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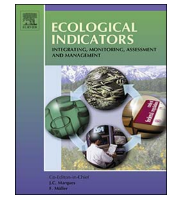

Power and limitation of soil properties as predictors of variation in peak plant biomass in a northern mixed-grass prairie

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A B S T R A C T

Soil properties are thought to affect annual plant productivity in rangelands, and thus soil variables that are consistently correlated with plant biomass may be general indicators of rangeland health. Here we measured several soil properties (e.g. aggregate stability, organic carbon, total nitrogen) and tested each as a would-be predictor of local variation in peak aboveground grassland biomass. Individual properties explained a slight (≤10%) amount of variation in plant biomass. Plant biomass was mainly (negatively) associated with two soil properties, subsurface soil carbonate concentration and the stability of soil macroaggregates near the soil surface. Less important predictive variables included: elevation, plant community composition, surface soil organic carbon, and soil carbon:nitrogen. Plot-to-plot variation in plant biomass is seemingly difficult to predict based on soil properties, including popular indicators of soil and rangeland health and even root biomass. While protection of soil is critical to overall rangeland ecosystem function, our findings suggest that the relationship between soil properties and plant biomass in natural grasslands is complex. Thus, there may not be one or even several soil properties that consistently predict appreciable variation in peak grassland biomass, especially variation within an ecosystem independent of precipitation.

1. Introduction

Rangelands are the most common biome type in the world, occurring in vast regions (Ellis and Ramankutty, 2008). Many have relatively low productivity, yet the capacity of rangelands to annually produce plant biomass (and animal biomass) is a fundamental ecosystem function and measure of their sustainability (De Groot et al., 2002; Havstad et al., 2007). The accurate assessment of whether rangeland function is improving, stable, or degrading is of local to global importance (e.g. Baveye et al., 2016; Eldridge et al., 2016), especially since these regions are understudied relative to their geographic area (Martin et al., 2012). One approach is to indirectly monitor ecosystem function/health (e.g. Reeves and Baggett, 2014; Stephens et al., 2015) with, for example, ground-based data of various indicators of ecosystem function (Pellant et al., 2005; Tongway and Hindley, 2004). There are, however, innumerable putative indicators (e.g. animal, insect, plant, soil, spectral) of ecosystem function and health which ideally require objective (i.e. evidence-based) selection criteria (Andrews and Carroll, 2001; Ludwig et al., 2004; Rezaei et al., 2006). Robust indicators seemingly should be well-documented, highly correlated with ecosystem functions, and have minimal collinearity with other indicator variables (Andrews and Carroll, 2001). Unfortunately, it may be slow, logistically and analytically difficult, and expensive to discern optimal indicators from a large pool of would-be indicators (Andrews and Carroll, 2001; Rezaei et al., 2006; Toledo et al., 2014) and to then determine the importance of each in separate rangeland types. To our knowledge, relatively few studies have attempted to determine the best minimum set of soil properties to predict local variation in plant biomass in natural grasslands (Reinhart et al., 2016; Rezaei et al., 2006).

Despite the popularity of measuring many putative indicators of ecosystem function by land managers and scientists (e.g. Herrick et al., 2010; https://vimeo.com/channels/raythesoilguy), few studies have actually quantified the predictive accuracy of an indicator or determined the best (and worst) predictors (Rezaei et al., 2006; Wang, 2010). One of the most relevant studies tested the importance of many biological, chemical, and physical soil properties on productivity of Iranian rangelands (i.e. total yield, herbaceous plant production, and utilizable forage) (Rezaei et al., 2006). Two of the most important predictor variables were a nutrient cycling index (sensu stricto Tongway and Hindley, 2004) and soil profile effective thickness. Some scientists are starting to acknowledge 1) that many putative soil (health

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or quality) indicators may not explain appreciable amounts of *actual* variation in ecosystem function (Baveye et al., 2016; Bennett et al., 2010; Letey, 1991; Oldfield et al., 2015; Reinhart et al., 2015) and 2) the importance of quantifying the predictive uncertainty of such indicators.

Here we tested (i.e. mensurative experiment) whether local variation in grassland peak (aboveground) biomass could be predicted by other plant, soil, and/or site properties. While moderately large amounts of year-to-year variation in plant biomass ($r^2 \geq 0.74$) was explained by annual variation in precipitation (Wiles et al., 2011), the best predictive soil properties (i.e. soil physical, microbial, and chemical properties) have explained only slight amounts ($0.15 \leq r^2 \leq 0.19$) of local (plot-to-plot) variation in plant biomass in the Northern Great Plains (Reinhart et al., 2016; Reinhart et al., 2015). In previous work, we were able to explain slight amounts of plot-to-plot variation in plant biomass by subsurface (5–15 cm) microbial biomass ($r^2 = 0.18$), plant available nutrients (boron [$r^2 = 0.19$], manganese [$r^2 = 0.17$], and phosphorus [$r^2 = 0.18$]; Reinhart et al., 2016), and soil water infiltration data ($r^2 = 0.15$, Reinhart and Vermeire, 2016). Additional research in northern mixed-grass prairie in North Dakota indicated that comparable amounts of variation in annual net primary productivity were explained by plant (i.e. plant community composition) and soil properties (i.e. bulk density, infiltration, mollic horizon depth, silt, and soil organic matter) (Wang, 2010). We tested whether putative predictors explained appreciable (local) variation in peak plant biomass. Based on prior studies (e.g. Pellant et al., 2005; Rezaei et al., 2006; Wang, 2010), we predicted peak aboveground plant biomass would be positively associated with soil organic carbon concentration, soil organic matter, total nitrogen concentration, and water-stable aggregates.

2. Methods

2.1. Study site and system

Research was conducted at the USDA-Agricultural Research Service's Fort Keogh Livestock and Range Research Laboratory (Fort Keogh, 21,214 ha) near Miles City, Montana, USA. Mean annual precipitation was 34 cm (1937–2011). Peak above-ground annual productivity for this system occurs in July and is dominated by perennial C_3 graminoids (Vermeire et al., 2009). Fort Keogh is centrally located in the Northern Great Plains Steppe ecoregion where grasslands cover more than 22 million ha in five states in the USA and two Canadian provinces and are dominated by temperate and semiarid mixed-grass prairie (Martin et al., 1998). Average annual precipitation for this region ranges from less than 25–50 cm with most occurring during the growing season (May and June). The grasslands support an estimated 11 million animal unit months of livestock grazing.

The study site (46°18′20.8″N, 105°58′42.8″W) is a silty range site on an upland plain with a gentle slope (1.05° slope) and fine loamy soil (Eapa loam, frigid Aridic Argiustolls). Carbonates in the B horizon indicate the site is a calcareous grassland. The study site (0.3 ha) was selected because it matched one of the most common grassland types (*Hesperostipa comata*, *Bouteloua gracilis*, and *Carex filifolia*) in the Northern Great Plains (e.g. Coupland, 1961; Martin et al., 1998) and allowed us to sample across local gradients (plot-to-plot) in peak plant productivity while controlling many abiotic factors.

2.2. Sampling design

Nearly one third (0.1 ha) of the sampled area was within a livestock exclosure established in 1999 (Fig. 1). The other two thirds were equally divided among two pastures that on average were grazed at light to moderate levels (based on USDA-NRCS recommendations) primarily from May through October. In terms of pasture area per cow, pasture "A" averaged 16 ha per cow (522 kg = 1150 lbs) during May and October while pasture "B" averaged 14 ha per cow [between 1991 and 2011 the lowest unit area per cow per month was 2.2 and 2.8 ha per cow, respectively]. We fenced off the remaining sampling area (i.e. portions of pastures "A" and "B" shown in Fig. 1) from livestock in 2011 to prevent removal of pin flags and confounding of plant biomass measures.

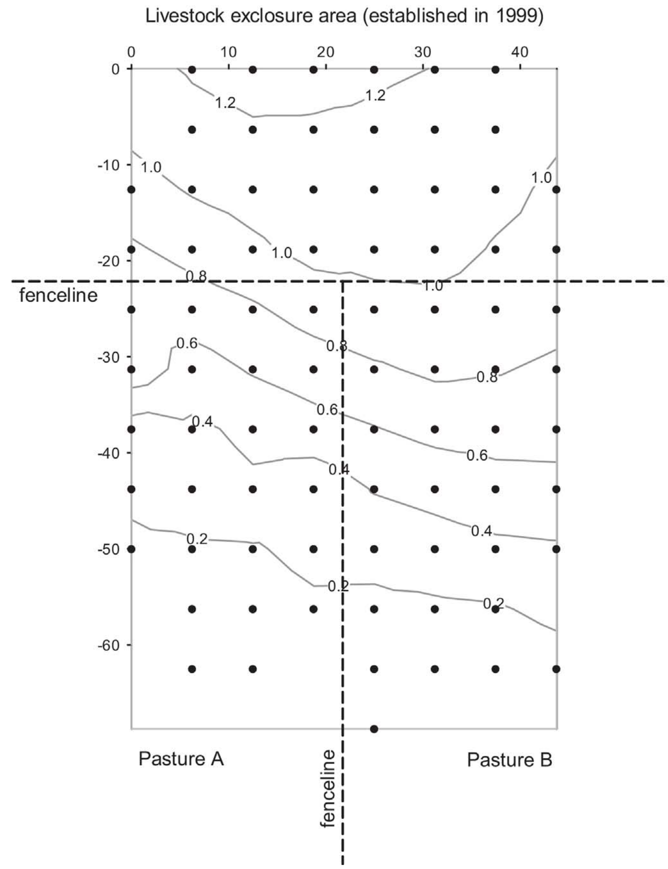

Fig. 1. Map of the sampling grid. Sampling was divided equally among three adjacent areas: a livestock exclosure and two adjacent pastures (A, B) grazed annually by cows. Systematic sampling points (n = 81) are shown (●), axes' units are meters, and contour lines represent elevation gain (m) relative to the lowest point in the sampled area. Map redrawn from Reinhart and Vermeire (2016).

2.3. Plant aboveground biomass and composition

We sampled annual aboveground biomass and community composition at peak production for 81 quadrats (0.25-m^2). Quadrats were placed 0.5 m to the east of each systematically placed point (Fig. 1) and clipped from July 5–12, 2011. The vegetation in the quadrat was clipped and separated by dominant species and functional groups. Dominant species included four graminoids (*Carex filifolia*, *Koeleria macrantha*, *Hesperostipa comata*, and *Pascopyrum smithii*) and one cactus (*Opuntia polyacantha*). Additional species were grouped as forbs, other grasses, or shrubs. Our intent was to measure variation in dominant plant species which are believed to be the main drivers of ecosystem function (Grime, 1998) and may affect soil properties (Derner et al., 2006; Gould et al., 2016; Schuman et al., 2009). Plant material was dried to constant weight, separated into current-year and older material, and weighed. Because *Opuntia* is difficult to dry, we used a correction calculation (0.2 × fresh weight), derived by researchers at Fort Keogh, to estimate the dry weight of *Opuntia*.

2.4. Soil core analysis

We measured several soil properties including: root biomass, soil