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Measuring soil disturbance effects and assessing soil restoration success by examining distributions of soil properties

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Successful restoration of an ecosystem following disturbance is typically assessed according to similarity between the restored site and a relatively undisturbed reference area. While most comparisons use the average or mean parameter to represent measured properties, other aspects of the distribution, including the variance of the properties may assist in a more robust assessment of site recovery. Our purpose was to compare soil properties in different ages of reclaimed soils with those in reference areas by incorporating the potentially different distributions according to areas. On two sampling dates, in consecutive years, we examined soil properties on a chronosequence of reclaimed natural gas pipelines spanning recovery ages of <1–54 years, obtaining data on soil moisture, organic carbon, nitrogen, electrical conductivity, pH, and microbial abundance. To make the comparisons, we analyzed our data with a Bayesian hierarchical linear mixed model and obtained posterior predictive distributions for the soil properties. This allowed us to probabilistically quantify the extent to which a soil property from a reclaimed treatment was similar to that from an undisturbed reference. We found that the posterior predictive variance of most soil properties was particularly sensitive to disturbance and reclamation, especially, within the first few years of recovery. Response of this variance to disturbance, reclamation, and recovery was not necessarily accompanied by a shift in the posterior predictive mean value of the property. Patterns for all soil properties changed over time, with posterior predictive distributions of soil properties generally becoming more similar to those of the undisturbed reference sites as recovery time increased. We suspect these trends in altered variability coincide with the degree of spatial heterogeneity in soil properties that results following disturbance and reclamation, which is also coupled to patterns of vegetation recovery.

1. Introduction

Disturbances due to removal of vegetation as well as temporary removal and mixing of topsoil have lasting effects on above- and belowground ecosystem properties. Such disturbances, associated with extraction and transportation of fossil fuels, minerals and other resources, are widespread in the semiarid sagebrush steppe of intermountain North America. Successful restoration of sagebrush steppe is influenced by soil and micro-topographical characteristics (Chambers, 2000) as well as climate and precipitation patterns (Bates et al., 2006). As expected, disturbance results in reduction of plant species diversity and native plant species abundance, so that revegetation efforts face multiple challenges (Allen, 1995; Bowen et al., 2005; Wick et al., 2011). These aboveground effects are coupled with reduced soil organic carbon and nitrogen pool sizes (Anderson et al., 2008; Ganjegunte et al., 2009; Mummey et al., 2002; Wick et al., 2009a), along with reduced mineralization rates (Ingram et al., 2005), while soil microbial communities also experience declines in biomass, abundance, and diversity following disturbance (Dangi et al., 2012; Mummey et al., 2002; Stahl et al., 1988). Previously collected data suggest that vegetation and soil properties are consistently negatively affected by disturbance and that these effects may last in excess of 15–20 years (Mummey et al., 2002; Wick et al., 2009a).

The goal of restorationists is to “assist the recovery of ecosystems that have been degraded, damaged, or destroyed” to a

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Abbreviations: ANOVA, analysis of variance; HLMM, hierarchical linear mixed model; MCMC, Markov chain Monte Carlo; FA, fatty acid; PLFA, phospholipid fatty acid.

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stable, self-supporting state (Society for Ecological Restoration International Science and Policy Working Group, 2004). Towards this, the ecological conditions of restored sites are compared to those in reference sites using measurements of ecosystem structure and function; specifically, organism identity, abundance, and distribution, carbon and nutrient pools and transformation rates, soil chemical condition, water cycling, and site resistance to further degradation (Aronson et al., 1993; reviewed in detail by Whisenant, 1999). For such comparisons, first a historical or comparable undisturbed reference site is identified as an example of the specific site conditions that a recovered system should approximate (Aronson et al., 1995; White and Walker, 1997). Next, data collected from the restored and reference sites are analyzed to make meaningful assessments. Traditionally, these comparisons have been made using statistical methods such as t-tests or more generally, analysis of variance (ANOVA), which compare means or averages of the soil property across the different sites. These methods are tied to the assumption that the soil property has a normal distribution at each site and that the variance of the property across the sites is the same.

More recently, there has been recognition that assessment of the degree of variability of a property, i.e., the “spread” of its values, holds ecological relevance and should be recognized as a parameter of specific interest (Benedetti-Cecchi, 2003; Micheli et al., 1999; Palmer et al., 1997). As such, it has been suggested that the variability of ecosystem properties should be a consideration in the analysis of data in restoration settings (White and Walker, 1997). Understanding the patterns of variability that exist in the undisturbed state can inform an acceptable range of values for indicating a property’s recovery. Furthermore, a change in a property’s variance in response to perturbation aids in our understanding of the ecological consequences of disturbance, stability, and recovery (Collins, 1992; reviewed by Fraterrigo and Rusak, 2008).

When incorporating an explicit assessment of variability in an analysis, commonly used mean comparison methods such as ANOVA fall out of favor as they required that variances be equal across sites; adjustment of these procedures for unequal variances leads to other shortcomings. For example, transformations are commonly used for normalizing data, but the scale at which the data was collected is lost so that interpretation becomes complicated. Fraterrigo and Rusak (2008) present a selection of analytical approaches for detecting changes in variability across disturbance treatments—many of which require equal means across treatments or specific characteristics in the distribution of the data. However, it is desirable to have an approach that allows us to directly examine the characteristics of a property across experimental treatments, regardless of equality of means or variances.

In ecological studies, the environment and the soil are typically sampled using a nested design (e.g. sample points within transects/plots within treatments within sampling dates). At each level of sampling, uncertainty is introduced so assessing treatment effects requires statistical methods different from ANOVA. Gili et al., (2013) discuss the application and benefits of hierarchical linear mixed models (HLMMs) for ecological data collected from a nested design. An HLMM accommodates the multi-level nature of the sampling design, accounts for the correlation in data at each level, and partitions sources of variability through the addition of random effects. Data from each hierarchical level are innately correlated, and HLMMs account for that by providing a variance structure that reflects those relationships and their variation. As a result, HLMMs produce more precise estimates at each level, which improves treatment comparison.

Modeling soil data using an HLMM can refine our comparison of recovering soil properties to the undisturbed reference. Furthermore, Bayesian HLMMs produce posterior distributions for model parameters and posterior predictive distributions for the specific soil property of interest. Examining parameters and properties in terms of their distributions allows for easy interpretation as well as allowing for treatment variances to remain unequal so that we can gain inference from the spread of data. Additionally, comparing distributions is simple because they illustrate the relative location and variability of the quantity of interest. Bayesian models provide an interpretation directly in terms of probability; for instance, allowing us to state the posterior predictive probability that a soil property assumes the same range of values in two different treatments. As we illustrate in this paper, posterior predictive distributions provide an intuitive way to explore differences across treatment groups of a soil property. Use of posterior predictive distributions is discussed in general in Gelman et al., (2004), Christensen et al., (2011) and also demonstrated for a soil science application in Huzurbazar et al., (2013).

In this paper, given the nested design of our data collection, we model our data using a HMLM similarly to Gili et al. (2013); however, we augment the analysis by using the HMLM data model with priors on the parameters and proceed to compute posterior distributions for the parameters, and finally posterior predictive distributions for the soil properties of interest. Our purpose is twofold: (1) to examine soil properties on disturbed soils of different ages, in terms of their posterior predictive distributions, to better understand how disturbance and recovery influences the distributional characteristics of soil properties; and (2) to directly compare properties of restored soils to reference soils in a manner that indicates the probability of similarity and illuminates the factors influencing remaining differences.

2. Materials and methods

2.1. Study site description and sampling design

The field sampling location for all work was near Wamsutter, Wyoming (41° 41′ 17.11″ N, 107° 58′ 24.41″ W, elevation = 2052 m). This site lies within Wyoming’s Red Desert Basin and receives an estimated average 180 mm of precipitation per year (Western Regional Climate Center, 2013). The Red Desert is dominated by vegetation associated with big sagebrush (*Artemisia tridentata* Nutt.) and Greasewood (*Sarcobatus vermiculatus* (Hook.) Torrey). All research plots were established in Sagebrush steppe vegetation communities. Soils are classified as frigid typic haplocalcids: well draining, non-saline to slightly saline, calcareous soils originating from weathered sandstone (Natural Resources Conservation Service, 2012).

All research plots were established on a reclaimed pipeline corridor, wherein pipelines were installed directly adjacent to one another, allowing for climate, topography, and parent material to be consistent across study plots. The different installation dates allow for establishment of a chronosequence, or space-for-time substitution. Two undisturbed reference sites and five reclaimed pipelines were sampled, with pipeline treatments including the following recovery times (in years): <1, 4, 28, 35, and 54 (in 2010). On each pipeline and on each reference area (one directly on either side of the pipeline corridor), three 40 m transects were randomly established toward the center of the pipeline scar (and oriented parallel to the pipeline), which served as the basis for all sampling. Some transects fell beside one another, with less than 10 m separation, while others were separated by 10–20 m from end-to-end. All transects fell within a 200 × 20 m area, which was determined by pipeline (treatment) dimensions. The entire sampling area, including all treatments, fell within approximately one hectare. Both vegetation and soil sampling was conducted during springs of 2010 and 2011 during periods of active vegetation growth and prior to vegetation senescence.