Assessing Vegetation Disturbance Gradients at Piospheres in Arid and Semi-arid Environments with High Resolution Satellite Imagery

Potential Cast of Participants

Thomas Frank, Department of Geography, University of Illinois - Urbana
Janet Greenlee, Department of Geography, New Mexico State University
Michael Demers, Department of Geography, New Mexico State University
Walter Whitford, New Mexico State University
Dallas Bash, Directorate of Environment, Ft. Bliss
James Andre, Sweeney Granite Mountains Desearch Research Center
Introduction

Desert landscapes in the southwestern United States have been under increasing pressure because of population growth, recreational use, military training, and the historical overuse from grazing. The overall reduction in vegetation cover, the loss of native plant species, and the production of invasive weeds are among some of the most destructive outcomes. As such, vegetation type, cover density, and biomass are important indicators of the condition and trend in these arid and semi-arid environments. In particular, the volume of the vegetation canopy will affect the susceptibility of the degraded landscape to wind and water erosion (Renard et al., 1994; Toy & Osterkamp, 1995; Bilbro, 1992; Fryrear et al., 200). Healthy desert shrubs intercept both precipitation and wind-blown particles, thus stabilizing soils and protecting them from erosion (Chavez & MacKinnon, 1994); while capturing more wind-blown particulates, decreasing the amount of dust created by some of these disturbances. The amount of standing biomass is important because it indicates the ecological condition of the landscape.

Grazing has been conducted on both private and public lands in arid and semi-arid environments for generations. The long-lasting effects of over-grazing have been well established ( ). The site of the most intense disturbance in arid and semi-arid rangeland is where isolated water tanks are located (Figure 1).

Figure 1. Effect of over-grazing at water tanks in the Mojave National Preserve.
Plant species and cover density improve with distance from the point water source because of the concentration and intense use by cattle in the immediate vicinity of the water tank. Matchett (2002) indicates that grazing impacts on plant communities are greatest from about 55 to 220 yards from the tanks. Denudation of vegetation about the water tank will frequently occur in a near-circular fashion, which has lead to the use of the term *piosphere* to describe the disturbance pattern. The changes in vegetation diversity and cover density can be measured along this gradient using field transects. Field transects provide a relatively accurate inventory of plant species, species diversity, and cover density. Generally less available though are measures of standing biomass, unless destructive sampling is conducted.

**IALC Area of Research and Development Addressed**

Livestock grazing is commonly found in arid and semi-arid lands of low natural productivity, such as those rangelands in the southwestern United States. Rangeland management regulates the spatial extent and density of livestock, with the purpose of attaining or maintaining sustainable land use (CABLM, 1997). Assessment of range condition represents a starting point for management towards the potential selected by the range manager (Pendleton, 1989). This approach arises from the need to evaluate the current condition of a rangeland, to detect changes over time, and to prescribe measurement strategies to insure the long-term productivity and stability of the range resources.

Wide-spread, or long-term monitoring of range condition is expensive, and monitoring of change is often abandoned due to high costs and insufficient resources. Alternative, non-destructive, less expensive, and faster inventory and monitoring methods are always being sought. This proposal addresses the IALC inventory and measurement techniques request to develop improved landscape monitoring methods. The obvious disturbance pattern and resulting disturbance gradient away from the water tanks in these grazed rangelands makes the piosphere an attractive study site to assess the capabilities of new inventory and monitoring techniques.

**Objectives**

Remote sensing has been used for many years to inventory and monitor vegetation change in arid and semi-arid environments (Frank 1984; Pickup et al., 1993; Shoshany et al.; 1996; Tanser and Palmer, 1999). Until recently though, satellite remote sensing platforms, which offer cost-effective remote sensing, have not provided sufficient spatial detail to identify individual shrubs in regions where cover is sparse and vascular plants are widely scattered. Over the past four years, we have conducted research to determine whether the latest generation of high-resolution remote sensing systems can be used to estimate vegetation cover in arid environments. One outcome from this research has been the development of a new way to model the volume of shrub canopies, and to estimate the amount of standing woody biomass directly from remotely-sensed imagery. These methods were developed at study sites in the Mojave desert of southern California.
The objective of this new proposed research is to determine if these models and methods are robust enough to be applied across ecosystem boundaries. This will be tested by studying the disturbance gradients at piospheres located in arid sites in the Mojave desert; and semi-arid sites in the Chihuahan desert. The goal of this study will be to model shrub canopy volumes and standing biomass estimates with high-resolution satellite imagery, and to validate these estimates with field transects. Otero Mesa on Ft. Bliss Army Base in the Chihuahan desert of southern New Mexico, and the Mojave National Preserve in the Mojave desert of southern California are proposed study sites, because:

1) grazing has been a long time activity in both areas, and three grazing allotments have just been closed, with plans to close two additional allotments in the Mojave National Preserve;
2) vegetation type is similar to the study sites that we used to create the vegetation volume and standing woody biomass models;
3) we have conducted initial studies of vegetation gradients at five piospheres in the Mojave Preserve and at one piosphere on Otero Mesa, which create a baseline for assessing change in vegetation type and cover density; and
4) there are concurrent efforts being conducted by the U. S. Geological Survey and the Bureau of Land Management to create disturbance maps in the Mojave National Preserve, which provide synergy and data to support this proposed effort, while the Directorate of Environment at Ft. Bliss have similar research efforts underway.

Our previous research in these regions has led to the development of a model to predict standing woody biomass of individual shrubs or groups (clumps) of shrubs that can be identified in high-resolution remotely-sensed imagery. Our proposed research would:

1. test the ability of these models to predict vegetation volume and standing biomass along the piosphere disturbance gradients using high-resolution satellite imagery,
2. use these biomass predictions to determine the response and recovery of vegetation biomass to reduced grazing, and
3. perform the necessary field inventories to validate the effectiveness of the satellite-based estimations to measure biomass changes over time.

This study would be conducted over a three-year field season with a high expectation to assess vegetation response to allotment closure to grazing. As such, we would conduct a periodic assessment of change about selected piospheres, either on a scheduled basis or in response to precipitation events. Obviously a much longer-term monitoring program is sometimes necessary to observe changes in arid and semi-arid vegetation diversity, but this basic research effort should establish the protocol, and confidence in the protocol, to conduct such longer-term efforts with remote sensing techniques.
Literature Review of Remote Sensing in Arid Environments

Clements (1916) treatise on plant succession is the basis of the range condition concept. Samson (1919) applied these concepts to range management, which Dyksterhuis (1949) later built upon, codifying the relationship between secondary succession and range condition (Meeker & Merkel, 1984). The principal of plant succession holds that there are orderly processes of community change with a sequence of communities replacing one another in a given area, until a relatively stable community in equilibrium with environmental conditions is reached. (Pendleton, 1989). Secondary succession is any succession after the primary, following a disturbance that has changed the original vegetation, but has not profoundly altered the character of the site (Pendleton, 1989). The disturbance, which in respect to range management is livestock grazing, causes retrogression or community deterioration along a gradient or continuum. Secondary succession, if allowed to operate, restores the equilibrium of plant communities and soils following the reverse path of regressive changes.

The assessment of current range condition incorporates Clements’ successional theories to describe the status and tend (the directional change of range condition) of rangelands. The introduction of livestock acts as an external disturbance causing an interruption in community succession towards its natural climax, eliciting regressive changes in vegetation composition. If the disturbance remains, a disclimax or equilibrium is reached between grazing, vegetation, soil, and regional climate. Current range condition assesses the similarity of this vegetation composition compared to the original climax. The more intense the disturbance, the more dissimilar the vegetation community becomes from the climax. Once livestock are removed, secondary succession operates to restore the vegetation to the original climax community, following the reverse path of retrogression.

The linear reversible pathway taken by retrogressive changes following a disturbance and secondary successional changes after the removal of a disturbance has been challenged. Gleason (1926) and Egler (1954) both suggested that vegetation change following a disturbance could be regulated by chance and by conditions at the time of the disturbance. Thus, relative stages of dominance may be different on two identical range sites starting at the same stage of degradation, but separated in space or time (Laycock, 1991). Egler also stated that stages of dominance could be dictated firstly by the available seed source, and secondly by the life history of the species present. If, therefore, intense over-grazing eliminates the seed source of some climax vegetation, even if grazing is removed, the return of this vegetation will be indefinite, at least on a time scale meaningful to management. Friedel (1988) hypothesized that rangelands do not go through gradual stages of retrogression or secondary, but rather reach various levels or thresholds that are relatively stable unless additional pressure is added or removed from the system. For many range types, particularly in arid and semi-arid environments, some stages of succession become suspended or static for long periods of time. The threshold concept presented by Friedel seems to describe these stages quite well. Lack of change may be attributed to seed availability or seed dispersal, dominance of a particular life
form, climatic conditions, or fire. These factors may influence recovery despite management. This implies that if grazing is removed, range condition does not necessarily improve immediately, and any improvement are rarely gradual and continuous.

Succession is a particularly difficult concept in arid and semi-arid environments where the major driving force, precipitation, is variable and unpredictable. Linear concepts of plant succession are not to be discarded; they depict indeed some mainline sequences. However, there is increasing evidence that the response of vegetation to livestock grazing cannot easily be explained by the succession-retrogression model. Alternative stable states, discontinuous and irreversible transitions, as well as stochastic effects within ecological systems casts serious doubts on the simplicity, predictability, and linear nature of vegetation change assumed by the climax based approach to range management (Westoby, 1980; Friedel, 1991; Laycock, 1991). Multiple pathways of succession allowing for departures from mainline sequences, the concept of thresholds of environmental change, as well as prolonged ‘suspended’ stages other than climax, are useful concepts to range managers.

Ecological thresholds have become a popular way to account for the discontinuities of environmental change typically found in arid and semi-arid environments. Ecological thresholds can be defined as ‘the point of entry into a new domain or ecosystem function’ (Brown et al., 1999), and can be described as having two defining characteristics:

1. thresholds represent the boundary in space and time between two states of vegetation
2. once a threshold is crossed, return to the original state is not possible on practical time scale without substantial human intervention.

In arid and semi-arid regions, thresholds may represent the separation of grassland from woodland, palatable from non-palatable species, healthy from degraded soil, as well as the shift in dominance from perennial to annual species (Friedel, 1991). In terms of the management of rangelands, ecological thresholds can be defined as the point in time when processes that result in change in ecosystem function are entrained, and management actions must shift from maintaining existing processes to reversing degraded processes (Brown et al, 1999). The existence of ecological thresholds implies that simply by reducing the stocking rate a reversion to the former state does not necessarily follow. Having crossed an ecological threshold, the vegetation may remain in this state for long periods of time. Laycock (1991) has termed this ‘suspended’ stages of succession. Recovery is only initiated when a rare combination of environmental conditions occur, causing another threshold to be crossed. Numerous examples have been described in the literature (e.g., Laycock, 1991; Tisdale & Hironaka, 1981; West et al, 1984). Archer (1989) described how the introduction of livestock into a primarily grassy ecosystem in the Rio Grande Plains, has encouraged woody encroachment due to reduced fire frequency and to livestock overcoming dispersal limitations. Initially, gramminoid driven succession predominated within the grassy domain. Heavy grazing
altered the composition and productivity of herbaceous species, decreasing fire frequency and intensity, and thereby increasing the probability of woody establishment. Woody plants increased to a point whereby a threshold was crossed, shrub dominated processes became predominant, and the site moved to a stable woodland configuration. At this point, the removal of grazing will not allow the system to revert to grassland.

Traditionally, above ground biomass estimates have been obtained from remotely-sensed imagery through the application of spectral vegetation indices because of the positive correlation with measured biomass. The near-infrared (NIR), and red band reflectance have shown distinctive correlations with the amount of vegetation cover; therefore the Normalized Difference Vegetation Index (NDVI), or some derivation (e.g., SAVI), has been utilized most commonly (Phinn et al., 1996). Remote sensing in arid environments is challenged by the low abundance of photosynthetically active vegetation and special adaptations of shrubs; such as salt secretion of leaves to prevent full light absorption, and low tissue water content due to lack of consistent water (Dole & Rose, 1996). Where the plants are sparse and small with minimum spectral reflectance differences, NDVI would not be appropriate for obtaining standing biomass. Indeed, Frank (1994, 1985, 1884), demonstrated that vegetation brightness, or albedo, sufficiently differentiated vegetation cover in arid and semi-arid environments. Franklin and Turner (1992) supported these findings and noted that vegetation indices have been productive in many environments, but they are not as efficient in arid regions due to lack of vegetation captured through remote sensing and the decrease in “red edge.” The Li-Strahler canopy reflectance model was been utilized in the place of vegetation spectral indices for the estimation of biomass from SPOT imagery (Franklin & Turner, 1992), yet results were not promising due to the large pixel size in comparison to shrub size.

The majority of vegetation studies have been conducted with passive remote sensing instruments in the optical region. This technique is useful for large scale monitoring of major physical features, but it lacks the ability to give direct estimates of physical attributes of plants such as height, size, and density (Rango et al., 2000). Radar and LIDAR, which are active sensors, have shown promise to provide estimates of these physical attributes, but they require relatively expensive over-flights which can be cost prohibitive if monitoring of vegetation recovery is the issue.

Another approach to predict biomass over large regions is logarithmic regression analysis (Baskerville, 1972; Brown, 1976; Smith & Brand, 1983; Franklin & Hiernaux, 1991). For example, Smith and Brand (1983) estimated the biomass of shrubs and small trees using stem diameter and plant cover with:

\[ \ln(\text{biomass}) = a + b \ln(\text{cover}). \]

Brown (1976) used destructive sampling of the plant to predict biomass from basal diameter of the plant through a similar regression of:

\[ \ln(\text{weight}) = a + b \ln(\text{basal diameter}) \]
Brown found the weight to diameter relationship very strong with correlation coefficients from .70 to .97. More recently, Franklin and Hiernaux (1991) used log regression analysis to predict foliage and woody biomass in an African wooded grassland with structural features such as crown area, height, and circumference, achieving correlations higher than .80. By obtaining a crown area from direct field measurements or through remotely sensed imagery, a log regression equation could be directly applied to predict biomass.

**Methodology**

*Estimation of Standing Woody Biomass*

We have developed a procedure to estimate the volume of above ground vegetation and standing woody biomass of desert shrubs (Frank, Tweddale, & Lenschow, 2002). This model was derived from the regression of the modeled biomass estimates against the log of area of those shrubs, or groups of shrubs, derived from high-resolution remotely-sensed imagery. The intent of the model is to use high-resolution satellite imagery to monitor changes in the volume or standing biomass of desert shrubs, rather than just the area of shrub cover that is traditionally derived from remote-sensed imagery.

We were unable to differentiate between all shrub species with all of the spatial resolutions of imagery, so we stratified study areas into three dominant and co-dominant plant communities: *Chilopsis linearis* – *Chrysothamnus nauseosus* – *Larrea tridentata*; *Psorothamnus spinosa* - *Acacia Greggii*; and *Larrea tridentata* – *Ambrosia Dumosa*. Separate models were developed in the expectation that improved remote sensing capabilities in the future might enable better differentiation among shrub communities which would allow for specific biomass models to be used.

The basic elements of the model were:

1. The height and width of randomly selected shrubs were measured in the field. Height and width were used to compute the cylindrical volume of each shrub. A cylinder was chosen for volume calculations because of the similarity in shape of most shrub species.

2. The shrub canopies consisted of both the woody and leafy components of the plant, but also the open areas in the canopy. Most desert shrubs have relatively large openings in the canopy, which act as pathways for rainfall, wind and light to penetrate to the underlying surface. The amount of open area within a canopy is known as the gap fraction (GF); that is, the fraction of view, looking up from beneath the canopy, that is not blocked by canopy foliage (Bonhomme & Chartier, 1972; Andrieu et al., 1994). The gap fractions of the shrubs were measured twice. First, a Li-Cor plant canopy analyzer was used to automatically measure the gap fraction.
The plant canopy analyzer measured the amount of diffuse light captured by a fish-eye lens located at the end of a one meter wand. The wand was extended into the base of the shrub canopy to measure the amount of filtered light (less than 490nm) that passed through the canopy. Five concentric silicon rings in the lens captured light from five sky sectors with zenith angles of 7°, 23°, 38°, 53°, and 68°. The gap fraction was measured automatically by the instrument with a ratio of above canopy to below canopy readings (Welles, 1990). A 90° view cap was used to cover the fisheye lens to prevent perimeter shrubs and instrument operator from appearing in the readings. Gap fraction values ranged between 0 (sky completely blocked by foliage) to 1 (no foliage blocking sensor). Second, hemispheric digital images were acquired looking up from the base of each shrub. The gap fraction of the shrub was determined from the amount of sky visible within the image. Both pairs of measurements were regressed to validate the measurements, achieving an r-squared of .87. White et al., (2000) supports our findings that plant canopy analyzer and digital hemispheric images were found to have strong correlation. The shrub canopy volume of the cylinder was multiplied by 1.0 – gap fraction to determine the shrub canopy volume.
3. Since few shrubs were perfectly circular objects, the ratio of the shrub canopy area to the area of the top of the cylinder was determined. The shrubs actual canopy area was derived from high-resolution imagery. The shrub canopy volume of the cylinder was then multiplied by this corrected area ratio.
4. Since the amount of leafy component varied within the shrub canopy over time, in response to precipitation and drought, only the amount of standing woody volume could be predicted in the future using this model. Therefore, the hemispheric digital images were classified to determine the amount of woody and leafy percentages in the shrub. The leafy percentage was then removed from the shrub canopy volume calculations.
5. The shrub canopy volumes were converted into biomass estimates, kg/m³, by multiplying by published values of plant densities.

<table>
<thead>
<tr>
<th>Species</th>
<th>Specific Gravity</th>
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<tr>
<td>Chilopsis linearis</td>
<td>0.59 g/cm³</td>
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<tr>
<td>Larrea tridentata</td>
<td>1.10 g/cm³</td>
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<td>Psorothamnus spinosa</td>
<td>0.55 g/cm³</td>
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6. Modeled estimates of log biomass were then regressed against the log area of the shrubs as determined in a nested, multiple resolution data set, ranging from .2m to 2.0m spatial resolution. Results indicated that shrub biomass could be estimated from the shrub area measurements. The regressions were completed for all shrubs combined, regardless of species, in case species could not be identified from the imagery; and for three dominant species – *Chilopsis linearis, Psorothamnus spinosa, and Larrea tridentata* – *Ambrosia Dumosa*, in case species could be differentiated.
### Experimental Design

Quick Bird, high resolution (.61 meter) panchromatic satellite images would be acquired from Digital Globe because it provided the highest spatial resolution from a satellite platform which over repetitive, timely coverage for monitoring purposes. Our previous research indicated that this is sufficiently detailed enough to provide reliable biomass estimates for all three dominant plant communities. The images would be centered on a representative number of sample piospheres. Three image processing steps would be applied to each image:

1. images would be geometrically corrected using 1m digital ortho quarter quads for ground control point selection,
2. images would be classified using a clustering algorithm to discriminate shrub cover from background rock and soil,
3. shrub pixels would then be ‘clumped’ together to join adjacent shrub pixels into shrub features,
4. the size of each shrub or clump of shrubs would be measured,
5. the volume and woody biomass would be calculated from the size of each shrub or clump of shrubs using the equations derived from the regression models,
6. the location (x,y) of the shrub centroid and the predicted volume/biomass recorded for spatial analysis testing, and
7. maps would be produced showing the amount of shrub biomass in relationship to water tank locations.

### Regression Equations for Woody Biomass

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<tr>
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<th>R²</th>
<th>0.5m Equation</th>
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<th>1m Equation</th>
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<th>1m Pan Equation</th>
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<td>.54*</td>
<td>SWB = 4.05Cov⁻¹⁺⁻⁰⁵</td>
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<td>Ambrosia Dumosa</td>
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(SWB) represents standing woody biomass.  (Cov) represents imagery cover estimates.

* significant correlation (P<.05).
Hypothesis 1. The shrub volume/biomass model is robust across similar ecosystems, such that the regression equations will provide relatively accurate estimates in new places or at new times.

1. Some level of field validation should be conducted at new research sites to provide confidence that similar results can be repeated using the same model development and parameters. We would use smaller number of shrub samples at the new study sites to confirm these results, however, we would not have access to all of the nested spatial resolutions. Our new sites would be validated using the .6m QuickBird imagery only.

Trend surface, spatial regression, and raised incidence models would be applied to determine if spatial patterns exist within the distribution, and whether these pattern are influenced by the water tank. The underlying assumption is that grazing impacts are greatest near the tank, so is shrub volume/biomass influenced by the distance of the shrub to the water tank.

Hypothesis 2. Livestock disturbance is at its most intense around the water tanks, since cattle crowd this area to obtain drinking water. As distance increases away from the tank, livestock disturbance becomes less concentrated since fewer livestock graze in the area. So, a gradient in livestock disturbance exists, decreasing with distance. The area closest to the tank is the most heavily disturbed, and according to the succession-retrogression model, will be synonymous with an early successional state. As distance increases, vegetation cover and diversity should increase as the community moves closer to the climax.

If a linear positive relationship is found between vegetation cover and diversity, and distance from the water tank, then the vegetation is corresponding to the succession-retrogression model.

If a non-linear relationship is found, the existence of a threshold is possible.

Shrub volume/biomass is influenced by distance from the shrub to the water tank.

1. one-dimensional spatial effects. Simple least squares spatial regression of shrub volume/biomass and distance (h) of the shrub to the water tank. Distance will be assessed with linear and non-linear effects; e.g., \( h, e^h \).

2. multi-dimensional spatial effects. Apply trend surface analysis (spatial regression), with shrub volume/biomass as dependent variable, and independent covariates of shrub location (x,y) and distance of shrub to water tank (h). Trend surface analysis involves fitting a polynomial function of the spatial coordinates of the shrubs to the observed volume/biomass of these shrubs by ordinary least squares regression. Often, covariates other than location can be included into the regression model to further understand or ‘explain’ spatial variations. In our case, we’ll use distance from water tank.
Analysis of the residuals from the regression will elicit patterns associated with the distribution of shrub biomass in relation to the water tank.

3. semi-variance. Test the spatial covariance of the distribution of standing biomass in incremental distances from the point source – semi-variance. This will provide information on how far the effects of the piosphere.

Hypothesis 3. Shrub volume/biomass is related to distance from water tank, and other factors, such as shrub age. Size class indices will be used as a measure of age parameters. The techniques described in our methodology will be used to assess size class structures (in highly impacted and even in moderately trampled areas) to show change in survivorship and recruitment over time.
References


Matchett, John. USGS Press release.


