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Short communication

Estimating *Arundo donax* shoot biomass

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Abstract

We developed an equation for estimating *Arundo donax* shoot dry weight from shoot length. The equation, shoot dry weight (g) = 14.254 (standard error = ±0.275) × shoot height^2 (m), was as effective at explaining a high proportion of total variation in shoot dry weight (R^2 = 0.90) as more complicated equations containing additional morphometric parameters. Tested against two independent datasets, the equation provided accurate estimates of dry weight for shoots ranging from 0.3 to 7.06 m height (dataset 1, $P < 0.0001$, R^2 = 0.87, N = 29; dataset 2, $P < 0.0001$, R^2 = 0.82, N = 192). The equation provides aboveground biomass estimates from stem counts and heights more rapidly than harvest methods.
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1. Introduction

Plant biomass is typically measured by harvesting plants from sample plots and determining their dry weight. This approach is appropriate for simple communities of short-lived plants (Whittaker and Marks, 1975). In communities composed of long-lived plants with complex structures, this approach is more difficult (Whittaker, 1961). Dimension analysis is an alternative to harvest techniques (Whittaker, 1962). This method involves deriving equations describing growth relationships from intensive measurements of a relatively small number of sample plants. These equations are then used to estimate biomass from plant characteristics (e.g. stem height, stem diameter, etc.) that are more easily measured. For example, Daoust and Childers (1998) estimated individual biomass for nine species of wetland plants using various morphological measurements. Van et al. (2000) developed an equation for predicting *Melaleuca quinquenervia* (Cav.) S. T. Blake aboveground biomass based on stem diameter. Sidorkewicj and Fernandez (2000) used a line intersection method to estimate foliage length for *Potamogeton pectinatus* L. Using non-destructive sampling methods allows repeated biomass estimates of individual plants over time. This capability is important for estimating impacts of management techniques such as biological control in permanent field plots where destructive sampling is not possible (Van et al., 2000). In addition, recent interest in these types of equations has focused on their application to estimating carbon pools and fluxes between vegetation and the atmosphere (Chave et al., 2005).

Arundo donax L. is a tall perennial reed that is frequently found growing in water and is classified as an emergent aquatic plant (Cook, 1990). It is a C_3 grass (Rossa et al., 1998) that may grow in large dense clumps up to several meters across and containing stems (up to several hundred per clump) that may reach 9 m in height. In riparian habitats throughout the United States, from northern California to Maryland *A. donax* is an invasive weed (Bell, 1997). In California, it often acts as a transformer species (Richardson et al., 2000) changing the control of riparian habitats from being flood-regulated processes to those that are fire-regulated (Rieger and Kreager, 1989).

The purpose of this study was to develop an equation for estimating *A. donax* biomass from measurements more easily obtained than collecting harvest estimates.

2. Methods

We collected 212 individual *A. donax* stems from three sites in northern California (site 1 = 38°41.212′N 121°52.659′W;

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site 2 = 38°38.199′N 121°51.485′W; site 3 = 38°33.692′N 121°52.349′W) on several sampling dates (6/6/99, 9/1/99, 4/23/03, 4/28/04, 5/24/04, 6/7/04 and 6/21/04). For each stem we measured its height, the number of leaves, the number of branches, the diameter at the base, top, and at the midpoint of the stem. We determined the dry weight of individual stems and leaves by drying them for 48 h at 80 °C. For stems that had branches, the combined dry weight of all branches per stem was also determined. Individual leaves were photographed and their areas and lengths determined using an image analysis program (Sigma Scan Pro, SPSS, Inc., Chicago, Illinois, USA). A coin was included in each photograph for internal calibration. Using a randomization procedure, we selected 29 shoots from the dataset to use as validation dataset.

With the remaining shoots, we used the regression procedures within SAS (SAS Institute Inc., 1999) to evaluate statistical relationships between various morphological measurements and biomass. The procedure we used allows for the calculation of all possible linear regression models based on a given set of predictor variables. We chose to use the linear approach because it yields simple models whose terms are easily interpreted, methods for comparing various models are more straightforward, and other authors have reported that the power function adequately summarized results for many types of species (see Batschelet, 1973 and references cited therein). Because the goal was to minimize the number of measurements required to estimate stem biomass, we selected the equation with the fewest number of variables that resulted in the highest value of the coefficient of determination (R^2). Once the appropriate regression equation was derived, we used it to estimate the biomass of each of the 29 shoots in the validation dataset based on shoot height. We compared the estimated dry weights with the actual shoot dry weights in two ways. First, we calculated a linear regression of the estimated shoot dry weights versus the actual shoot dry weights, and secondly, we calculated a *t*-statistic to compare the actual and estimated dry weights (SAS Institute Inc., 1999).

In order to further test the selected equation, we collected additional *A. donax* from sites in Mississippi (32°17.998′N, 90°52.064′W, 8/26/05), Texas (34°04.889′N, 99°02.024′W, 8/18/05), and California (site 1, 39°15′N, 122°15′W, 8/26/05; site 2, 33°56.675′N, 117°28.642′W, 9/8/05). A 0.2 m × 0.3 m rectangular metal quadrat was placed within individual *A. donax* clumps. The number of stems within the quadrat was counted and recorded. Each stem was cut at ground level using shears. Its height was determined to the nearest centimeter with a cloth-measuring tape. Each stem was then cut into smaller sections, which were sealed in paper bags and returned to the laboratory at Davis, California where the dry weight of each was determined as above. The biomass of each shoot in this second validation dataset was also estimated using the equation selected above based on shoot height. We compared the estimated dry weights with the actual shoot dry weights using the two methods described above. We used estimated and measured shoot biomass to determine *A. donax* biomass (g m^{-2}) at each site.

3. Results

The shoots used in this study displayed considerable morphological variation and were representative of *A. donax* from habitats in northern California (Table 1). On average 20% of shoot biomass was allocated to leaves for shoots <1 year old and about 13% to a combination of branches and leaves for plants >1 year old. The relationship between shoot weight and shoot height was not well-described by a straight line (Fig. 1A). A regression equation with the square of shoot height as the independent variable was as effective as any other single independent variable or combination of independent variables at explaining variation in shoot dry weight (Table 2). In fact, adding up to four additional terms to the equation only increased R^2 by 0.04. This finding agrees with the widely demonstrated usefulness of power functions in relating an organism's weight to its height or some other linear dimension of size (Batschelet, 1973). Power functions have the general form of $y = ax^n$. For this reason, we calculated a regression equation with no intercept term. The resulting equation, shoot weight (g) = 14.254 (S.E. = ±0.275) × shoot height^2 (m) was statistically significant ($P < 0.0001$).

The predictive capabilities of this equation were tested by applying it to the first validation dataset. Estimated shoot weights from this equation were very close to measured shoot weights (Fig. 1B). Results of Student's *t*-test indicated no significant difference between the estimated mean (121.8 g) and actual mean dry weights (138.2 g) for the shoots in the validation dataset (*t*-statistic = 0.31, $P = 0.76$, degrees of freedom (d.f.) = 46). The estimated values were on average 88.1% of the measured values. Comparison of the estimated

Table 1
Characteristics for two age classes (<1 year and >1 year old) of *A. donax* shoots used in this study to derive the power function relating shoot biomass (g) to shoot height (m)

Variable	Stem age	*N*	Mean	Standard deviation
Stem weight (% of total)	<1 year	186	79.7	11.9
Leaf weight (% of total)		186	20.3	11.9
Branch weight (% of total)		186	0	0
Number of branches		186	0	0
Leaves/shoot		186	10.3	6.1
Stem length (g/cm)		186	0.27	0.18
Leaf (g/cm^2)		111	0.0087	0.0015
Base diameter (mm)		186	20.4	5.6
Mid diameter (mm)		152	18.1	5.5
Top diameter (mm)		152	10.1	3.6
Stem weight (% of total)	>1 year	26	86.4	11.2
Leaf weight (% of total)		26	4.4	8.3
Branch weight (% of total)		26	8.8	10.3
Number of branches		26	12.9	13.4
Leaves/shoot		26	7.8	5.8
Stem length (g/cm)		26	0.76	0.30
Leaf (g/cm^2)		–	–	–
Base diameter (mm)		26	23.1	5.6
Mid diameter (mm)		10	18.8	3.6
Top diameter (mm)		10	6.0	1.7

– Indicates that measurements were not collected.

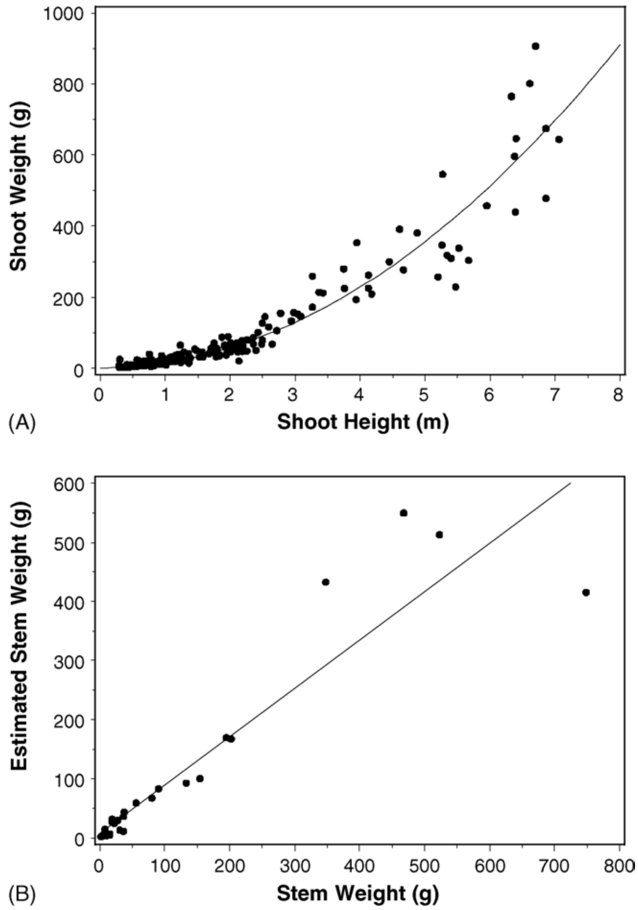

Fig. 1. (A) *A. donax* shoot dry weight (g) versus shoot height (m). The line represents the equation, shoot weight (g) = 14.254 (S.E. = ±0.275) × shoot height^2 (m) and (B) estimated shoot weight vs. measured shoot weight for the validation dataset. The line was fit by linear regression, $P < 0.0001$, $R^2 = 0.87$, $N = 29$.

shoot weights for the second validation set with the measured weights (Fig. 2) also indicated no significant differences between the mean values (*t*-statistic = 0.16, $P = 0.87$, d.f. = 412). In fact, the mean estimated shoot weight

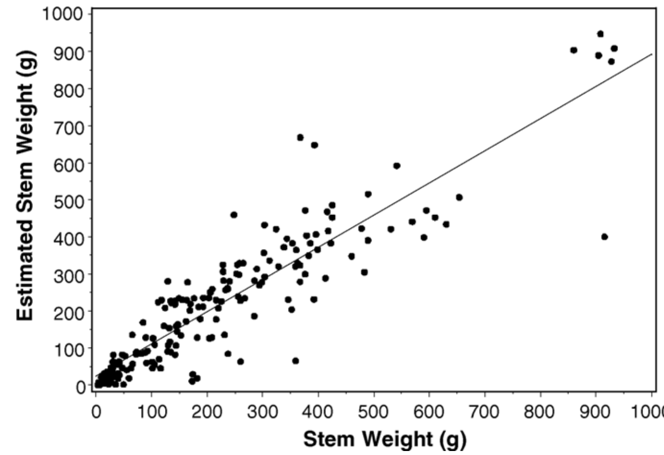

Fig. 2. *A. donax* estimated shoot weight vs. measured shoot weight for the second validation dataset. The line was fit by linear regression, $P < 0.0001$, $R^2 = 0.82$, $N = 192$.

(212.24 g) was 98.6% of the measured mean shoot weight (215.25 g).

A. donax shoot density (n m^{-2}) and biomass (kg m^{-2}) at sites in the United States are given in Table 3. Mean biomass from harvested plots did not differ significantly from mean biomass estimated using the equation (*t*-statistic = 0.39, $P = 0.72$, d.f. = 27). Given the close agreement between actual shoot dry weight and those predicted with the equation discussed above, it is not surprising that the estimated biomass values (kg m^{-2}) are quite similar to those actually measured. It is notable that an equation derived from northern California *A. donax* shoots yields good biomass estimates for plants in Texas and Mississippi.

4. Discussion

We developed a simple accurate equation for predicting biomass of individual *A. donax* shoots from more easily determined shoot height. This equation may be useful in

Table 2
Results of regression model selection procedure based on R^2

Number of variables in model	R^2	Variables in model
1	0.90	Shoot height^2
1	0.89	Shoot height
1	0.19	Top diameter
2	0.93	Shoot height, shoot height^2
2	0.93	Shoot height^2, top diameter
2	0.92	Shoot height^2, mid diameter
3	0.94	Shoot height, shoot height^2, mid diameter
3	0.94	Shoot height, shoot height^2, base diameter
3	0.94	Shoot height, shoot height^2, top diameter
4	0.94	Shoot height, shoot height^2, base diameter, mid diameter
4	0.94	Shoot height, shoot height^2, mid diameter, top diameter
4	0.94	Shoot height, shoot height^2, base diameter, top diameter
5	0.94	Shoot height, shoot height^2, base diameter, mid diameter, top diameter

This table gives R^2 for regression equations relating stem dry weight (g) to combinations of five independent variables (shoot height (m), shoot height^2, diameter at the top of the shoot (mm), diameter at the midpoint of the shoot (mm), and diameter at the base of the shoot (mm). Only the top three equations in each category are listed. For example, there were 10 possible regression equations that contained two independent variables; only the three with the greatest R^2 are included in this table.

Table 3
Mean (±standard error, S.E.) *A. donax* shoot biomass (kg m^{-2}) and shoot number (n m^{-2}) for sites in California, Mississippi, and Texas

Date	Site	Shoot height (m)		Estimated biomass (kg m^{-2})		Measured biomass (kg m^{-2})		Number of shoots (n m^{-2})		*N*
		Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	
08 Aug 05	Cache Creek, CA	4.23	0.56	25.57	3.12	30.17	5.95	83.3	25.3	3
08 Aug 05	Capay, CA	3.92	0.64	22.6	4.35	21.27	5.35	72.0	11.0	3
08 Aug 05	Maxwell, CA	3.31	–	19.4	–	17.50	–	100.0	–	1
08 Aug 05	Williams, CA	2.70	0.35	10.46	3.15	11.58	4.21	73.6	21.4	5
26 Aug 05	West Paoli, CA	2.44	0.20	10.63	4.22	12.37	4.28	74.8	17.7	6
08 Sep 05	Redlands, CA	1.96	0.58	3.83	1.96	7.13	1.62	49.7	16.7	3
09 Sep 05	Norco, CA	1.73	0.01	9.23	1.64	6.80	1.54	177.7	29.4	3
26 Aug 05	Vicksburg, MS 1	3.99	0.06	19.73	1.74	16.13	2.00	77.7	5.3	3
26 Aug 05	Vicksburg, MS 2	4.05	0.25	19.97	2.40	16.10	1.16	78.0	11.0	3
26 Aug 05	Vicksburg, MS 3	5.46	1.05	38.9	18.28	39.97	17.83	72.3	5.3	3
26 Aug 05	Vicksburg, MS 4	3.53	0.26	10.75	3.19	11.30	3.56	50.3	11.8	4
26 Aug 05	Vicksburg, MS 5	4.79	0.12	26.33	1.16	29.13	4.58	72.3	5.3	3
18 Aug 05	Elliot, TX	1.99	0.35	2.57	0.43	3.07	0.44	50.0	19.1	3
19 Aug 05	Kirby, TX	2.86	0.55	10.17	1.97	nd	nd	61.0	14.7	3
19 Aug 05	Kerr County, TX	3.73	0.30	10.17	1.68	nd	nd	44.3	5.7	3
20 Aug 05	Big Bend, TX	3.20	0.50	10.47	0.83	nd	nd	55.3	14.7	3
All dates	All Sites	3.37	0.26	15.67	2.39	17.12	2.94	74.5	7.8	–

These values are averaged across all quadrats at each site. Values across all dates and all sites are based on $N = 16$, except for the measured biomass where $N = 13$.

structural plant modeling (Hanan, 1997). In combination with counts of the number of stems m^{-2} and their heights, this equation provides a method for estimating aboveground biomass of *A. donax* in several geographically dispersed populations in the United States. Because it is both accurate and less time-consuming, this method may be useful in evaluating management techniques used to control *A. donax*. Future refinements in remote sensing technologies, such as Lidar (*li*ght *d*etection *a*nd *r*anging), which may be used to estimate the distribution of heights (Harding et al., 2001; Sun and Ranson, 2000) and stem density (Maltamo et al., 2004) within a plant canopy, will extend the application of the equation.

There are few published data on *A. donax* aboveground biomass in natural systems with which to compare the present data. Sharma et al. (1998) reported data from two sites at Jaipur (Rajasthan, India). They reported that total aboveground standing crop ranged from 3.63 to 5.71 kg m^{-2} at Amanishah Drain and from 6.40 to 16.74 kg m^{-2} at a site on the campus of the University of Rajasthan. Five of 13 measured values for standing crop in California, Mississippi, and Texas were greater than the maximum value reported by Sharma et al. (1998). We observed that the number of stems m^{-2} ranged from 50 to 178. Sharma et al. (1998) reported ranges of 56–92 and 167–320 stems m^{-2} for the two sites they studied. Indian shoot lengths were comparable to the present data (Table 3) ranging from 3.5 to 4.9 m. Information on *A. donax* biomass was provided by Perdue (1958). However, Perdue (1958) reported annual yields (0.72–9.66 kg dry matter m^{-2} $year^{-1}$) of natural stands of *A. donax*. It should be noted that these values are not directly comparable to standing crop as they represent the amount of dry matter that can be sustainably harvested yearly. Coincidently, Perdue (1958) described the site that yielded 9.66 kg m^{-2} $year^{-1}$ as a site where the ''crop consisted of many persistent bases of old culms and undoubtedly represented the growth of a number of years''. This description may equally apply to some of the sites reported here.

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References

Batschelet, E., 1973. Introduction to Mathematics for Life Scientists. Springer-Verlag, New York, p. 495.

Bell, G., 1997. Ecology and management of *Arundo donax*, and approaches to riparian habitat restoration in Southern California. In: Brock, J.H., Wade, M., Pysek, P., Green, D. (Eds.), Plant Invasions: Studies from North America and Europe. Blackhuys Publishers, Leiden, The Netherlands, pp. 103–113.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87–99.

Cook, C.D.K., 1990. Aquatic Plant Book. SPB Academic Publishing, The Hague, The Netherlands, p. 220.

Daoust, R.J.D.L, Childers, 1998. Quantifying aboveground biomass and estimating net aboveground primary production for wetland macrophytes using a non-destructive phenometric technique. Aquat. Bot. 62, 115–133.

Hanan, J., 1997. Virtual plants–integrating architectural and physiological models. Environ. Model. Softw. 12, 35–42.

Harding, D.J., Lefsky, M.A., Parker, G.G., Blair, J.B., 2001. Laser altimeter canopy height profiles methods and validation for closed-canopy, broadleaf forests. Remote Sens. Environ. 76, 283–297.

Maltamo, M., Eerikainen, K., Pitkanen, J., Hyyppa, J., Vehmas, M., 2004. Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions. Remote Sens. Environ. 90, 319–330.

Perdue, R.E., 1958. *Arundo donax*—source of musical reeds and industrial cellulose. Econ. Bot. 12, 368–404.

Richardson, D.M.P.P., Rejmanek, M., Barbour, M.G., Panetta, F.D., West, C.J., 2000. Naturalization and invasion of alien plants: concepts and definitions. Divers. Distr. 6, 93–107.

Rieger, J.P., D.A. Kreager, 1989. Giant reed (*Arundo donax*): a climax community of the riparian zone. in: Protection, management, and restoration for the 1990's: Proceedings of the California Riparian Systems Conference, 22–24 September, 1988. Davis, California. General Technical Report PSW-110. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station Berkeley, California, pp. 222–225.

Rossa, B., Tuffers, A.V., Naidoo, G., von Willert, D.J., 1998. *Arundo donax* L. (Poaceae)—a C3 species with unusually high photosynthetic capacity. Bot. Acta 111, 216–221.

Sharma, K.P., Kushwaha, S.P.S., Gopal, B., 1998. A comparative study of stand structure and standing crops of two wetland species, *Arundo donax* and *Phragmites karka*, and primary production in *Arundo donax* with observations on the effect of clipping. Trop. Ecol. 39, 3–14.

Sidorkewicj, N.S., Fernandez, O.A., 2000. The line intersection method to estimate total foliage length in *Potamogeton pectinatus* L. Aquat. Bot. 68, 79–85.

SAS Institute Inc, 1999. SAS/STAT User's Guide, Version 8, Cary, North Carolina, p. 3884.

Sun, G., Ranson, K.J., 2000. Modeling Lidar returns from forest canopies. IEEE Trans. Geosci. Remote Sens. 38, 2617–2626.

Van, T.K., Rayachhetry, M.B., Center, T.D., 2000. Estimating above-ground biomass of *Melaleuca quinquenervia* in Florida, USA. J. Aquat. Plant Manag. 38, 62–67.

Whittaker, R.H., 1961. Estimation of net primary production of forest and shrub communities. Ecology 42, 177–180.

Whittaker, R.H., 1962. Net production of shrubs in the Great Smoky mountains. Ecology 43, 357–377.

Whittaker, R.H., Marks, P.L., 1975. Methods of assessing terrestrial productivity. In: Lieth, H., Whittaker, R.H. (Eds.), Primary Productivity of the Biosphere. Springer-Verlag, New York, pp. 55–118.