DRYLAND ANALYSIS AND MONITORING

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Contents

Summary

The Millennium Ecosystem Assessment's 2005 study of the state or condition and trend of the world's drylands had conservatively estimated that 20 % of this landscape is seriously degraded. However, estimates of degradation vary from a low as 10% to a high of 80% of drylands. The wide variation in the estimates reflects the lack of agreed upon indicators and the lack of comparable monitoring and assessment methodologies. Many climate change models predict increasing aridity in the future including shifts in spatial distribution and losses and addition of new lands.

Monitoring in drylands used primarily for commercial and subsistence livestock operations, typically concentrates on indicators related to plant-herbivore interactions and soil stability in relation to trampling. Most monitoring in drylands typically concentrates first on vegetation attributes and secondarily on soils attributes where

vegetation attributes, such as cover, usually serve as a proxy for soil attributes such as soil erosion. This is due to an observed negative linear correlation between declining vegetation cover and increased erosion. Assessment requires time series data of the drivers of change including human and herbivore population and demographics, climate, and fire data.

1. Introduction

Drylands cover an estimated 41 % of the terrestrial land surface and provide ecosystem goods and services for over 38% of the world's human population. However, a study in 2005 of the state or condition and trend of the world's drylands had conservatively estimated that 20 % of this landscape is seriously degraded. However, estimates of degradation vary from as low as 10% and as high as 80% of drylands. Additionally, many climate change models predict increasing aridity in the future including shifts in spatial distribution and losses and addition of new lands. These estimates are indicative of the fact that the condition and trend of land degradation and/or desertification is not known at regional, national, and global spatial scales because 1) an agreed upon definition of drylands has not been used, 2) degradation and desertification are not clearly defined, 3) standard protocols for monitoring and assessment at country and global spatial scales do not exist, including the use of a set of ecological indicators related to declines in the physical and biological components of drylands, and 4) there is usually a failure to account for both spatial and temporal scale in observation and interpretation of dryland response to disturbances in order to separate human management practices from the impacts of climatic events. Consequently, there is a need to define a number of terms so that we can begin what may be a substantive and interesting discourse. Secondly, once we have provided these definitions we will discuss methods used to primarily monitor and assess changes in the biological and physical components of drylands, now called ecosystem goods and services.

2. Definitions

At least since the late 19th and early 20th century drylands have been climatically defined as land surface areas where the aridity index (AI); i.e., the ratio of the long-term MAP (mean annual precipitation) to MPET (mean annual potential evapotranspiration) is 0.05 to 0.65. This definition has its roots in the development of the field of climatic geography and it is the agreed upon definition of drylands by the 192 countries that signed the United Nations Convention to Combat Desertification (UNCCD). The AI was used to set the extent of dryland for the 2005 Millennium Ecosystem Assessment and the more recent 2009 assessment of soil carbon in drylands by UNEP. Figure 1 shows that > 50% of the land surface of the United States of America (USA) is dryland using this 50-year mean (1950 – 2000) definition.

From a hierarchical perspective, Drylands can be viewed from a number of **levels-of-organization or criteria** including for example the community, ecosystem and landscape levels-of-organization. Levels-of-organization are **scale-independent** categories that are used to organize how nature is inventoried, monitored, or assessed. Each of these criteria tend to have methods, techniques, and tools that are somewhat unique to themselves with overlaps that have been manifest as cross-scale interactions

or explanations of change usually at lower levels-of organization. For example, genomic approaches such as genetic arrays and parallel computing-based phylogenetic analyses, tend to use high throughput sequencing tools at the cell organelle-level to determine both community composition and mediators of biogeochemical cycles (ecosystem processes) of the macro- and microbial communities that make up dryland biological soil crusts and root mycorrhizal systems. Whereas ecosystem scientists may use stable isotope methods to measure foliar and soil nitrogen dynamics. This perspective of ecological criteria being both scale-independent and technique-dependent provides a powerful tool for new research insights as well as support for the basic monitoring and assessment of ecological phenomena.
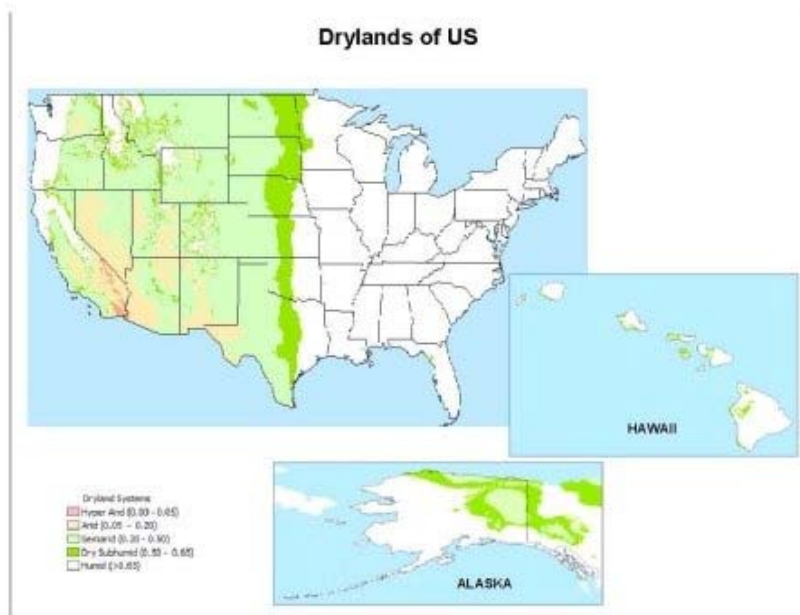

Figure 1. The mean extent of dryland ecosystems within the United States of America (USA). Dryland is defined as the 50-year mean (1950 to 2000) of the ratio of the long-term MAP (mean annual precipitation) to MPET (mean annual potential evapotranspiration), also called the aridity index (AI) that ranges between 0 and 0.65. The 50-year mean of the AI is from the WORLDCLIM 1-km gridded dataset (http://www.worldclim.org/). This figure is from unpublished data by Washington-Allen et al

Key words used in contemporary ecological monitoring and assessment programs include inventory, monitoring, assessment, benchmark or references, ecological indicators, condition or state (or dynamic regime), and trend to identify a few. An **inventory** is a one time collection and/or measure of phenomena of interest and provides an estimate of the condition or state of phenomena. **Condition or state** is an estimate of some characteristic of a phenomenon, e.g., vegetation canopy cover, at one point in time. More specifically, these phenomena can either be biological or physical attributes of drylands (e.g., collection of flora and fauna for species lists) or processes such as soil erosion that is occurring within Drylands. State and condition are also referred to as a **regimen or dynamic regime** to account for temporally consistent or dynamically stable ecosystem behavior. **Ecological indicators** are characteristics or

attributes of phenomena that are being inventoried over time or **monitored**. Consequently, **monitoring** is inventory of (hopefully) a suite of ecological indicators of land degradation over time. Monitoring frameworks such as environmental impact statements (EIS) or ecological risk assessments exist that define indicators or endpoints in different ways. Ecological risk assessment characterizes ecological indicators as **assessment endpoints and measurement indicators**, where an assessment endpoint is an explicit statement of the actual environmental value that is to be protected and a measurement indicator is an expression of an observed or measured response to a disturbance. The assessment endpoint must be unambiguous, e.g., the confusion between desertification, land degradation, and sustainability, and have social value to stakeholders. A measurement indicator can be directly derived from an assessment endpoint or if the assessment endpoint is not directly measurable or observable, then the measurement indicators may be proxies or surrogates for assessment endpoints. A measurement indicator is appropriate to the spatial and temporal scale and dynamics of a disturbance; it has a consistent response within the systems measured; it possesses low natural variability or high signal-to-noise ratio; it is a diagnostic of the disturbance, i.e., the pattern of response in statistical or spatial models allows separation of most disturbance types that may be acting simultaneously; and it is broadly applicable across sites and regions. This last trait allows comparison between sites.

Scale is considered in both space and time and has two main characteristics called grain and extent. **Grain** is the finest resolution in time and space and **extent** is the boundary condition in time and space. For example, El Niño Southern Oscillation (ENSO) events in general have return intervals of 3 to 7 years, but very strong El Niño Southern Oscillation (ENSO) events have return intervals of every 10 to 15 years. However, the impacts (enhanced plant growth or drought induced decline) of ENSO in some systems are lagged by 1 to 2 years. The period to see an effect is the grain at 1 to 2 years and the temporal extent of the phenomena for monitoring purposes is 30 years, because this event must be replicated in order to separate climate effects from management interventions. ENSO has a global spatial extent and its impact on soil moisture is observed at the individual plant or cell level and at temporal scales that has implications for the evolution of both flora and fauna.

A **disturbance** is defined here as a discrete event in time, e.g., a drought, or fire, that significantly reduces the abundance of a natural resource, e.g., vegetation or soil nutrients, and can be characterized in terms of the magnitude of its impact, e.g., the area impacted, its intensity, e.g., the temperature of a fire or the stocking rate of livestock, frequency, and return interval. Disturbance frequency is further characterized as either chronic or acute. **Chronic** disturbances are usually low in magnitude but high in frequency over the time of observation and thus their impacts are cumulative to natural resources. For example, moderate-levels of herbivory or gradual loss of trace minerals are usually considered chronic disturbances. **Acute** disturbances are usually high in magnitude and low in frequency, usually one-time impacts that occur discretely in time, e.g., a petroleum spill or wildfire. Both types of disturbances are actually designated relative to the ecological resilience of the Dryland being monitored, i.e., an acute disturbance could be re-designated a chronic disturbance depending on the scale of the period of observation. **Ecological resilience** is the degree, manner and pace of recovery of indicators after a disturbance.

Trend, usually statistically measured by linear and polynomial regression for direction (increasing or decreasing), strength (deviations from a fit function or residuals), and rate (slope), is the overall temporal or spatial trajectory of an indicator. Time trends are easily understood by stakeholders and generally are not biased in an obvious way. The direction of trend can be increasing, decreasing, or stable. However, if a trend is not considered in relation to a benchmark/reference, the results may be misleading. For example, the trend of nitrogen loss from a Dryland may be stable, but this stability may be at a level near depletion. The establishment of a **benchmark** and the subsequent analysis of trend will allow an assessment of ecological resilience, i.e., the response and recovery of an ecosystem in relation to a disturbance. A time series of data allows examination of specific characteristics of resilience including for example, elasticity (time to recovery) and amplitude (the magnitude of the initial departure of a measurement indicator from the benchmark state). Monitoring characterizes the response of Dryland measurement indicators to disturbance and their direction of change, but monitoring does not provide information on what may have caused the response of a measurement indicator. In other words, in order to understand how change has occurred, it is necessary to conduct an assessment to determine cause and effect. A benchmark reference, or standard is a baseline value of a measurement indicator by which an indicator can be compared and judged. A benchmark can be representative of initial conditions, central tendencies (mean, mode, or median), or boundary conditions. Boundary or gradient conditions can be either minimum or maximum conditions or chosen percentiles or standard deviations from the average. The choice of a benchmark is dependent on dynamic human value systems that vary widely. However, a benchmark that is commonly used by pastoralists to manage their natural resources is the state of vegetation and soil attributes during severe and repeated droughts, which is a boundary condition. Consequently, the condition of most measurement indicators can be considered in terms of departure of a value of a particular indicator from the value (state) of that indicator during a severe drought period.

Desertification is defined by the United Nations Convention to Combat Desertification (UNCCD) as land degradation in Drylands due to various factors including climatic variations and human activities. This defines it as a process, but desertification has also been defined as an endpoint or state of irreversible change after a threshold or tipping point for indicators of land degradation has been exceeded. Dryland scientists and managers define physical and biological **degradation** in terms of declines in ecosystem processes that relate to functional and structural changes in ecosystems. These include changes in the composition and abundance of fauna and flora and the physical loss and change in quality of soil, air, and water.

3. Theory

Drylands are viewed as **Trigger-Transfer-Reserve-Pulse (TTRP)** ecosystems, (see Chapter *Environmental Soil Management*). In these systems where climatic drivers, management interventions, and disturbances are viewed as triggers that lead to transfers of nutrient containing sediment or dust by processes like **wind and water erosion** that lead to deposition and storage of these nutrients, and increased productivity of above- and below-ground fauna and flora at reserve zones or accumulation patches that are also

called **"islands-of-fertility"** at the local spatial scale. These islands-of-fertility are manifest at the landscape spatial scale as a series of spatial patterns characterized as bare ground, spotted, labyrinthine or striped, termitaria, and near complete homogenous coverage of vegetation. Each of these spatial states differ in connectivity of soil and vegetation patches, the spatial distribution of nutrients, and the degree of self organization with the bare ground end state having near complete connectivity of soil patches, high levels of wind and water erosion, and low levels of dispersed nutrients. The near homogenous vegetation cover end state has highly connected vegetation patches with homogenous distribution of high levels of soil nutrients. Ecosystem simulation models have shown that a number of processes, but primarily water availability, drive this gradient of spatial patterns and that these patterns are self-perpetuated or organized by positive feedback loops where negative feedback events such as high levels of grazing or fire can lead to decreased connectivity of vegetation patches and conversely **increased connectivity** of soil patches that leads to increased run-off or rill flow and leakiness of soil nutrients from the landscape -another positive feedback loop. Increased leakiness including increased wind and water erosion that leads to the transfer of critical nutrients out of Dryland ecosystems, is indicative of a degradation loop. This feedback loop results in a decline in ecosystem processes and function.

This array of spatial patterns can be viewed as different states of the landscape consistent with a **state-and-transition model (S&T). The S&T model** presents predictions of the trajectory of response in space and time of ecosystems (states) to different drivers. States are recognized by site stratification, but this discourse suggests that pattern may be diagnostic of drivers (see New Thinking in Rangeland Eology) and that drivers may be diagnostic of pattern. Ecosystem responses to drivers include self-organization in spatial pattern, discrete (thresholds) and continuous dynamics of indicators such as connectivity, biomass, or canopy cover, that results in multiple stable states or dynamic regimes. Behaviors such as dynamic regimes, thresholds, and self-organization, are diagnostic of Drylands as complex adaptive systems.

Within the TTRP model, ecological indicators respond to drivers in both a gradual and discontinuous manner. Catastrophe theory has been suggested as a mathematical framework that accounts for these behaviors of ecological indicators in response to external drivers such as climate, fire and management interventions like grazing management (Figure 1). The ecological indicators that are monitored for response in Drylands are divided into the biotic (e.g., metrics of biodiversity, abundance or productivity of fauna and flora) and abiotic or physical (e.g., pattern metrics, loss and change in chemistry of air, water, and soil) components of an ecosystem. Monitoring and assessment has traditionally concentrated on the impacts to vegetation, particularly changes in species composition or physiognomy, and soil resources. However, the contemporary focus has been a shift from a community perspective, i.e., the monitoring of changes in plant community composition, to an ecosystem perspective, i.e., a concentration on changes in pattern (e.g., species composition) in response to changes in processes (e.g., water availability) and vice versa. Additionally, the interaction of rates of change, i.e., slow with fast and/or synchronous with asynchronous, of pattern and process, are seen as determinants as to whether the outcome is gradual or at a tipping point.

4. Procedure for Dryland Monitoring and Assessment

This proceeds by establishing both management and monitoring objectives at a grain and extent (monitoring period and site boundaries) of the scale of interest. Here we adapt a ten step approach that was developed in 2009 by the United States Department of Agriculture's Agricultural Research Service (USDA ARS), Natural Resources Conservation Service (NRCS), the US Department of the Interior's Bureau of Land Management (USDI BLM), and a non-governmental agency (NGO): the Nature Conservancy (http://www.rangelandmethods.org/) to account for M&A at different spatial and temporal scales where

1) Define and refine management and monitoring objectives
2) Stratify the globe, nation, region, or landscape into homogenous monitoring units or patches across a number of abiotic constraints,
3) Assess the historical and current status of the monitoring site by development of hypotheses or predictions about the response of ecosystem components to different drivers. This process includes identification of drivers, i.e., disturbances, climatic events, and management interventions.
4) Select ecological or measurement indicators and a monitoring design that includes statistical sampling design, number of plots/study areas, measurements and measurement frequency.
5) Select the monitoring location and spatial hierarchy. Temporally, the scale of interest must consider history or more particularly legacy affects.
6) Establish monitoring plots, develop baseline and reference or benchmark periods and locales, and record long-term data.
7) Record seasonal dynamics of ecosystem indicators
8) Assess annual condition and feedback to management decisions and adjust
9) Repeat interannual measurements, compare to previous years data, and interpret changes with respect to hypothesized responses.
10) Refine management decisions based on hypothesis tests and observations.

The appropriate statistics for examination of a time series of measurement indicators is time series analysis. Characterization of the direction and strength of a trend can be accomplished with regression analysis. The magnitude of the coefficient of determination (r^2) from a linear or polynomial regression is a measure of the strength of the trend. Detection of thresholds in the time series can be simply accomplished using the autocorrelation function (ACF), which then allows delineation of the time series into different period states.

An **assessment** is conducted to answer the questions what and why or "What brought this change about?" and "Why did this happen?" i.e., to establish cause-and-effect. During an assessment predictions or hypotheses are made, usually as a series of "if" and "then" statements, and then inferences are made in the form of statistical analyses between time series of measurement indicators that represent an attribute of drylands and disturbances, including management data such as livestock stocking rates (Figure 2). Figure 2 is a comparison of above-ground biomass data for US Drylands, that was derived form the Moderation Resolution Imaging Spectroradiometer (MODIS) satellite

data on net primary productivity (NPP), and livestock numbers for US Drylands standardized as Animal Units (AU) for cattle, goats, and sheep from 2000 to 2006 –This is an assessment. An assessment is the inference of the causal mechanisms behind change. In retrospective assessments, the outcome or the response of measurement indicators has already occurred and, at least after the preceding characterization, is already known. However, a problem for landscape-scale studies, with the exception of climatic data, is that time series of data for causal factors, i.e., disturbance factors such as land management interventions, is usually not available. Secondly, climatic data that is compared to measurement indicators usually needs to be scaled from the point data collected at different weather stations to the larger spatial scales of interest, either by averaging or interpolation, unless the climatic data is already collected at the scale of interest. However, besides the impacts of grazing disturbance detected by a piospheric analysis, the effects of fires, particularly the area and perimeter burned, can be detected by time series of Landsat imagery. When sufficient disturbance data is available then correlations with measurement indicators can be determined using a first-order difference regression model instead of an ordinary least squares regression (OLS).
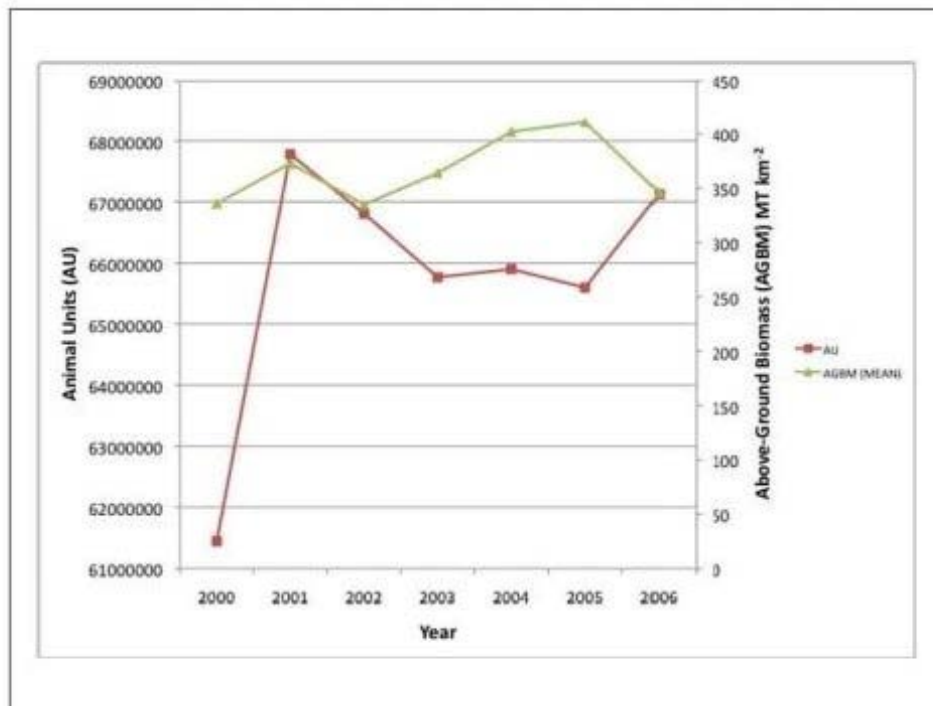

Figure 2. An example of an assessment where total livestock (Cattle, Sheep, and Goats) Animal Units (AU) within the dryland portion of the United States of America (USA) is compared to total above-ground biomass (AGB) within US Drylands from 2000 to 2006. AGB (in Metric Tons per square kilometer) is derived from the net primary productivity (NPP) product that is produced from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the TERRA and AQUA satellite platforms. The general fit is a 3rd order polynomial with an $r^2 = 0.78$ and a fit threshold peak of 63.5 million AU before a decline. This figure is from unpublished data by Washington-Allen et al.

OLS regression results between time series must be interpreted with caution because they assume that the mean and variance of a time series are constant over time and the

covariance between two time periods depends only on the lag or distance between the time periods, that is, they are stationary. The measurement indicators and disturbance and climatic factors may contain stochastic trend and therefore be nonstationary. Nonstationarity violates the assumption of OLS, which tend to overstate the statistical significance of variables with stochastic trend otherwise termed "spurious regressions". The Dickey-Fuller test statistic can be used to detect stochastic trend, but is not reliable with short time series (17 to 30 observations). One way to reduce the likelihood of a spurious regression is to detrend the time series, thus removing the stochastic trend. This entails transforming the times series using either order of differencing, running means, lags, or some other smoothing operation. The analysis of an NDVI time series versus temperature and precipitation and the analysis of SAVI response versus the Palmer Drought Severity Index (PDSI) and different grazing variables, used the following first order difference regression model

$$\Delta Y = \beta_0 + \beta_1 \Delta X + E \qquad\qquad [1]$$

In which ΔY and ΔX are the first differences of X and Y, and β_0 and β_1 are the regression coefficients, and E is a stochastic error term. Note that Forty years of data is considered a relatively short ecological time series; however a very good reference for aid in analyzing these data sets is <u>Chaos in real data: The analysis of non-linear dynamics from short ecological time series</u>, edited by J.N. Perry, R.H. Smith, I.P. Woiwod, and D.R. Morse.

In the following sections, M&A methods is divided into Paleoecological, Climate, Vegetation, Soils, Remote Sensing, and Modeling methods.

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[These are 20 selected annotated references. A more extensive bibliography is available from the authors on request by e-mail at washington-allen@tamu.edu.]

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Biographical Sketches

Robert A. Washington-Allen has BS in Zoology from The Ohio State University, USA, where he worked with Honey Bees, and from Utah State University, USA a MS in Range Ecology and a Doctorate in Ecology. He was a U.S Peace Corps volunteer in Lesotho, southern Africa from the early 1980's teaching first high school science and then later as a USAID subcontractor, he served as a Lecturer at the Lesotho Agricultural College teaching soil and rangeland courses. His MS study was conducted on the Bolivian Altiplano where he used remote sensing technology to detect forage resources that had high ecological resilience in the face of repeated droughts. He was a research scientist for 10-years at the Department of Energy Oak Ridge National Laboratory and then a Research Assistant Professor with the Center for Regional Environmental Studies in the Department of Environmental Sciences at the University of Virginia. During this past time, his doctoral and current research in southern Africa (Mozambique, Namibia, and South Africa) as an Assistant Professor of Environmental Monitoring & Assessment in the Department of Ecosystem Science & Management at Texas A&M University and as an Adjunct Professor in the Department of Geography at the University of Tennessee, is aimed at further developing the use of remote sensing technology for assessing Dryland degradation at local to global scales within the scope of the UNCCD.

Sujith Ravi has a BS in Agriculture from the Kerala Agricultural University in India and a MS and Doctorate in Hydrology from the Department of Environmental Sciences at the University of Virginia. He is currently an Assistant Research Professor at the University of Arizona (B2 Earth Science & Biosphere 2). He is a broadly trained environmental scientist interested in understanding the impacts of climate change on terrestrial ecosystems, in particular on drylands. At the Biosphere 2 facility, he is participating in a unique interdisciplinary research effort connecting hydrology, ecology and soil sciences to investigate the ecohydrological & biogeochemical implications of land degradation/desertification.