

# Predictive equations for biomass and fuel characteristics of Argentine shrubs

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## Abstract

Predictive equations for estimating shrub biomass in semi-arid scrub ecosystems are essential for evaluating shrub encroachment, conducting ecosystem-level studies of net primary productivity (NPP) and nutrient cycling, and examining effects of different fire regimes. In this study, we developed predictive equations to estimate total aboveground biomass and biomass of foliage and stems of the 8 most common shrubs in the semi-arid scrub (Monte) of central Argentina. We also examined the relationship between shrub size and proportions of these components for the dominant species, *Larrea divaricata* Cavanilles (creosotebush), and determined fuel characteristics (dead-to-live ratio, bulk density) of the 8 shrub species. Regression analyses were used to examine the relationships between aboveground biomass and 5 field measurements (diameter of the longest stem, shrub height, maximum crown width, crown width at right angles to maximum crown width, and crown volume). A natural log-log model based on a single variable best described this relationship in most cases. The easiest field measurement for 6 of the 8 species was diameter of the longest stem, and this measure was often the best predictor of shrub biomass. As *L. divaricata* increased in size, the proportional biomass of large stems increased, and biomass of foliage and small stems decreased. This pattern suggests productivity may decrease with shrub age. The mass of dead material was low in most shrub species. Bulk densities were comparable to those of shrubs in other semi-arid ecosystems. Equations developed here will allow rapid and accurate estimation of shrub biomass in the Monte of Argentina.

**Key Words:** Semi-arid scrub, *Larrea*, shrub biomass, Monte, Argentina

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## Resumen

Las ecuaciones predictivas para estimar la biomasa de arbustos en ecosistemas semiáridos son esenciales para evaluar incrementos en la densidad de arbustos, para conducir estudios de productividad primaria neta (PPN) y ciclo de nutrientes y para examinar los efectos de diferentes regímenes de fuego. En este estudio se desarrollaron ecuaciones predictivas para estimar biomasa aérea total y biomasa de hojas y ramas de las 8 especies de arbustos más comunes en el arbustal semiárido (Monte) del centro de Argentina. También se examinó la relación entre el tamaño del arbusto y la proporción de cada uno de estos componentes en la especie dominante, *Larrea divaricata* Cavanilles (jarilla), y se determinaron características combustibles (proporción de muerto a vivo, densidad de la corona) en las 8 especies. La relación entre biomasa aérea y 5 medidas tomadas en el campo a los arbustos (diámetro de la rama más larga, altura, ancho máximo de la corona, ancho perpendicular al ancho máximo y volumen) fue evaluada mediante el uso de análisis de regresión. En la mayoría de los casos, el modelo logarítmico natural con una sola variable fue el que mejor describió esta relación. La medida más fácil de tomar en el campo en 6 de las 8 especies fue el diámetro de la rama más larga, la que frecuentemente fue la que mejor predijo la biomasa de los arbustos. El aumento en tamaño de *L. divaricata* fue acompañado por un aumento en la proporción de biomasa aportada por las ramas grandes, y por un descenso en la proporción de biomasa aportada por hojas y ramas pequeñas. Este patrón sugiere que la productividad de los arbustos decrecería con la edad. La cantidad de material muerto fue escasa en la mayoría de las especies. La densidad de la corona de los arbustos fue comparable a la de arbustos en otros ecosistemas semiáridos. Las ecuaciones desarrolladas aquí permitirán una estimación rápida y precisa de la biomasa de arbustos en el Monte de Argentina.

Shrubs are a major component of vegetation in semi-arid ecosystems worldwide, and their ability to dominate these systems is a matter of ecological and economic concern (Schlesinger et al. 1990). Predictive equations for estimating shrub biomass from relatively simple morphometric data collected in the field have been developed for shrubs in a variety of ecosystems (see Etienne 1989, Catchpole and Wheeler 1992 for reviews), but are generally lacking for the semi-arid Monte of Argentina (Braun et al. 1979). This ecosystem is similar to creosotebush [*Larrea tridentata* (Sesse & Moc. ex DC) Cov.]-dominated regions in North

America, and covers an area of 600,000 km<sup>2</sup>, or about 16% of Argentina (Ragonese 1967). Reliable equations to estimate woody vegetation biomass are needed for evaluating rates of shrub encroachment, for estimating fuel loads for fire models and evaluating effects of various fire management regimes, as well as for ecosystem-level studies of net primary productivity (NPP) and nutrient cycling.

Our research had 3 objectives: 1) to develop predictive equations to estimate total aboveground biomass, as well as biomass of foliage and stems (grouped by diameter class) of the 8 most common shrubs in Monte of central Argentina; 2) examine the relationship between shrub size and relative proportions of components (foliage and stems) for the dominant species, *Larrea divaricata* Cavanilles (creosotebush); and 3) determine fuel characteristics (dead-to-live ratio and bulk density, i.e., biomass per unit volume occupied by biomass and air) of these 8 species.

## Materials and Methods

### Study Area

Shrubs were collected at Los Ranqueles Ranch (18,000 ha) located 15 km E of Lihue Calel National Park (38° 00' S, 65° 00' W) in La Pampa province, Argentina. The climate is characterized by hot summers, cool winters, and low, unpredictable rainfall (mean annual precipitation from 1983 to 1993 was 524 ± 175 mm (Dirección de Estadística y Censos 1981, 1991, Lihue Calel National Park, unpubl. data). The vegetation consists of a mosaic of shrub patches and open areas. *L. divaricata* generally comprises 80–90% of the shrub biomass; other less abundant shrubs include *L. cuneifolia* Cavanilles (jarilla macho), *Condalia microphylla* Cavanilles (piquillín), *Geoffroea decorticans* (Gill ex Hook. et Arnott) Burkart (chañar), and *Prosopis flexuosa* DC var. *depressa* F.A.

Roig (alpataco dulce) (Instituto Nacional de Tecnología Agropecuaria 1980). Open areas and the understory below shrubs consist of subshrubs [e.g., *Acantholipia seriphioides* (A. Gray) Moldenke (tomillo), *Senna aphylla* (Cay.) Irwin & Barneby (pichanilla)], grasses (e.g., *Stipa* spp.), and herbs [e.g., *Medicago minima* (L.) Grufberg (trébol de carretilla), *Erodium cicutarium* (L.) L'Herit. Ex Ait. (alfilerillo), and *Baccharis* spp.].

### Shrub Sampling

Shrubs of *Chuquiraga erinacea* Don (chilladora), *C. microphylla*, *G. decorticans*, *L. cuneifolia*, *L. divaricata*, *L. nitida* Cavanilles (jarilla crespá), and *P. flexuosa* var. *depressa* were sampled during the period of maximum leaf area (late spring to early autumn) of 1993–1994 and 1994–1995. Individual plants were selected to encompass a range of heights and canopy forms observed in the field (Table 1). Saplings (individuals 3.20-m height) of the tree *Prosopis caldenia* Burkart (caldén) were also collected and treated as shrubs in this analysis. All shrubs were measured for: 1) diameter of the longest stem at 10 cm above the ground (dls) to the nearest 0.05 mm using a caliper, 2) height from ground level to the tallest living tissue (h) to the nearest 5 cm, 3) maximum crown width (mcw) to the nearest 5 cm, and 4) crown width at right angles to mcw (cw90) to the nearest 5 cm. Shrubs were then cut at ground level and placed in separate bags. Diameter of the longest stem was not measured in *C. microphylla* or *P. flexuosa* var. *depressa* because the canopy structure and abundant thorns of these species made it difficult and impractical to measure.

All shrubs were transported to the laboratory, dried at 65°C to a constant weight, and weighed to determine total biomass. A representative sample of each individual (about 25 %) was selected and separated into foliage and live and dead stems. Stems were further divided into diameter

classes representing standard time lags for equilibrating fuel moisture models as follows: <6 mm (1 hour), 6–25 mm (10 hrs), >25–76 mm (100 hrs) (Fosberg 1970, Rothermel 1972, Kessel et al. 1978, Pereira et al. 1995). All components were then weighed separately.

### Data Analysis

Biomass of each component was calculated by multiplying the proportion of each component in the subsample by the total biomass of each shrub. Crown volume (vol) was calculated using the formula for the solid object that best fits the natural shape of each shrub species (Ludwig et al. 1975, Murray and Jacobson 1982, Molinero 1983, Etienne 1989) as follows: *Larrea* spp., *P. caldenia*, *G. decorticans*, and *C. erinacea*, inverted cone [ $\frac{1}{3} R^2 h$ , where R = radius, calculated as  $(mcw + cw90)/4$ ]; *C. microphylla*, upper half of a spheroid ( $\frac{4}{3} R^2 h$ ); *P. flexuosa* var. *depressa*, upper half of a prolate spheroid ( $\frac{4}{3} mcw cw90h$ ).

Regression analyses were conducted with the statistical package SPSS (SPSS Inc. 1996) to examine the relationship between total aboveground biomass, and the bioass of each component and each of the field measurements (dls, h, mcw, cw90 and vol). The following linear models were evaluated: 1) simple linear ( $y = b x$  and  $y = a + b x$ ); 2) natural logarithmic ( $y = a + b \ln(x)$ ); 3) natural log-log ( $\ln(y) = \ln(a) + b \ln(x)$ ); 4) exponential ( $\ln(y) = \ln(a) + b x$ ); and 5) multiple regression ( $y = a + b_1 x_1 + b_2 x_2$  and  $\ln(y) = \ln(a) + b_1 \ln(x_1) + b_2 \ln(x_2)$ ). The best models for each species were selected based on the maximum values of the coefficients of determination ( $r^2$ ) and standard errors of the estimate ( $S_{y,x}$ ). When more than 1 model presented similarly good fit to the data, the regression equation with the fewest parameters was chosen as the best model.

Although logarithmic models often are used to predict biomass of shrubs from

**Table 1. Number of individuals, ranges of measurements [dry weight (w), volume<sup>1</sup> (vol.), and height (h)] and mean values ± SE of bulk density ( $\psi_b$ ) and dead to live ratio (dl) of each species.**

Species	n	w (g)	vol (ms <sup>3</sup> )	h (m)	b (g m <sup>-3</sup> )	d/l
<i>C. erinacea</i>	10	90.5 – 5026.2	0.02 – 1.09	0.40 – 1.10	4955.4 ± 400.9	0.02 ± 0.01
<i>C. microphylla</i>	15	25.8 – 41326.1	0.02 – 43.28	0.20 – 2.40	1785.0 ± 163.8	0.02 ± 0.01
<i>G. decorticans</i>	15	11.2 – 11228.3	0.001 – 2.48	0.20 – 2.70	4854.8 ± 511.7	0.02 ± 0.01
<i>L. cuneifolia</i>	15	17.6 – 10503.7	0.02 – 5.79	0.40 – 2.30	2285.8 ± 224.1	0.01 ± 0.00
<i>L. divaricata</i>	30	63.4 – 24085.0	0.03 – 20.17	0.55 – 3.30	1324.1 ± 77.9	0.01 ± 0.00
<i>L. nitida</i>	15	49.4 – 31923.3	0.03 – 16.83	0.45 – 2.85	1671.2 ± 100.5	0.04 ± 0.01
<i>P. caldenia</i>	15	89.3 – 14257.5	0.06 – 7.54	0.50 – 3.20	1396.9 ± 115.8	0.01 ± 0.00
<i>P. flexuosa</i> var. <i>depressa</i>	15	107.6 – 19705.2	0.49 – 94.00	0.30 – 2.00	158.7 ± 11.3	0.17 ± 0.04

**Table 2.** Best fit linear equations and power equations for predicting total aboveground biomass, foliage biomass, and biomass of stems by diameter class (<6, 6–25, > 25 mm) for 8 woody species.  $S_{y,x}$  = standard error of the estimate for linear equations ( $S_{y,x1}$ ), back-transformed values from log-log models ( $S_{y,x2}$ ), and power equations ( $S_{y,x3}$ );  $r^2$  = coefficient of determination for linear equations ( $r_1^2$ ) and power equations ( $r_2^2$ ); w = dry weight (g); vol = volume (m<sup>3</sup>); dls = diameter of the longest stem at 10-cm height (mm); mcw = maximum crown width (m); cw90 = crown width at right angles to mcw (m); h = height (m); ln = natural log. Total biomass equations using dls are presented for all species in which this variable was measured, even though this was not always the best predictor, because dls is the easiest variable to measure and is a good predictor of biomass. All models are significant at  $p < 0.005$ .

Species	n	Biomass	Best fit linear equation	$S_{y,x1}$	$S_{y,x2}$	$r_1^2$	Power equation	$S_{y,x3}$	$r_2^2$
<i>C. erinacea</i>	10	Total	$\ln(w) = 6.55 + 2.55 \ln(mcw)$	0.28	513.66	0.95	$w = 786.93 mcw^{2.31}$	502.03	0.91
			$\ln(w) = 1.11 + 2.21 \ln(dls)$	0.84	1084.83	0.56	$w = 30.99 dls^{1.46}$	922.66	0.68
	10	Leaves	$\ln(w) = 6.80 + 0.96 \ln(mcw)$	0.29	286.87	0.84	$w = 899.47 mcs^{1.04}$	281.63	0.80
		< 6 mm	$\ln(w) = 5.70 + 1.34 \ln(cw90)$	0.32	103.10	0.92	$w = 292.70 cw90^{1.44}$	103.28	0.81
		6–25 mm	$\ln(w) = 7.58 + 0.90 \ln(vol)$	0.41	166.61	0.95	$w = 1982.46 vol^{0.92}$	165.59	0.95
<i>C. microphylla</i>	15	Total	$\ln(w) = 6.77 + 2.93 \ln(mcw)$	0.29	5592.90	0.98	$w = 1692.02 mcw^{2.24}$	2374.36	0.96
			$\ln(w) = 5.04 + 2.19 \ln(mcw)$	0.23	162.74	0.98	$w = 116.42 mcw^{2.43}$	160.62	0.98
	15	< 6mm	$\ln(w) = 6.39 + 2.40 \ln(cw90)$	0.35	572.30	0.95	$w = 342.58 cw90^{2.82}$	345.65	0.99
		6–25 mm	$w = -2448.99 + 3578.03 cw90$	653.98		0.96			
<i>G. decorticans</i>	15	Total	$\ln(w) = -2.15 + 2.64 \ln(dls)$	0.32	886.67	0.98	$w = 0.41 dls^{2.31}$	406.15	0.99
			$\ln(w) = 3.71 + 2.60 \ln(h)$	0.46	51.20	0.92	$w = 43.27 h^{2.65}$	42.63	0.97
	15	< 6 mm	$\ln(w) = 5.15 + 2.80 \ln(h)$	0.33	577.41	0.96	$w = 318.40 h^{1.80}$	283.82	0.86
		6–25 mm	$\ln(w) = -4.17 + 2.96 \ln(dls)$	0.24	348.83	0.99	$w = 0.07 dls^{2.58}$	276.72	0.96
		> 25 mm	$\ln(w) = 6.99 + 0.90 \ln(vol)$	0.29	428.87	0.92	$w = 1149.97 vol^{0.65}$	360.00	0.79
<i>L. cuneifolia</i>	15	Total	$\ln(w) = -0.60 + 2.72 \ln(dls)$	0.47	1804.25	0.93	$w = 6.73 dls^{1.94}$	613.85	0.95
			$\ln(w) = 5.69 + 0.60 \ln(vol)$	0.33	135.93	0.93	$w = 233.83 vol^{0.81}$	79.11	0.97
	15	< 6 mm	$\ln(w) = 6.45 + 0.77 \ln(vol)$	0.36	367.91	0.95	$w = 677.67 vol^{0.63}$	219.63	0.94
<i>L. divaricata</i>	14	6–25 mm	$\ln(w) = 7.05 + 1.16 \ln(vol)$	0.53	3024.72	0.95	$w = 1670.55 vol^{0.70}$	372.93	0.98
			$\ln(w) = 7.19 + 0.93 \ln(vol)$	0.32	2423.82	0.96	$w = 1410.32 vol^{0.94}$	2307.43	0.87
	30	Leaves	$\ln(w) = -0.72 + 2.71 \ln(dls)$	0.44	3731.82	0.93	$w = 6.11 dls^{2.03}$	3509.81	0.70
			$\ln(w) = 4.40 + 1.68 \ln(cw90)$	0.54	211.19	0.83	$w = 88.51 cw90^{1.77}$	200.89	0.66
<i>L. nitida</i>	15	Total	$\ln(w) = 5.37 + 1.93 \ln(cw90)$	0.43	419.71	0.91	$w = 285.02 cw90^{1.61}$	405.18	0.76
			$\ln(w) = 6.49 + 1.24 \ln(vol)$	0.43	1036.75	0.96	$w = 764.32 vol^{1.11}$	1142.68	0.89
	11	> 25 mm	$\ln(w) = 5.03 + 1.15 \ln(vol)$	0.65	794.16	0.62	$w = 70.43 vol^{1.60}$	607.11	0.80
			$\ln(w) = 7.39 + 0.99 \ln(vol)$	0.26	3221.38	0.99	$w = 12.14 vol^{2.74}$	4185.39	0.77
			$\ln(w) = -0.76 + 2.77 \ln(dls)$	0.60	2676.48	0.92	$w = 0.30 dls^{2.85}$	2203.00	0.94
<i>P. caldenia</i>	15	Leaves	$\ln(w) = 4.46 + 1.97 \ln(mcw)$	0.50	131.24	0.85	$W = 89.61 MCW^{1.95}$	130.54	0.91
			$\ln(w) = 6.18 + 0.83 \ln(vol)$	0.29	270.20	0.96	$w = 386.34 vol^{0.83}$	141.11	0.96
	15	6–25 mm	$\ln(w) = 6.86 + 1.30 \ln(vol)$	0.40	2451.62	0.97	$w = 1389.00 vol^{0.88}$	380.75	0.98
			$\ln(w) = -0.43 + 2.18 \ln(dls)$	0.28	1200.28	0.97	$w = 0.08 dls^{2.68}$	1030.40	0.93
			$\ln(w) = 5.27 + 0.88 \ln(vol)$	0.33	67.64	0.94	$w = 219.94 vol^{0.84}$	62.89	0.89
<i>P. flexuosa</i> var. <i>depressa</i>	15	Total	$\ln(w) = -0.32 + 1.85 \ln(dls)$	0.27	267.93	0.96	$w = 106 dls^{1.76}$	267.85	0.85
			$\ln(w) = 5.84 + 2.85 \ln(cw90)$	0.41	517.63	0.93	$w = 220.83 cw90^{3.78}$	412.51	0.89
	8	> 25 mm	$\ln(w) = 5.75 + 1.98 \ln(vol)$	0.45	288.08	0.87	$w = 373.91 vol^{1.75}$	238.78	0.96
			$\ln(w) = 6.24 + 2.63 \ln(cw90)$	0.32	2313.61	0.96	$w = 208.02 cw90^{3.60}$	1893.13	0.88
15	Leaves	$\ln(w) = 3.19 + 0.85 \ln(vol)$	0.40	160.33	0.95	$w = 61.99 vol^{0.61}$	117.51	0.91	
		< 6 mm	$\ln(w) = 4.52 + 0.98 \ln(vol)$	0.27	1240.57	0.98	$w = 70.91 vol^{0.99}$	1009.05	0.87
12	6–25 mm	$\ln(w) = 5.16 + 1.98 \ln(mcw) + 3.25 \ln(h)$	0.59	0.94					

other morphometric data (Murray and Jacobson 1982, Hughes et al. 1987, Pereira et al. 1995), log-antilog transformations sometimes can result in biased estimates of biomass (Tausch and Tueller 1988). Therefore, where a logarithmic model was selected as the best model, we also present the corresponding nonlinear model, and compare the standard error of the estimate from this model with the standard error of the estimate calculated using back-transformed estimates from the logarithmic model. For these comparisons, predicted biomass from the logarithmic equation was converted to the arithmetic form (anti-log) and the standard error was computed using actual biomass and the

corresponding predicted biomass. Regressions were not performed on the component of stems > 25 mm for *L. cuneifolia*, *L. nitida*, *C. erinacea*, and *P. flexuosa* var. *depressa* because only a few individual plants of these species had large stems (n = 5, 4, 2, and 0, respectively).

For *L. divaricata*, the relationships between total biomass and relative proportions of the various components (leaves, stems < 6 mm, stems 6–25 mm, stems > 25 mm) were examined using best fit nonlinear models. The model with the highest  $r^2$  was selected for graphical presentation.

Dry weight and volume of total aboveground biomass were used to calculate bulk density for each species. Packing

ratio, the ratio between bulk density and specific gravity (i.e., biomass per unit volume occupied by the biomass alone), is commonly used to describe the compactness of fuel (Rothermel 1972, Van Wilgen et al. 1990, Pereira et al. 1995). In fire models, specific gravity is usually considered a constant (Rothermel 1972); thus, bulk density is the primary variable that determines compactness (Brown 1981).

## Results and Discussion

For all shrub species, at least 1 of the morphological measurements was a good predictor of total aboveground biomass, as

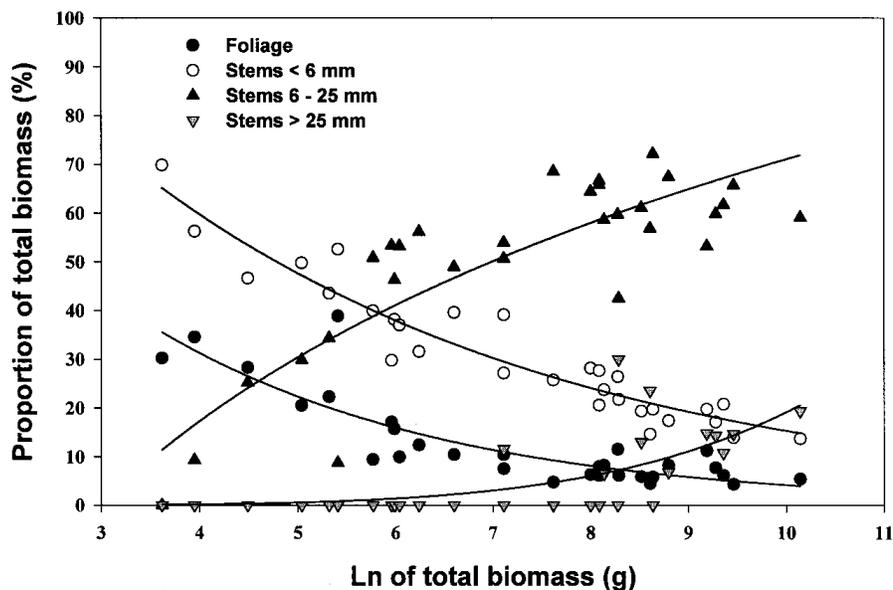


Fig. 1. Proportional biomass of foliage and stems as a function of total biomass of *L. divaricata* ( $n = 30$ ). Foliage ( $y = 120.76 e^{-0.34x}$ ,  $r^2 = 0.75$ ); stems < 6 mm diameter ( $y = 148.38 e^{-0.23x}$ ,  $r^2 = 0.90$ ); stems 6–25 mm diameter ( $y = -64.15 + 58.69 \ln(x)$ ,  $r^2 = 0.73$ ); stems > 25 mm diameter ( $y = 0.001 x^{5.20}$ ,  $r^2 = 0.44$ ). Ln = natural log. All models are significant at  $p < 0.0001$ .

well as the biomass of each component (Table 2). Predictive equations developed using a single independent variable had a better fit to the data when compared to equations using 2 independent variables in all but 1 case (6–25 mm stems of *P. flexuosa* var. *depressa*). The easiest field measurement to make for 6 of the species was diameter of the longest stem, and equations for total aboveground biomass using this variable had a good fit to the data except for *C. erinacea* (Table 2).

In most cases, a natural log-log model gave the best fit between field measurements and total aboveground biomass, and between field measurements and biomass of components for linear models (Table 2), similar to results reported in other studies (Brown 1976, Ohmann et al. 1976, Murray and Jacobson 1982, Rittenhouse and Sneva 1977, Braun et al. 1979, Bryant and Kothmann 1979, Hughes et al. 1987, Pereira et al. 1995). In all species except *L. nitida*, standard errors of the estimate computed from power equations were lower than those calculated using back-transformations from log-log regression. Coefficients of determination generally were high for both log-log and power equations. In view of the potential for bias in predicting biomass from equations developed with transformed data (Sprugel 1983), power equations provide a good alternative to log-log equations for the shrub species in our study.

The plot of total aboveground biomass

vs the proportion of biomass components for *L. divaricata* (Fig. 1) indicates that as shrubs grow, the proportions of foliage and stems < 6 mm decrease, while the proportions of stems of 6–25 mm diameter and larger increase. If carbon respired by live stem tissue represents an increasingly larger amount of carbon fixed in foliage by photosynthesis, then productivity of shrubs should decrease with age. This age/productivity relationship is well known for trees in a variety of ecosystems (Ryan et al. 1997, Carey et al. 1998), but it is poorly documented for shrubs.

*C. erinacea* and *G. decorticans* had the highest bulk densities, *Larrea* spp., *P. caldenia*, and *C. microphylla* were intermediate, and *P. flexuosa* var. *depressa* had a much lower bulk density (Table 1). With the exception of *P. flexuosa* var. *depressa*, bulk densities of shrubs in our study area are comparable to those of shrubs in other fire-prone ecosystems (Van Wilgen et al. 1990, Pereira et al. 1995). Dead material was a small component of total aboveground biomass of the shrubs examined; the maximum mean value was 17 % dead material for *P. flexuosa* var. *depressa* (Table 1). For all species, stems < 6 mm diameter represented most of the dead material [e.g.,  $90.8 \pm 5.4\%$  for *P. flexuosa* var. *depressa*].

As in North America, livestock ranching is the predominant land use in creosote-bushdominated ecosystems in Argentina.

Overgrazing in semi-arid ecosystems in North America has favored shrubs over herbaceous vegetation (Schlesinger et al. 1990). The impacts of livestock grazing in Argentine Monte have not been assessed, but similar patterns may occur. Fire is an important natural component of these ecosystems, and is used extensively as a management tool to control shrubs. The predictive equations for biomass developed in this study will allow rapid and accurate estimation of shrub biomass in the Monte of Argentina. This information is essential for monitoring the effects of grazing on shrub dynamics, for examining the impacts of different fire regimes on the aboveground biomass of shrubs, and for studies of ecosystem productivity.

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