grazing management types (YL, RG, Mixed [4]) from both field and remote sensing observations (data not shown).

Figure. 4. A typical *Opuntia engelmannii* community in the northern SRER (Photo credit: M. McClaran).

4. CONCLUSIONS

- Ground-based transect data revealed that the overall time-series of woody cover change was not uniform. Rather, it exhibited three distinct phases: Rapid expansion, abrupt decline and stabilization. Interactions among physical environments, fire and livestock grazing were complex and difficult to decipher.
- Remote sensing observations indicated net declines in woody cover especially at sites with recent fires. Notable exceptions occurred at low elevations where cacti proliferated.
- This study confirms that temporal and spatial dynamics of woody cover change are not uni-directional and are influenced by complex combinations of drivers.

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