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Double Sampling Methods in Biomass Estimates of Andean Shrubs and Tussocks[☆]

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ABSTRACT

The natural Andean vegetation environment is the most important resource available to local pastoralist economies. Knowledge of its attributes is vital in assessing ecosystem properties and improves management decision making. However, there is a lack of research on models that estimate species and life-form biomass for the Puna. We developed a series of models that facilitated the estimation of biomass while avoiding the direct harvesting of the most representative Puna steppe plant species in Jujuy, Argentina. The models thus developed are useful tools in the evaluation of changes in ecosystem dynamics through time and space. Allometric equations were developed for the dominant shrubs (*Baccharis boliviensis*, *Fabiana densa*, *Parastrephia quadrangularis*, *Tetraglochin cristatum*, *Ocyroe armata,* and *Adesmia* sp.) and tussock grasses (*Jarava ichu*, *Festuca crysophylla,* and *Cenchrus chilense*). A field record of the maximum diameter, perpendicular diameter, and height of each plant; number of individuals per plot; and tussock grasses and shrub cover across all vegetation communities was undertaken. Linear regressions including plant measures demonstrated a good fit ($R^2 > 0.7$, $P < 0.001$) to the biomass for individual plants and surface area. The predictive equations developed allow for the rapid and accurate estimation of shrub and tussock biomass. This is essential to monitor the effects of grazing for impact assessment of the different management practices and vegetation dynamics.

Introduction

The Puna, or Altiplano, is a high-altitude Andean ecosystem present in Bolivia, Chile, Peru, and Argentina, where it covers 10,000 km^2 (Alonso and Viramonte, 1987). The plant communities consist mainly of shrub-steppe, with tussocks, short grasses, and dicotyledonous herbs (Cabrera, 1971; Ruthsatz and Movia, 1975). These constitute the main available forage for livestock. This livestock is composed mainly of sheep *(Ovies aries),* llamas *(Lama glama)* (Göbel, 2001; Wawrzyk and Vilá, 2013), and wild vicuñas *(Vicugna vicugna)* (Borgnia et al., 2010; Vilá, 2012; Arzamendia and Vilá, 2014). Native vegetation is the only source of forage, and its seasonal and interannual variability and availability impacts the livestock productive system. Shrubs are also a fuel source, while tussocks are employed as construction material (Genin et al., 1995). Plant biomass is a crucial vegetation attribute that is strongly linked to climate and water availability, as well as other ecosystem properties, such as nutrient cycling, and above-ground net primary, secondary, and livestock production and land degradation (Singh et al., 1975; McNaughton et al., 1989; Fernández et al., 1991). Thus, it is vital to have suitable methods in place to assess above-ground plant biomass, as this is indispensable for carrying capacity estimation and overgrazing avoidance management.

Previous work in the Puna has focused on botanical composition, vegetation units, and cover (Cabrera, 1971; Ruthsatz and Movia, 1975; Bonaventura et al., 1995; Arzamendia et al., 2006). To date there is no published research on models that estimate species and life-form biomass from this area.

Given its accuracy, direct harvest is a widely used method for evaluating vegetation biomass, but it is expensive in both time and resource requirements (Sala and Austin, 2000; Pucheta et al., 2004). Non-destructive techniques, also known as *double sampling methods,* allow for biomass estimates to be calculated from diverse vegetation species

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using allometric equations, augmented through recourse to dimension data obtained in the field (Sala and Austin, 2000; t'Mannetje, 2000).

In this article, we develop a set of predictive models of aboveground biomass; these are then used to estimate North Argentinean Puna shrub and tussock biomass. In turn, these models provide a rapid assessment indicator of environmental disturbances caused by management practices and long-term climate changes, such as duration and intensity of droughts, and for studies of vegetation dynamics.

Methods

Study Site

The study site is located in Santa Catalina (21°56′47.47″S, 66°3′7.32″ W) northwestern Jujuy Province, Argentina. The elevation ranges between 3 700 and 3 800 meters above sea level, and the area covers approximately 14 000 hectares. The climate is cold and dry, presenting an annual average temperature of 7.7°C and a mean annual precipitation of 375 mm, concentrated mainly over the summer wet season (Buitrago, 2000). At the western edge of the study area, steep mountain slopes describe a rough terrain of rocks and shallow soils. The general slope within the study area is oriented toward the East, where the Santa Catalina River flows. The river runs through flat ground, and this area then presents more developed soils and a markedly lower percentage of rock cover.

Phytogeographically, the study site is classified as Andean-Patagonic Domain, Puna Province, with the dominant plant formation being a shrub-steppe (Cabrera, 1971). Dominant shrubs are *Baccharis boliviensis* and *Fabiana densa,* which occur on slopes and foothill areas; *Parastrephia quadrangularis, Tetraglochin cristatum, Baccharis incarum,* and *Ocyroe armata,* which are found on moderate slopes, as well as flat and riparian areas. Dominant tussock grasses are *Jarava ichu,* present on slope and flat areas, and *Festuca crysophylla* and *Cenchrus chilense,* located on flat, riparian, and/or humid areas.

Vegetation Sampling

Aiming to cover all vegetation communities at the study site, we randomly located 136 sampling plots, each 0.5 × 1 m. The size of sampling plots was selected on the basis of the range of plant sizes found in the field in preliminary studies. Sampling was performed during the dry season (September 2012, 2013) and during the wet season (April 2013, February 2014). Due to the intense rain storms and a river flood in summer 2013, the field work of that year was carried out in April, when the rains were less intense. In each plot, all individual plants were measured using a tape measure and registered, through classification into species and life-form (shrub or tussock). The parameters measured in the plants were the standards of this type of work (Assaeed, 1997; Hierro et al., 2000; Oliveras et al., 2014): total height, the vertical distance from ground level to the tallest living tissue (H, cm), maximum diameter (DIAM1, the maximum crown width above the ground, cm), and perpendicular diameter (DIAM2, cm) crown width at right angles to DIAM1. Each individual plant was measured and then cut at ground level and placed in a separate paper bag. Those shrubs whose crown exceeded the limit of the plot were harvested in total form. These were then dried at 60°C to achieve a dry weight. Finally, the dried samples were weighed (g) to the nearest 0.1 g. Shrub and tussock cover (sum of tussocks and shrubs crown area) was assessed through visual estimation of the sampling plots (Matteucci and Colma, 1982), thereby classifying cover into 10 incremental categories of 10%, between 0 and 100.

Data Analysis

Species-specific linear regression equations were developed using the plant dimension measures obtained in the field. The response variable was DW (dry weight), and the explanatory variables were H (height), DIAM1 (maximum diameter), and DIAM2 (perpendicular diameter). Variables were transformed into natural log (ln), thus ascribing to accepted normality and variance homogeneity assumptions (Quinn and Keough, 2002). Analysis was conducted using R statistical software (R Core Team, 2015).

The best allometric equations for each shrub and tussock species were selected according to the highest adjusted coefficients of determination (adjusted *R*-squared), significance (*P* value) of the regression coefficients and residual standard errors (Quinn and Keough, 2002). When several models presented similarly good fit to the data, the regression equation with the smallest number of parameters was chosen.

Data validation was performed through a linear regression between fitted and measured biomass ($g\ m^{-2}$) and by evaluating the confidence intervals of the equation parameters using bootstrap (10 000 replicates) (Crawley, 2007). These data were obtained by taking into consideration the dry weight sum of all individuals in the plot, thereby rendering a dry weight plot total. Models for each life-form, shrub, and tussock grasses were developed to simplify biomass-per-area estimations for use in wider-scale analysis.

Furthermore, our data were run in a model developed for Patagonic steppes by Flombaum and Sala (2007). This model had been developed for estimating biomass through recourse to specific species and life-form cover. The Flombaum and Sala (2007) model was deemed useful for other arid environments, such as the Puna, which is why it was applied to our data.

Results

A total of six shrub species and three tussock species were sampled during the dry and wet seasons. Shrub species were *B. boliviensis*, *F. densa*, *P. quadrangularis*, *T. cristatum*, *O. armata*, and *Adesmia* sp.; tussock species were *J. ichu*, *F. crysophylla*, and *C. chilense*. The sampled species were then modeled using at least one of the dimension measurements obtained in the field. We found that all the equations developed were statistically significant (Table 1 and Fig. 1).

Table 1
Summary statistics from shrub and tussock species.

Species	No.	Variable DW (g) mean (min-max)	H (cm) mean (min-max)	Diam1 (cm) mean (min-max)	Diam2 (cm) mean (min-max)
Baccharis boliviensis	60	97.10 (0.29-897.50)	30.55 (5.00-85.00)	33.93 (8.00-83.00)	27.42 (6.00-75.00)
Tetraglochin cristatum	36	96.59 (2.58-523.50)	22.42 (5.00-39.00)	31.08 (7.00-70.00)	24.94 (4.00, 58.00)
Festuca crysophylla	39	77.67 (1.00-1140.00)	42.45 (10.00-74.00)	42.56 (12.00-90.00)	32.49 (7.00-70.00)
Ocyroe armata	10	92.85 (194.2-420.50)	76.70 (45.00-114.00)	8.80 (49.0-9.70)	77.70 (45.00-134.00)
Jarava ichu	29	21.94 (0.32-183.20)	28.82 (9.00-58.00)	20.69 (5.00-70.00)	13.84 (5.00-52.00)
Parastrephia quadrangularis	36	192.10 (15.28-814.50)	34.67 (10.00-74.00)	51.44 (18.00-100.00)	40.50 (17.00-90.00)
Fabiana densa	16	29.26 (1.38-105.40)	21.11 (10.00-45.00)	20.67 (8.00-38.00)	14.89 (5.00-34.00)
Adesmia sp.	8	23.13 (1.00-74.43)	19.62 (3.00-31.00)	21.88 (10.00-32.00)	18.14 (5.00-30.00)
Cenchrus chilensis	9	58.76 (0.590-11.67)	63.89 (56.00-74.00)	10.00 (4.00-14.00)	6.44 (3.00-10.00)

DW, dry weight in g; H, height in cm; Diam1, maximum diameter in cm; Diam2, perpendicular diameter in cm.

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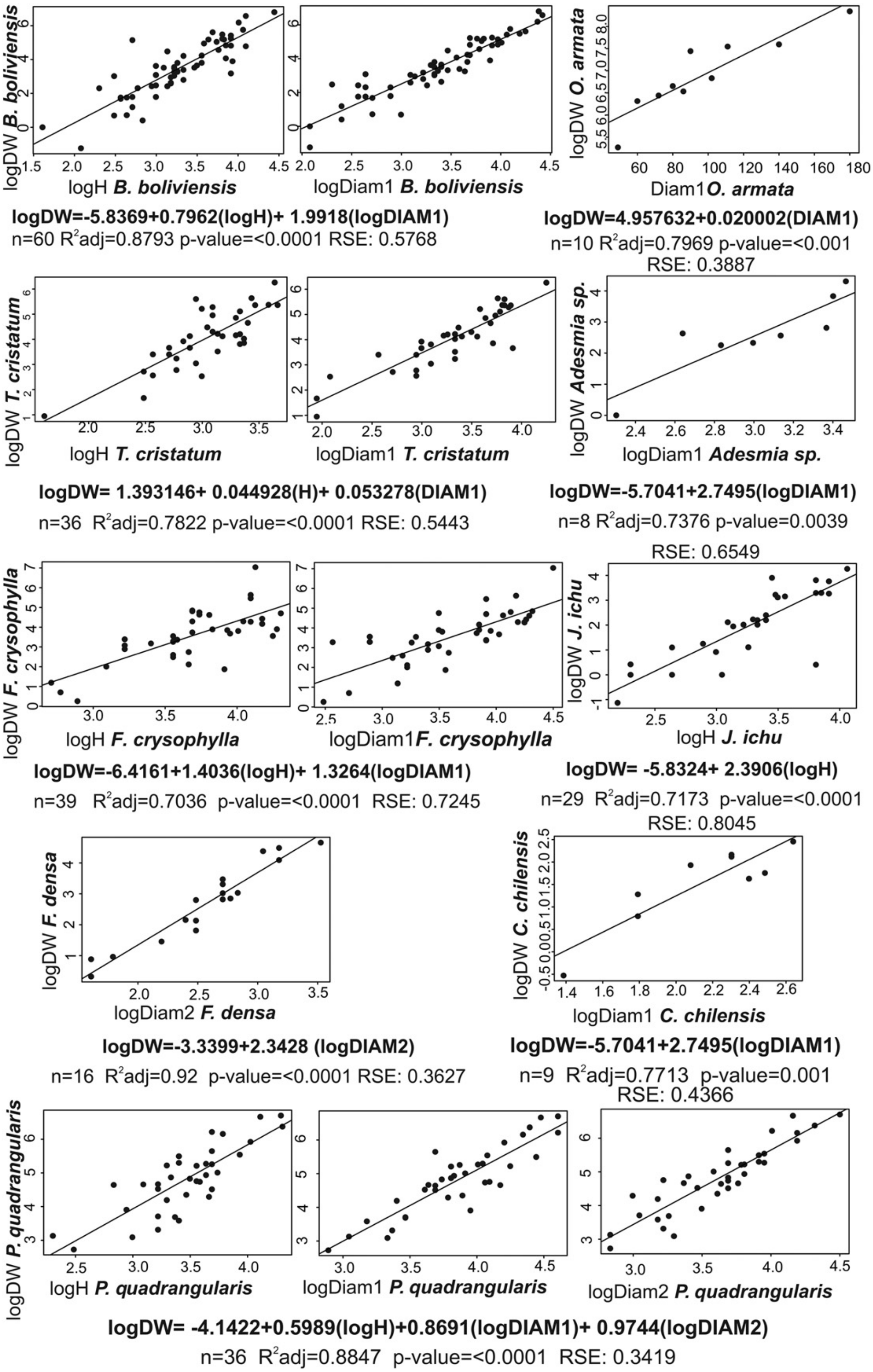

Figure 1. Allometric relationships between lnDW (dry weight natural log) and measures performed in the field including biomass predictive equations and their adjusted R^2, *P* value, standard residual error (RSE), and total number of plants harvested (n) for each species.

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We ran the models using all possible combinations, considering one, two, or three variables. We chose models that showed the lowest standard residual error (RSE) and *P* value and the highest adjusted *R*-squared. In one case, the best model included all three variables, while in most of the models two variables were better than one.

In hemispherically shaped plants—*B. boliviensis, T. cristatum,* and *J. ichu*—the two variables that best explained dry weight variation were maximum diameter and height. For the species that showed similar values across these two variables, such as *F. crysophylla, O. armata,* and *Adesmia* sp., the best variable was maximum diameter. The dry weight variation of *P. quadrangularis* fitted to the model that included the three variables. *Fabiana densa* had its best fit to the model that used only one parameter (perpendicular diameter). This was probably due to its cylindrical shape.

Model validation showed that the models were adequate in predicting the values measured in the field expressed as DW (g m^{-2}). The linear regression between registered biomass data and the fitted values relationship between dry weight per plot (sum of all individuals found in each plot, g m^{-2}) measured through direct harvesting and that calculated through double sampling equations produced an adjusted *R*-squared of 0.89.

Shrub and tussock cover ranged from 25% to 50% and showed variability among vegetation units. Shrub and tussock cover also demonstrated an adequate correlation with biomass, with an adjusted *R*-squared from the linear model of 0.45. Equations that included dimension measures (H, DIAM1, and DIAM2) were found to better fit the data than cover percentage (see Fig. 1).

Models for life-forms also showed a good fit to the data. For shrub biomass (transformed to natural log), the best model included all variables transformed to natural log ($\ln DW = \ln H\ 0.5334 + \ln DIAM1\ 1.2235 + \ln DIAM2\ 0.7983 - 4.5637$, *P* value < 0.00001; adjusted *R*-squared: 0.88 and RSE: 0.59). The shrub model had a high correlation with measured data per m^2 ($P < 0.0001$, adjusted *R*-squared: 0.89, RSE: 209.5).

For grasses, ln DW, H (untransformed), and ln DIAM1 were the variables included in the best fitted model ($\ln DW = H\ 0.028829 + \ln DIAM1\ 1.455765 - 3.017395$, *P* value: < 0.00001; adjusted *R*-squared: 0.73 and RSE: 0.84). When referred to areas (m^2), this model showed a moderate correlation with measured values ($P < 0.001$, adjusted *R*-squared: 0.40, RSE: 74.99). Life-form and individual species models had a high correlation with each other ($P < 0.0001$, adjusted *R*-squared: 0.84, RSE: 384.6), as well as with the dry weight of grasses ($P < 0.0001$, adjusted *R*-squared: 0.94, RSE: 21.61).

Applying Flombaum and Sala's (2007) predictive model to our data of plots containing only shrubs or tussocks yielded a moderate correlation (adjusted *R*-squared 0.65, $P < 0.0001$). Similarly, life-form data were run using the same model (Flombaum and Sala, 2007). Our model showed a high correlation with shrubs ($P < 0.0001$, adjusted *R*-squared: 0.67, RSE: 147.5) and grasses (0.84, $P < 0.0001$, adjusted *R*-squared: 0.68, RSE: 28.29).

Discussion

We developed models that facilitated the estimation of biomass for the most representative plant species of Puna steppe in Jujuy. This method allows us to conduct a rapid assessment, which is often necessary, given the need to advise communities in relation to their management decisions. While other remote methods may be used, they usually work at different scales (such as satellite imagery). Furthermore, some of these remote methods are unviable due to their high cost and because highland atmospheric conditions often preclude routine flights.

All species-specific and life-form specific models were highly significant and included a number of variables that could be easily measured in the field. This result is consistent with models developed for other arid and semiarid ecosystems (Fernández et al., 1991; Assaeed, 1997; Hierro et al., 2000; Guevara et al., 2002; Nafus et al., 2009; McClaran et al., 2013; Oliveras et al., 2014). These models mostly used simple dimension measurements of major species, while vegetation cover estimates were not accurate. Although there was no previous research on this in the study area or of the species analyzed, there was a strong correlation with models developed for Patagonian environments (Flombaum and Sala, 2007). Nevertheless, the existing equations were less accurate and had a higher error (RSE), as well as a lower adjusted *R*-squared.

Dryland perennial species are key for nutrient accumulation, soil fertility, organic matter increase, topsoil retain, and carbon capture (Wezel et al., 2000; Genin and Alzérreca, 2006; Lozano et al., 2013). Therefore, they play an important role in the health of systems at risk from climate change (Wezel et al., 2000; Sala et al., 2012). Tussock grasses and shrub species are essential for Puna rangeland ecology (Arzamendia et al., 2006; Genin and Alzérreca, 2006), given that most of these species are foraged during the dry season and in years of severe drought, even though they are not necessarily preferred (Borgnia et al., 2010). Rural people in the region use *P. quadrangularis*, *B. boliviensis,* and *F. densa* as their main fuel source. Tussock grasses such as *Festuca* spp. and *J. ichu* are also used to build the roofs of rural houses (Genin et al., 1995). Taking into account the importance of these life-forms, the allometric equations developed in this study can help contribute to the assessment of these valuable ecosystem components. A further advantage of not harvesting plants is the possibility of studying their change through time within the Puna system. We found that H, DIAM1, and DIAM2 were adequate explanatory variables to predict aboveground biomass from shrubs and tussock grasses of Puna.

Implications

The natural vegetation of the Puna is the most important resource available to local pastoralist economies. So, developing predictive equations to monitor Puna vegetation is a much-needed tool in improving management and conservation strategies. Also, these predictive equations reduce the time and money taken up by monitoring, thereby potentially increasing the number of monitoring points, and thereby better addressing spatial variability. The use of plant dimensions that can be easily registered in the field, allow for the rapid assessment of biomass, when linked to a valid, accurate methodology grounded in scientific rigorousness. Nevertheless, more accurate monitoring is required in this arid region, given its susceptibility to climate change, overgrazing and desertification.

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