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Research paper

# Biomass from young hardwood stands on marginal lands: Allometric equations and sampling methods

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ABSTRACT

We developed allometric equations for small-diameter woody species growing on mixed forest marginal lands, which are potential sources of biomass for bioenergy. Eleven species of trees and shrubs were sampled from a site located in eastern Canada. Equations derived in this study generally performed better than equations from the literature. Also, fixed-area plots (FAP) and line-intersect sampling (LIS) methods using both random or systematic selection of sampling units were compared to determine which method required the lowest number of measurements to estimate stand biomass for the same precision.

The fixed-area plots method was successfully used to estimate relatively accurately oven-dry biomass per hectare. Results indicated that potentially harvestable woody biomass (oven dry basis) varied between 33-41 and 12–13 t ha$^{-1}$ for the most and least productive marginal sites respectively. On the most productive site, LIS estimates (between 20 and 42 t ha$^{-1}$) were usually lower than those obtained using different FAP sampling methods (i.e. systematic or random, small (50 m$^2$) or large (100 m$^2$) plots), but similar on the more open sites (between 10 and 14 t ha$^{-1}$). Small FAP resulted in a plot without measurements in one case. Moreover, estimates based on small FAP were generally higher, even if not significantly different from larger plot estimates. We therefore suggest using FAP with 100 m$^2$ plots to estimate small-diameter woody biomass on marginal lands with dense vegetation, while LIS, even if promising for open stands, needs further evaluation before recommendation.



## 1. Introduction

Due to urban migration and increasing intensification of agricultural practices, previously cultivated marginal lands are being abandoned at an increasing rate, particularly in eastern North America and Europe; thereby leaving hundreds of thousands of hectares to natural recolonization by vegetation, such as shrubs and trees [1–3]. Given the long-term inevitable decrease in availability of crude oil [4,5], plus concerns associated with climate change, there is a growing interest in renewable "greener" energy sources and diversification of the energy sector [6–8]. Bioenergy, which includes both biofuel production and biomass burning for heat or electricity production, may be an interesting avenue to diversify local and national economies, favouring land occupation and rural development [9]. In Quebec, an eastern Canadian province,

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Vouligny and Gariépy [10] estimated that there are nearly 109,000 ha of abandoned marginal lands. An unknown proportion of this area could be exploited for bioenergy feedstock production, depending on site fertility and accessibility. Young irregular natural stands composed of pioneer species with little commercial importance that grow on marginal and abandoned lands may be perceived negatively by farmers [11,12]. However, if farmers can be shown a return on investment or a reduction in heating costs for farm buildings, they may support the use of marginal lands for biomass production while maintaining other ecological functions, such as wildlife habitat and windbreaks [8,9,11,12]. The potential for harvesting biomass on these marginal lands may be significant [9,13,14], but the available biomass stocks need to be estimated accurately for the decision-making process before encouraging their utilization.

Sampling methodologies used to efficiently estimate the amount of biomass that can be harvested from young irregular forested sources have not been thoroughly evaluated [15]. Also, there is a lack of adequate allometric equations to accurately estimate standing biomass of small-diameter woody species growing on marginal lands [16–18]. Equations currently available for saplings and understory trees developed using data from mature forests do not apply well to young trees growing on marginal lands [16,19,20] or may simply be lacking entirely for non-commercial species. Equations that include both diameter and height are needed, since they will be more flexible and precise when applied to different sites and account for differences in stand density [16,17,21].

The challenge in choosing the best sampling method to obtain stand estimates, i.e. the one which, for a desired accuracy, requires the minimum number of measurements while minimizing bias, needs to be addressed for estimating biomass on young hardwood stands on marginal land. The use of fixed area plots (FAP sampling) with detailed tree measurements for biomass estimates is a commonly applied procedure. Its application may provide relatively accurate estimates, but may be time consuming and expensive when plot establishment in terms of size and number is considered. Plot size, which depends on the characteristics of the stands under study (age, stand density, number of species, variability in terms of diameter and height, etc.) [22–27], must be carefully chosen as it may affect the precision and cost of the estimates. . Other methods, such as horizontal point sampling or line-intersect sampling (LIS) [28,29], may be more efficient (i.e. less time consuming) in estimating standing biomass, but need further evaluation [28,30,31]. However, horizontal point sampling is a method requiring equipment and expertise that farmers and some landowners may lack. Moreover it may be difficult to apply in very dense stands with many small stems. LIS, which is generally used for the inventory of coarse woody debris [32,33], has recently been used to determine standing biomass of natural forests in Delaware, eastern USA. This field sampling method was coupled with LIDAR remote sensing technology and used to extrapolate estimates of standing biomass at a state-wide level [31], thus raising new interest in this sampling technique.

In this paper, our objectives were to (1) develop allometric equations for small-diameter woody species growing on marginal lands recolonized by natural vegetation after land abandonment; (2) compare our allometric equations with those from the literature to evaluate expected gains in accuracy; (3) test FAP and LIS to estimate the amount of oven-dry biomass per hectare and find the most reliable method requiring the lowest number of samples and (4) make recommendations on the sampling methods to be used when dealing with small-diameter woody species growing on marginal lands.

## 2. Materials and methods

### 2.1. Study area

The study site is located in a forested area adjoining the Rivière-du-Loup airport (47°46′23.9″ N, 69°34′26.4″ W, elevation 113 m), in Quebec, eastern Canada. The nearest weather station with climate data for the 1981–2010 period is located in Saint-Arsène (47°57′00.0″ N, 69°23′00.0″ W, elevation 76 m, 25.2 km from the study site). This location receives on average 963.5 mm of precipitation annually, 72% of which falls as rain, including 462 mm during the May–September period (Saint-Arsène Climate Normals 1981–2010 [34]). Annual average daily temperature is 3.5 ± 2.9 °C (mean ± std. dev.), with spring and summer monthly average temperatures ranging from 9.3 ± 1.5 (May) to 17.6 ± 1.2 °C (July). On average, the frost free period lasts 135 days, with the first frost occurring on October 1 and the last on May 18. From 1981 to 2010, the snow cover reached on average 43 cm in March, with snow disappearing by the end of April and starting to accumulate again in November. The area is characterized by a flat to gently rolling terrain.

The study area can be described as a young hardwood stand of variable density, species composition and canopy cover growing on marginal lands within the balsam fir-yellow birch bioclimatic domain [35]. This site was chosen to represent abandoned lands recolonized by natural vegetation in southern Quebec. No information was available on the history of the site. This site had variable vegetation structure; it was occupied by tall shrubs and young trees of commercial and non-commercial timber species. It included open areas with more abundant tall shrubs and herbaceous vegetation. Shrubs included serviceberry (*Amelanchier* spp.), elderberry (*Sambucus Canadensis* L. var *Canadensis*), red-osier dogwood (*Cornus stolonifera* Michx.) and beaked hazel (*Corylus cornuta* Marsh.). Small and medium trees included grey alder (*Alnus rugosa* (DuRoi) Spreng.), paper birch (*Betula papyrifera* Marsh.), cherries (*Prunus* spp., specifically *Prunus pensylvanica* L.f. and *Prunus virginiana* L.), willows (*Salix* spp.), balsam poplar (*Populus balsamifera* L.), trembling aspen (*P. tremuloides* Michx.) and American Mountain-ash (*Sorbus americana* Marsch.).

### 2.2. Development of allometric equations

To develop allometric equations for small diameter species (DBH < 100 mm), trees and tall shrubs were sampled by selecting small, medium and tall plants to cover the range of diameter and height observed in the field. In August 2014, between 8 and 12 plants from each of the aforementioned species were cut as close as possible to the ground. A mark was made at 15 and 130 cm (breast height) from the ground before felling the plant. Diameter at ground level (DGL), at 15 cm from the ground (D15) and at breast height (DBH, if the plants reached 1.3 m), and height were recorded after felling.

Leaves were manually removed to obtain woody biomass. Larger plants (DBH > 20 mm) were generally separated into three approximately equal parts (the base, middle and top), plus the stump, which was defined for this study as the part between the D15 mark and the ground. Each plant or plant part was weighed in the field with an electronic scale (±1 g) to obtain its fresh weight, without leaves. If the part or plant was too heavy or too big to be easily carried to the laboratory, a subsample from each part (base, middle, top and stump) was taken, weighed in the field to obtain the fresh weight, and carried to the laboratory for drying. Otherwise, the entire plant was cut into small pieces using a small hand saw, weighed in the field, put into paper bags, and carried to the laboratory for drying at 70 °C for 72 h. Plant dry weight was calculated as: dry weight = fresh weight *(dry weight sample/fresh weight sample); and plant dry weight = sum of dry weights of plant parts.

Of the 11 species sampled (Table S1 in supplementary material), four were shrubs (*Amelanchier* spp., *Corylus cornuta*, *Cornus stolonifera* and *Sambucus canadensis*) and their equations were developed based on basal diameter (i.e. DGL) and height, while the equations for the tree species were based on DBH and height measurements.

Only the best model (i.e. allometric equation) developed for each species is presented in this paper. Various forms of allometric equations were tested (not shown for conciseness), but in the end only two types of models, including both diameter (D) and height (H), were retained as the best ones with respect to precision for estimating dry weight of the plant (including the stump, $DryW_{wS}$):

$$DryW_{wS} = a\, D^b H^c \quad (1)$$

$$DryW_{wS} = a + b\, D + c\, D^2 + d\,(D\, H) \quad (2)$$

The models were initially evaluated by visually inspecting residual plots and graphs of fitted vs. observed values to see if they were appropriate. The models retained were then ranked in terms of root mean square error. The coefficient of determination ($R^2$) and mean percent error are also presented for comparison with other studies.

$R^2$ for all models was calculated following the formula for linear and nonlinear models given by Cornell and Berger [36]. Root mean square error (RMSE), a measure of accuracy of the model, was divided by the mean observed value and expressed as a percentage (sometimes referred to as RMSE normalized to the mean).

We compared the equations from this study (Table 1) with equations found in the literature for small diameter species, selecting only equations developed for eastern North America, whenever possible (Table S2 in supplementary material). As authors sometimes presented only component equations (e.g. Refs. [26,37,38]), we had to add or subtract components to obtain woody aboveground biomass (see Table S2).

Harvesting machines are not able to cut plants extremely close to the ground surface, even less so on irregular terrain, which differs from plantations for which these machines were usually developed. For example, the Biobaler®, a round baling system used for harvesting small-diameter woody biomass [39], generally cuts between 10 and 30 cm from the ground surface. By defining the stump as the piece of plant stem below the D15 mark, we developed an equation to convert plant biomass with stump ($DryW_{wS}$) to biomass without stump ($DryW_{woS}$), which we considered the "harvestable" biomass (see Equation (5) in the result section).

### 2.3. Evaluating biomass per hectare: comparison of different sampling methods

To test various sampling methods, two study sites (Square 1 and Square 2) were established in the forested area along the airport runway (Fig. 1). The study sites were identified by delimiting two square areas of 0.5 ha (70.71 m × 70.71 m) within the forested area, leaving a buffer zone of at least 10 m from the trail separating the two forested areas, the fence and the access road.

For the comparison of different sampling methods to obtain stand estimates, DBH and species were recorded only for plants with a DBH greater than 20 mm (i.e. mainly trees, but also some tall shrubs). Some samples were missing for some measurements (DGL, DBH, H, $DryW_{wS}$ (stump not collected sometimes) or $DryW_{woS}$) due to operational reasons, and thus the number of plants sampled and of those used for the development of equations may differ between tables (compare Tables 1, 2 and 4), depending on which variables had missing values. For the purpose of comparing sampling methods, we developed power models to predict "harvestable" biomass ($DryW_{woS}$, i.e. without the stump) based only on diameter for the species present in the area (Table 2). The models were fitted on a logarithmic scale as suggested by Mascaro [40] for this type of models for small-diameter plants to account adequately for heteroscedastic data. Predictions were back-transformed and corrected for logarithmic bias according to Baskerville [41]. DBH did not show a good relationship with $DryW_{woS}$ for shrub species. Hence, DBH measurement was converted to DGL for *Amelanchier* spp. and "other shrubs" (see Table 2 for the relationship between DBH and DGL), and biomass was estimated with allometric models based on DGL.

Two sampling methods were tested: (1) fixed-area plots (FAP) [42] and (2) line-intersect sampling (LIS) [30]. Random and systematic FAP sampling was used to estimate aboveground dry woody biomass. Using the same data, we also estimated stand density and basal area. Once the two squares were delimited (Fig. 1), random points were selected using QGIS software (random point tool) [43] and used as centres for FAP. Two plot sizes were tested, for both random and systematic sampling, using nested circular plots with the same centre: the smaller plots measured 50 $m^2$ (i.e. 3.99 m radius), while the larger plots measured 100 $m^2$ (i.e. 5.64 m radius). For systematic FAP sampling, a starting point was drawn from those already established for random FAP sampling, and a direction was randomly selected. After establishing the first systematic plot (corresponding to an existing random plot), the other systematic plots were then distributed at regular intervals

**Table 1**
Allometric models based on diameter and height for estimating oven-dry leafless biomass of the aboveground part of the plant (including the stump; $DryW_{wS}$), in grams (g).

| Species | Fitted model | n | RMSE (g) | RMSE (%) | $R^2$ | Adj. $R^2$ | Mean%Error |
|---|---|---|---|---|---|---|---|
| *Amelanchier* spp. | $DryW_{wS} = 0.0005904\, DGL^{1.5485591}\, H^{1.5153692}$ | 12 | 34.86 | 16.59 | 0.97 | 0.97 | −11.34% |
| Other shrubs[a] | $DryW_{wS} = 412.93011 - 58.33215\, DGL + 0.85505\, DGL^2 + 0.12816(DGL \cdot H)$ | 34 | 105.26 | 40.77 | 0.89 | 0.89 | −9.46% |
| *Alnus rugosa* | $DryW_{wS} = 0.11644\, DBH^{2.17022}\, H^{0.30955}$ | 9 | 27.79 | 1.65 | 0.99 | 0.99 | 4.69% |
| *Betula papyrifera* | $DryW_{wS} = 16.134\, DBH^{2.4408}\, H^{-0.6207}$ | 10 | 240.69 | 11.24 | 0.99 | 0.98 | 1.52% |
| *Populus balsamifera* | $DryW_{wS} = 3.273 \cdot 10^{-7}\, DBH^{0.8681}\, H^{3.097}$ | 11 | 158.58 | 9.31 | 0.99 | 0.99 | −0.37% |
| *Populus tremuloides* | $DryW_{wS} = 0.34905\, DBH^{2.22387}\, H^{0.06639}$ | 12 | 365.27 | 22.84 | 0.94 | 0.93 | 1.72% |
| *Prunus* spp. | $DryW_{wS} = -1.561 \cdot 10^3 + 92.69\, DBH - 2.473\, DBH^2 + 0.2362\,(DBH \cdot H)$ | 8 | 177.51 | 9.71 | 0.98 | 0.96 | 0.66% |
| *Salix* spp. | $DryW_{wS} = 0.005941\, DBH^{1.233489}\, H^{1.346887}$ | 9 | 264.18 | 29.91 | 0.95 | 0.93 | −8.57% |
| *Sorbus americana* | $DryW_{wS} = 13.4382\, DBH^{2.0951}\, H^{-0.4311}$ | 11 | 46.43 | 10.59 | 0.99 | 0.98 | −3.75% |

n: sample size used to develop the equation; RMSE: root mean square error expressed in grams (g); RMSE (%): root mean square error expressed as a percentage of the mean; $R^2$: coefficient of determination; Adj. $R^2$: Adjusted coefficient of determination; Mean%Error: Mean percentage of error; DGL: Diameter at ground level (mm); DBH: diameter at breast height (mm); H: height (cm).
[a] The model for "other shrubs" was fitted by pooling together data for *Cornus stolonifera, Corylus cornuta* and *Sambucus canadensis*.

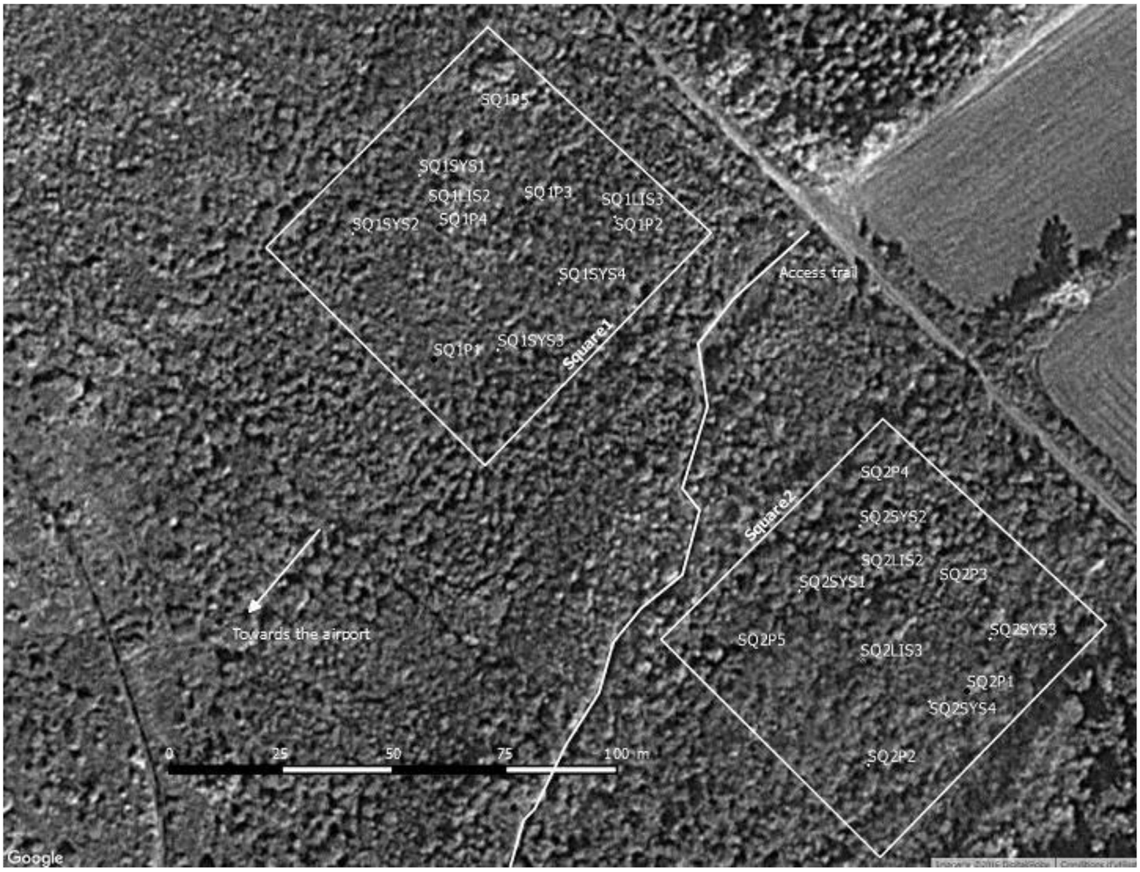


**Fig. 1.** Approximate position of sampling points in the study area (Square 1: top left; Square 2: bottom right). See Table 3 for the names of the sampling points in each sampling method. Map data: Google, Digital Globe © 2016.

**Table 2**
Allometric models based on diameter only for estimating oven-dry leafless biomass of the aboveground part of the plant (without the stump; $DryW_{woS}$), in grams (g).

| Species | Fitted model | n | RMSE (g) | RMSE (%) | $R^2$ | Adj. $R^2$ | Mean%Error |
|---|---|---|---|---|---|---|---|
| [*Amelanchier* spp. + Other shrubs] | $DGL = 5.31699 + 1.33801\ DBH$ | 74 | – | – | 0.92 | 0.92 | – |
| *Amelanchier* spp. | $DryW_{woS} = 1.0806\ \exp(-3.6242 + 3.0357\ \ln DGL)$ | 13 | 71.33 | 33.79 | 0.88 | 0.87 | −14.68 |
| Other shrubs[a] | $DryW_{woS} = 1.1577\ \exp(-3.1380 + 2.6489\ \ln DGL)$ | 37 | 173.23 | 78.80 | 0.65 | 0.64 | −32.15 |
| *Alnus rugosa* | $DryW_{woS} = 1.0070\ \exp(-0.5578 + 2.2339\ \ln DBH)$ | 11 | 276.32 | 17.26 | 0.98 | 0.98 | −1.29 |
| *Betula papyrifera* | $DryW_{woS} = 1.0228\ \exp(0.0905 + 2.1107\ \ln DBH)$ | 11 | 237.97 | 12.68 | 0.99 | 0.98 | −4.16 |
| *Populus balsamifera* | $DryW_{woS} = 1.0226\ \exp(-1.0798 + 2.3160\ \ln DBH)$ | 13 | 263.63 | 18.17 | 0.99 | 0.99 | −4.11 |
| *Populus tremuloides* | $DryW_{woS} = 1.0590\ \exp(-0.1252 + 2.0608\ \ln DBH)$ | 12 | 365.75 | 24.07 | 0.94 | 0.93 | −10.85 |
| *Prunus* spp. | $DryW_{woS} = 1.0161\ \exp(-0.1201 + 2.2131\ \ln DBH)$ | 11 | 782.27 | 29.77 | 0.96 | 0.95 | −2.90 |
| *Salix* spp. | $DryW_{woS} = 1.0484\ \exp(-0.3452 + 2.2148\ \ln DBH)$ | 12 | 262.93 | 19.72 | 0.96 | 0.96 | −9.02 |
| *Sorbus americana* | $DryW_{woS} = 1.0247\ \exp(-0.2029 + 2.2147\ \ln DBH)$ | 13 | 852.45 | 41.04 | 0.97 | 0.97 | −4.63 |

n: sample size used to develop the equation; RMSE: root mean square error expressed in grams (g); RMSE (%): RMSE expressed as a percentage of the mean; $R^2$: coefficient of determination; Adj. $R^2$: adjusted coefficient of determination; Mean%Error: mean percentage of error.
Equations used for estimating biomass when comparing sampling designs. Equations were of the form $DryW_{woS} = CF^*\exp(a+b^*\ln(D))$, where CF is a bias correction factor for the logarithmic transformation used to fit the model; D is diameter at breast height (DBH, mm) or diameter at ground level (DGL, mm), depending on the species. A model to convert DBH to DGL is presented for shrubs (including *Amelanchier* spp.). Statistics ($R^2$, AdjR2, RMSE, RMSE%, Mean%Error) are calculated on back-transformed values (i.e. in original units, grams (g)).
[a] The model for "other shrubs" was fitted by pooling together data for *Cornus stolonifera, Corylus cornuta* and *Sambucus canadensis*.

(20 m) in the direction selected. When the border of the study area was within less than the radius of the larger plot plus a buffer zone (i.e. approximately 7–8 m), the remaining systematic plots were placed on a second line, at a distance of 40 m from the original line and parallel to it. In the end, a total of five random plot centres and five systematic plot centres, of which only four new points, were identified in each study area.

LIS consisted of laying out a sampling line (transect) and tallying trees/shrubs whose crown projection crossed the line [28,30,31]. LIS was compared with estimates from FAP sampling. Two types of LIS were tested: (1) transects with fixed length (20 m), using three points drawn from those selected for random FAP as starting points and a randomly selected direction for each point (random LIS); and (2) transects with fixed length (20 m), using one point drawn from those selected for systematic FAP as starting point and selecting randomly a direction, and then establishing two other points at 20 m distance, and then tracing parallel transects (systematic LIS). The following formula was used to estimate stand variables using

**Table 3**
Estimated harvestable dry leafless biomass ($DryW_{woS}$, excluding the 15-cm stump) expressed on a per hectare basis (kg ha$^{-1}$), and estimated stand density (ha$^{-1}$) according to various sampling methods. Plot estimates are reported for each sampling unit; mean ± standard deviation (SD) and coefficient of variation (CV(%) = SD/mean*100) are reported for the different types of sampling designs for Square 1 and Square 2: FAP sampling using small (S) and large (L) plots, with random or systematic designs; LIS and alternative estimation method for LIS (ALT.ESTIM.) using random or systematic designs.

| FAP | $DryW_{woS}$ (kg ha$^{-1}$) | | Stand density (ha$^{-1}$) | | LIS | $DryW_{woS}$ (kg ha$^{-1}$) | Stand density (ha$^{-1}$) | ALT. ESTIM. $DryW_{woS}$ (kg ha$^{-1}$) | ALT. ESTIM. Stand density (ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | L (100 m$^2$) | S (50 m$^2$) | L (100 m$^2$) | S (50 m$^2$) | | 20-m transect | 20-m transect | 20-m transect | 20-m transect |
| *Square* 1 | | | | | | | | | |
| **Random** | | | | | **Random** | | | | |
| SQ1P1 | 480 | 0 | 300 | 0 | SQ1P2 | 17946 | 11571 | 20605 | 11000 |
| SQ1P2[a] | 23261 | 19999 | 14000 | 14000 | SQ1P4 | 2370 | 2887 | 2346 | 2500 |
| SQ1P3 | 15223 | 14370 | 13800 | 14200 | SQ1P5 | 10641 | 7973 | 10586 | 7500 |
| SQ1P4 | 4396 | 3819 | 3200 | 3200 | | | | | |
| SQ1P5 | 16758 | 25038 | 10200 | 13400 | | | | | |
| Mean ± SD | 12023 ± 9359 | 12646 ± 10588 | 8300 ± 6252 | 8960 ± 6820 | Mean ± SD | 10319 ± 7793 | 7477 ± 4363 | 11179 ± 9144 | 7000 ± 4272 |
| CV(%) | 78% | 84% | 75% | 76% | CV(%) | 76% | 58% | 82% | 61% |
| **Systematic** | | | | | **Systematic** | | | | |
| SQ1P2[a] | 23261 | 19999 | 14000 | 14000 | SQ1LIS2 | 4628 | 4096 | 4714 | 3500 |
| SQ1SYS1 | 3879 | 7758 | 4200 | 8400 | SQ1LIS3 | 26520 | 19063 | 25048 | 17000 |
| SQ1SYS2 | 11537 | 13240 | 11000 | 12200 | SQ1P3 | 11783 | 13511 | 10757 | 11500 |
| SQ1SYS3 | 1382 | 2471 | 1500 | 2600 | | | | | |
| SQ1SYS4 | 26018 | 23932 | 19200 | 17400 | | | | | |
| Mean ± SD | 13215 ± 11123 | 13480 ± 8743 | 9980 ± 7203 | 10920 ± 5672 | Mean ± SD | 14310 ± 11163 | 12223 ± 7566 | 13507 ± 10442 | 10667 ± 6789 |
| CV(%) | 84% | 65% | 72% | 52% | CV(%) | 78% | 62% | 77% | 64% |
| *Square* 2 | | | | | | | | | |
| **Random** | | | | | **Random** | | | | |
| SQ2P1 | 48816 | 50023 | 17100 | 15200 | SQ2P1 | 24310 | 16360 | 20707 | 13000 |
| SQ2P2[a] | 29415 | 24087 | 10600 | 9400 | SQ2P2 | 19958 | 9854 | 25399 | 9000 |
| SQ2P3 | 38485 | 47942 | 22100 | 23000 | SQ2P3 | 17798 | 7548 | 19632 | 7500 |
| SQ2P4 | 33538 | 53632 | 5300 | 8600 | | | | | |
| SQ2P5 | 27698 | 29815 | 13500 | 14400 | | | | | |
| Mean ± SD | 35590 ± 8484 | 41100 ± 13232 | 13720 ± 6370 | 14120 ± 5763 | Mean ± SD | 20689 ± 3317 | 11254 ± 4570 | 21913 ± 3067 | 9833 ± 2843 |
| CV(%) | 24% | 32% | 46% | 41% | CV(%) | 16% | 41% | 14% | 29% |
| **Systematic** | | | | | **Systematic** | | | | |
| SQ2P2[a] | 29415 | 24087 | 10600 | 9400 | SQ2LIS2 | 16494 | 8432 | 22019 | 10500 |
| SQ2SYS1 | 25129 | 9877 | 7200 | 3200 | SQ2LIS3 | 23236 | 14442 | 33985 | 14000 |
| SQ2SYS2 | 34351 | 49602 | 12200 | 13800 | SQ2P4 | 31080 | 5799 | 71116 | 10000 |
| SQ2SYS3 | 44321 | 85906 | 9300 | 17200 | | | | | |
| SQ2SYS4 | 33540 | 34151 | 22200 | 21000 | | | | | |
| Mean ± SD | 33351 ± 7150 | 40725 ± 29120 | 12300 ± 5829 | 12920 ± 6915 | Mean ± SD | 23604 ± 7300 | 9558 ± 4430 | 42373 ± 25601 | 11500 ± 2179 |
| CV(%) | 21% | 72% | 47% | 54% | CV(%) | 31% | 46% | 60% | 19% |

[a] This point was also used as random start to establish the first systematic plot centre.

**Table 4**
Sample size calculation with indication in parentheses of the equivalent number of trees to be measured to estimate biomass per hectare with the desired precision (i.e. expressed as a percentage of the mean with 95% confidence level) according to the average number of trees sampled in each sampling design (i.e. L FAP, S FAP, LIS, LIS ALT.ESTIM, with random (Rnd) or systematic (Syst.) designs) in each area (Squares 1 and 2).

| Biomass per hectare | Average number of trees sampled | 15% precision | | 20% precision | | 30% precision | |
|---|---|---|---|---|---|---|---|
| | | nb. plots or transects | Equivalent nb. trees | nb. plots or transects | Equivalent nb. trees | nb. plots or transects | Equivalent nb. trees |
| *Square* 1 | | | | | | | |
| L FAP (Rnd) | 85 | 106 | 9010 | 61 | 5185 | 28 | 2380 |
| S FAP (Rnd) | 50 | 122 | 6100 | 70 | 3500 | 32 | 1600 |
| L FAP (Syst) | 85 | 123 | 10455 | 70 | 5950 | 33 | 2805 |
| S FAP (Syst) | 50 | 74 | 3700 | 43 | 2150 | 20 | 1000 |
| LIS (Rnd) | 18 | 100 | 1800 | 57 | 1026 | 27 | 486 |
| LIS (Syst) | 18 | 106 | 1908 | 61 | 1098 | 28 | 504 |
| LIS (Rnd) ALT.ESTIM. | 18 | 117 | 2106 | 67 | 1206 | 31 | 558 |
| LIS (Syst) ALT.ESTIM. | 18 | 104 | 1872 | 60 | 1080 | 28 | 504 |
| *Square* 2 | | | | | | | |
| L FAP (Rnd) | 130 | 12 | 1560 | 8 | 1040 | 5 | 650 |
| S FAP (Rnd) | 68 | 20 | 1360 | 13 | 884 | 7 | 476 |
| L FAP (Syst) | 130 | 10 | 1300 | 7 | 910 | 5 | 650 |
| S FAP (Syst) | 68 | 90 | 6120 | 52 | 3536 | 24 | 1632 |
| LIS (Rnd) | 21 | 7 | 147 | 5 | 105 | 4 | 84 |
| LIS (Syst) | 21 | 19 | 399 | 12 | 252 | 7 | 147 |
| LIS (Rnd) ALT.ESTIM. | 21 | 6 | 126 | 4 | 84 | 3 | 63 |
| LIS (Syst) ALT.ESTIM. | 21 | 65 | 1365 | 37 | 777 | 18 | 378 |

LIS:

$$X = \frac{10^4 m^2 \cdot ha^{-1}}{L} \sum \left( \frac{x_i}{d_i} \right) \quad (3)$$

where X is the estimate of the variable per hectare (e.g. stand density, basal area or biomass, depending on the definition of $x_i$); L is the length of the transect in meters (i.e. 20 m); $d_i$ is the diameter of the *i*th-tree crown (expressed in meters) measured as the sum of the two radii of the crown perpendicular to the transect line [31]; and $x_i$ can be equal to 1 for each *i*th-tree to estimate stand density; or equal to *i*th-tree cross-sectional area at breast height ($= \pi$ DBH$^2$/4, with DBH expressed in m) to estimate basal area (according to Andrianarivo [30]); or *i*th-tree biomass to estimate biomass per hectare (according to Nelson et al. [31]).Samples from 100-m$^2$ random FAP (totaling 1101 plants) were used to explore differences in species composition between the two areas studied in terms of contribution to stand density, basal area and harvestable biomass (Fig. S1). A total of 2215 plants were measured for DBH in FAP plots and 234 plants in LIS plots (here, crown radii were also measured perpendicular to each transect).

Since biomass estimates of LIS in Square 2 were widely different from those observed with FAP sampling (Table 3), we tested an alternative calculation method for LIS, ignoring crown diameter measurement (which we considered difficult to measure in the field, especially in dense canopies). This is equivalent to assuming that all plants had more or less the same probability of selection, regardless of crown diameter. We present this new estimation in Table 3 and call it LIS alternative estimation (ALT. ESTIM.).

Calculation of the sample size required to obtain a desired precision in the estimation of mean biomass per hectare was performed using a formula for simple random sampling (SRS) provided by Freese [44]:

$$n = \frac{t^2_{\alpha,n-1}\, s^2}{d^2} \quad (4)$$

where n is the number of plots or transects required; t is Student's t-value at $\alpha = 0.05$ confidence level; $s^2$ is the variance; and d is the confidence interval or desired precision (calculated as a percentage of the mean biomass per hectare). The calculation of sample size (n) was done iteratively with the t-value initially corresponding to *n-1* degrees of freedom, where *n* is the number of plots (5) or transects (3) used for the sampling design tested, but finally based on the degrees of freedom for the calculated *n*, following an iterative procedure reported by MacLean and Olstaff [45].

Based on sample size calculations for SRS [44], we estimated how many sampling units (plots or transects) would be necessary on average to estimate biomass per hectare with a precision of 15, 20 or 30% of the mean (Table 4). Using the average number of plants sampled within each type of sampling unit (i.e. 20-m transects, 50-m$^2$ and 100-m$^2$ circular plots), the equivalent number of plants to be measured for each level of precision was also approximated (Table 4).

## 3. Results

### 3.1. Biomass equations and estimates for individual species

Descriptive statistics of the sampled plants are reported in Table S1 (supplementary material). Diameter at breast height (DBH) of trees ranged between 8 and 90 mm, while basal diameter (DGL) of shrubs ranged between 8 and 45 mm. Average tree species height varied from 278 cm for *S. americana* to 423 cm for *P. balsamifera*, while shrubs were on average smaller than 250 cm. Oven-dry aboveground leafless biomass ($DryW_{WS}$) averaged between 154 and 253 g for shrubs and between 438 and 1952 g for trees. The maximum leafless tree biomass was observed for balsam poplar (8432 g).

For the majority of species, the power model based on diameter and height (Equation (1)) was better in terms of RMSE and $R^2$, and met model assumptions in terms of distribution of residuals (Table 1). Individual species models for *C. cornuta*, *C. stolonifera* and *S. canadensis* did not fit well, with very low $R^2$ and high RMSE, probably due to the irregular form of these shrubs. Thus, we decided to pool together these species to develop an equation for "other shrubs", i.e. not including serviceberry (Table 1). The equation for *Amelanchier* spp. fitted well ($n = 12$, $R^2 = 0.97$), probably because this tall shrub has characteristics that are more like those of a small tree, i.e. stronger apical dominance and usually single stemmed. In general, equations for tree species had very high $R^2$ values ($\geq$0.95) and were quite accurate (low RMSE%; Table 1 and Fig. 2). For example, the equation for *A. rugosa* had an $R^2 = 0.99$, RMSE% = 1.65, and mean percent error of 4.69% only. Relatively lower $R^2$ and higher RMSE% were obtained for *P. tremuloides* ($R^2 = 0.94$, RMSE% = 22.84) and *Salix* spp. ($R^2 = 0.95$, RMSE % = 29.91).

Estimated biomass based on our equations was generally closer to the observed value than that based on equations from the literature, especially for *A. rugosa*, *B. papyrifera*, *P. balsamifera*, *Prunus* spp., *S. americana*, *Amelanchier* spp. and *Sambucus canadensis* (Fig. 2). In some cases, our estimates and those from the literature were comparable in terms of accuracy (e.g. *Salix* spp.). Estimates for *C. stolonifera* and *C. cornuta* were equally poor for our equations and for those from the literature (Fig. 2). However, these shrubs are small (very low biomass per plant) and the error associated with their biomass estimation is probably minor at the stand level (less than 1% of biomass per hectare based on our sampling, see Fig. S1).

A very good linear relationship was found between aboveground biomass with stump ($DryW_{WS}$) and aboveground biomass without stump ($DryW_{WOS}$). Therefore, we developed the following equation to allow the conversion between biomass estimates, pooling all species together:

$$DryW_{woS} = -22.4457 + 0.9711\, DryW_{wS} \quad (5)$$

$$\left( R^2 = 0.99;\ \ F-\text{value} = 2.59 \cdot 10^5,\ \ n = 123,\ \ p-\text{value} < 0.0001 \right)$$

### 3.2. Species contribution to density, basal area and harvestable biomass

Based on 100-m$^2$ random FAP, basal area was estimated at 6.6 ± 5.2 and 17.3 ± 5.1 m$^2$ ha$^{-1}$, for Square 1 and 2, respectively. In Square 1, the most common species in terms of number of plants sampled (i.e. stand density) were *P. tremuloides* (42%), *Prunus* spp. (21%), *B. papyrifera* (21%) and *S. americana* (9%), totaling 93% of species composition. In Square 2, the most common species were *P. tremuloides* (26%), *Prunus* spp. (25%), *P. balsamifera* (18%), *Salix* spp. (14%) and *A. rugosa* (10%). In Square 1, *B. papyrifera* and *P. tremuloides* contributed the most in terms of basal area and biomass followed by *Prunus* spp. (Fig. S1). In Square 2, *P. balsamifera*, *Prunus* spp., *P. tremuloides*, *Salix* spp. and *A. rugosa* represented 90% of the biomass and 94% of the basal area.

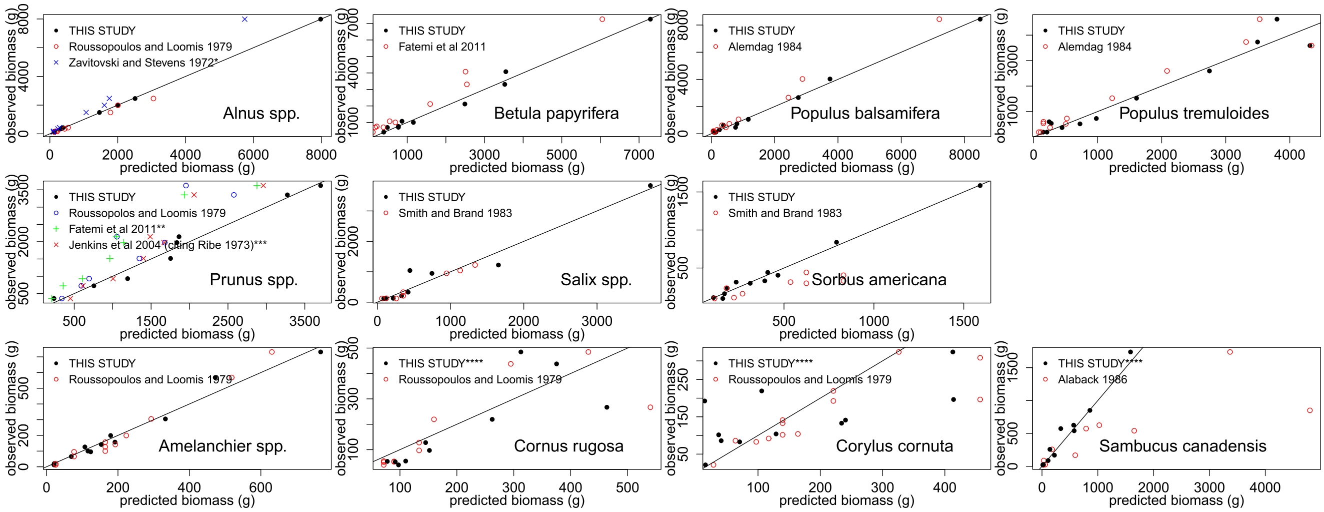


**Fig. 2.** Comparison of predictions of aboveground leafless biomass from this study and from the literature with observed biomass (observed vs. predicted; black circles indicate predictions from this study) for tree (upper and middle rows) and shrub (bottom row) species. The 1:1 line indicates perfect coincidence between observations and predictions. Points below the line indicate that the model overpredicts biomass, and those above the line indicate underpredictions. Some references are cited in the supplementary material: see Table S2 [59,60,61,62].

### 3.3. Estimating average biomass per hectare and stand density

Plot estimates of harvestable biomass ($DryW_{woS}$) and stand density are reported for the different methods compared in Table 3. Biomass estimates from large and small plots were similar (no significant difference between small and large FAP estimates, paired *t*-test, t = 1.51, d.f. = 17, p-value = 0.15), even if smaller plots more often yielded higher estimates (Table 3).

Using small plots (50 $m^2$), no trees/shrubs were measured in plot SQ1P1 (Table 3), probably indicating that for Square 1 (more open area), this plot size is too small. For Square 1, dry “harvestable” biomass estimates from large (100 $m^2$) random plots varied between 0.5 and 23.3 t $ha^{-1}$. Similar estimates were found with systematic plots (Table 3). Both random and systematic plots showed highly variable estimates (coefficient of variation (CV) being 78% and 84% for random and systematic plots of 100 $m^2$, respectively) for Square 1. Stand density estimates were also quite variable (between 0 and 19,200 $ha^{-1}$) due to the presence of two plots with a lower number of plants in both random (SQ1P1 and SQ1P4) and systematic (SQ1SYS1 and SQ1SYS3) sampling, with variability comparable to or slightly lower than that of biomass estimates (CV varying from 52% to 76% for stand density). The LIS estimate for biomass from random transects (10.3 t $ha^{-1}$) was lower than that obtained with FAP, while the LIS estimate from systematic transects (14.3 t $ha^{-1}$) was higher. Variability between plots was comparable for LIS and FAP (CV of 76–78% vs. 65–84%, respectively). Using the alternative method of estimation for LIS, the estimates for biomass were closer to those obtained with FAP. Indeed, the estimate from random transects increased (11.2 t $ha^{-1}$), while that from systematic transects decreased (13.5 t $ha^{-1}$; Table 3).

Estimated biomass was much higher in Square 2 than Square 1 (Table 3). For example, in large random FAP, the estimate was 35.6 ± 8.5 t $ha^{-1}$, with lower variability between plots than in Square 1 (CV = 24%). Lower CVs were also found for estimates based on small random plots (32%) and large systematic plots (21%) from this part of the stand, while a higher CV was observed for small systematic plots due to an extremely high (85.9 t $ha^{-1}$ for SQ2SYS3) and a relatively low estimate (9.9 t $ha^{-1}$ for SQ2SYS1) for the area. Stand density was slightly higher than that observed in Square 1 and varied between 12,300 and 14,120 $ha^{-1}$. LIS estimates of biomass were extremely low (20.7 and 23.6 t $ha^{-1}$ for random and systematic transects, respectively), compared with FAP estimates, while stand density estimates were only slightly lower than FAP estimates (Table 3). Using the alternative estimation method for LIS, the average biomass for systematic LIS (42.4 t $ha^{-1}$) was more similar to that obtained with FAP. However, the alternative estimate for random LIS did not change much (Table 3).

Sample size calculations based on the estimates obtained with each method are reported in Table 4 for the two areas studied. For the less dense area with the more variable cover, the number of plants to measure to obtain a desired precision of 20% of the mean was about 1000–1200 plants for LIS, up to 3500 plants for small FAP and over 5000 plants for large FAP. On the contrary, for the denser, more productive area (Square 2), for the same level of precision, the number of plants to measure was 1040 or less (excluding systematic small FAP, which yielded highly variable estimates; CV: 72%). The number of plots required for estimating biomass to a desired precision was similar for large FAP with both random and systematic sampling (Table 4). Sample size calculations showed that LIS sampling required the lowest number of measurements.

## 4. Discussion

The allometric equations developed in this study accurately describe small-diameter woody species (generally, $R^2 > 0.9$), with the best results obtained with trees. These equations were generally more precise than those from the literature or sometimes comparable (e.g. willows). Regarding allometric equations, this and other studies have shown that small diameter woody species may necessitate specific models [16,17,19,40]. Indeed, allometric relationships developed for mature trees or plants growing in the understory of closed-canopy forests may not accurately describe relationships for young trees growing in open stands.

The inclusion of height in allometric equations, to predict volume or biomass, may result in more flexible and accurate models [17,21], and is recommended by some authors [46], especially if models are to be used for stands with different characteristics (e.g. density and composition) than those for which they were developed. Even using diameter-only equations, our stand biomass estimates were in the range observed on marginal lands by other authors. For example, for marshes with *Salix* spp. in Saskatchewan, yields between 11 and 43 t ha$^{-1}$ were reported [47,48]. In Minnesota, the biomass of natural shrubs varied between 0.6 and 34.6 t ha$^{-1}$ [39], while in Quebec, Robert [15] estimated yields between 13.2 and 28.3 t ha$^{-1}$ for a marginal land. Bella and DeFranceschi [49] calculated woody biomass in young *P. tremuloides* stands to be between 5.1 and 13.4 t ha$^{-1}$ for stands up to 5 years old and between 37.4 and 86.2 t ha$^{-1}$ for 20-year-old stands. Biomass yields of 39 and 46 t ha$^{-1}$ were also reported in New Hampshire for two young northern hardwood stands (DBH < 12 cm, 14 and 16 years old, respectively) [17]. These estimates are also in agreement with values reported for *Betula* spp. stands on abandoned farmlands in northern Europe [18].

FAP sampling more accurately estimated biomass per hectare and other stand variables (density and basal area), resulting in potentially harvestable woody biomass estimates between 33-41 and 12–13 t ha$^{-1}$ for the most and least productive marginal areas, respectively. Based on these results, it seems that the choice of testing the sampling methods separately in two adjacent areas was appropriate. Testing the methods in one area only (for example, by delimiting a 1-ha study area) would have resulted in less accurate estimates due to the important differences between the two areas in terms of composition, stand density and biomass production. LIS estimates were in one case (denser area) most of the time lower than those obtained with the different FAP sampling methods (i.e. systematic or random, using small or large plots), suggesting that this method may be biased or has been inadequately applied (perhaps the sample size was too small or errors were made when evaluating crown diameter). An alternative empirical calculation for LIS was tested with mitigated results, but theoretical demonstration is needed to support this estimation method. Small FAP resulted in at least one case where a plot had no measurements (i.e. no plant had a DBH greater than or equal to 20 mm). Moreover, estimates based on small FAP plots were generally higher, even if not significantly different from larger plot estimates.

FAP sampling is widely used in forestry and various authors have made different recommendations concerning sample size and the number of sample plots [22,24,27,50,51]. For example, Hegyi [27] recommended an average number of trees per sample plot between 50 and 70 in young pine stands, a criterion that was respected in this study. However, few studies have explored the use of FAP for young hardwood stands on marginal lands. Smith [52] suggested that a too small sample plot could lead to bias in basal area and biomass estimates. For this reason, among the two sample plot dimensions tested, we suggest using the larger plot size (100 m$^2$).

Prior knowledge of the area, even if approximate, can be used to increase precision and efficiency of the sampling design through stratification [53,54], e.g. based on vegetation type, stand density and perceived productivity (e.g. groups of trees vs mainly low shrubs and isolated trees surrounded by herbaceous species). In heterogeneous stands, using stratified random sampling (e.g. identifying denser vs. more open areas on aerial photos) and different sample plot sizes (e.g. larger, in more open areas) may be a better strategy than using SRS over the entire stand as though it was homogeneous. We can assess the advantage of using stratification to estimate biomass per hectare, for example in random FAP sampling, by excluding the two extremely low estimates (for both biomass and stand density) for plots SQ1P1 and SQ1P4 (Table 3), which we may attribute to a stratum with more open vegetation. If we use only the remaining plots to estimate average biomass per hectare for the denser and more productive stratum inside Square 1, we obtain a higher mean biomass per hectare (on average, for large plots, 18.4 ± 4.3 t ha$^{-1}$), which would be estimated within 20% of the mean with only eight large plots. A variable closely related to biomass, but easier to estimate, may also be used for stratification (e.g. basal area has usually been found to be highly correlated with volume and biomass [50,55–57]). Moreover, different sampling methods may be applied within each stratum, in theory. For example, in our study, LIS performed well in the more open stand (with estimates comparable to FAP) and required less tree measurements, while FAP would be best used in the stratum of a closed-canopy forest. Concerning the choice between systematic or random sampling, our study did not find any clear advantage of using one method over the other. Systematic sampling with a random start may be easier to implement in the field (even without GPS) and ensures better coverage of the area to be studied [53], but may be biased if spatial patterns coincide with the regular interval between plots.

Other methods besides FAP need further investigation, especially since FAP is generally quite costly in terms of time and labour [25,58]. LIS in this study had variable results. Considerations such as length and number of transects [32], difficulties in measuring crown radius and establishing which canopies intersect the transect in dense young stands, may explain this and should be addressed in future studies. Meeuwing and Budy [28] proved that the use of variable radius plot sampling, also known as Bitterlich sampling, is possible for small-diameter trees growing in open formation such as on pinyon-juniper woodland. However, the use of this method for younger and/or denser hardwood stands has yet to be evaluated.

In conclusion, allometric models for small-diameter species, which may contain substantial sources of biomass for bioenergy production, should be developed since they are more accurate than those already available for mature or larger trees. Where possible, tree height may be included to obtain accurate predictions across different sites. Our equations, which include height, should be tested in other stands to validate their applicability to a larger region. Otherwise, if diameter-only equations are provided, they should be used with extreme caution when applied for different stands. Given time constraints, our equations are based on species sampled only at one site, but which included two very different types of stands. Equations encompassing multiple locations and types of stands should be developed. Component equations may also be developed for young stands [17,19], since there is a growing interest in new value-added bioproducts from specific plant parts (e.g. bark and leaves for the production of phytochemicals). FAP sampling with 100-m$^2$ plots gave reliable estimates and is considered acceptable, but other techniques should be tested in the future. LIS may offer some advantages for certain applications [25,30,58] and gave similar results to FAP sampling but only for more open areas, thus it deserves further evaluation before being recommended.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.01.023.

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