Biomass and Bioenergy 83 (2015) 196–205

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Evaluating sampling designs and deriving biomass equations for young plantations of poplar and willow clones

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form
6 August 2015
Accepted 30 September 2015
Available online 22 October 2015

Keywords:
Random sampling
Stratified sampling
Coppice SRIC
Clone-specific allometric equations
Biomass
Multi-stemmed plants

ABSTRACT

Short-rotation intensive culture (SRIC) for bioenergy production is at its pre-commercial stage in Canada. To be economically viable, these types of plantations need an accurate examination of actual yields, which requires precise and efficient estimation methods (i.e., specific allometric equations and sampling methods). At six SRIC plantations from three Canadian provinces (Quebec, Ontario and Alberta), 6 willow and 10 poplar clones were sampled and clone allometric equations were developed to estimate plant biomass. A stem selection approach was successfully used to develop plant allometric equations, reducing the number of stems to be measured by up to 81% in coppiced plantations relative to traditional stem equations. Clone-specific equations were more accurate than equations for groups of clones, but the difference in terms of RMSE% was generally small (less than 5%). Using extensive measurements of all the plants inside a plantation and a simulation approach, we also compared five sampling methods (simple random sampling, stratified sampling, systematic sampling, random and systematic cluster sampling) to estimate total biomass inside the plantation. Simple random sampling and stratified random sampling were the most efficient methods (i.e., increased precision for equal sample size) for the estimation of average plant biomass, survival and total plantation biomass. Stratified random sampling (based on the position inside the plantation) made it possible to reduce the sample size as compared to simple random sampling, but only at higher levels of precision (e.g., 25 less plants at 5% precision). Applications of sampling using remote sensing techniques and GIS are briefly discussed.

1. Introduction

Short-rotation intensive culture (SRIC) refers to plantations of selected genetic material from fast-growing species, such as willow and poplar clones, planted at high density (usually 10,000 to 20,000 cuttings ha^{-1}) and harvested repeatedly at very short rotations (2–5 years) [1–3]. These types of plantations have multiple objectives. They are most commonly implemented to produce biomass for bioenergy production, rehabilitate disturbed lands (e.g., soils contaminated by heavy metals), or produce rough mulch or material for bioengineering structures (e.g., living walls of

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http://dx.doi.org/10.1016/j.biombioe.2015.09.019
0961-9534/

willows on rivers to consolidate riverbanks or on highways to reduce noise and pollution from traffic). Moreover, in the future, these plantations may be part of strategies to sequester CO_2 (in soil and biomass) and reduce dependence upon fossil fuels [3,4]. SRIC plantations can be established on marginal lands for traditional agriculture and may produce additional revenues for farmers, since they can be harvested all year long and therefore have limited impact on other farming operations [2]. They are perennial crops that rely on coppicing, and periodic harvesting may last for approximately 20 years without the need to replant [5,6].

To be economically interesting, SRIC requires agronomical management, such as weed control (especially at plantation establishment), soil tillage (before initial establishment), fertilization [7] and irrigation under certain soil and climatic conditions, and a good organization of the market chain (e.g., establishing plantations near biomass factories and where there is a reliable demand) [3,5]. In North America, SRIC is still at a pre-commercial stage [8], with average yields between 6 and 12 oven-dry t ha^{-1} yr^{-1} [6]. In order to foster the deployment of short-rotation plantations at the commercial scale and fully evaluate their profitability, it is essential to develop tools to accurately and efficiently estimate biomass yield [9]. Indeed, in a recent experts' assessment of needs for short-rotation plantations, including SRIC systems, the need for valid biomass estimates for different clones and soil conditions was identified as a short-term priority (next 5 years [6]).

Two aspects are important for the estimation of harvestable biomass in a plantation: (1) accurate biomass estimates at the plant level and (2) reliable sampling and calculation approaches to estimate biomass per hectare or total biomass of a plantation (including evaluation of live plants per hectare or survival rate [3,10]). Traditionally, tree biomass has been estimated using allometric equations linking diameter with dry weight of the tree. However, for SRIC, the use of allometric equations must be rethought given the multi-stemmed nature of most poplar and willow clones following coppicing. As a consequence, it is important to develop a strategy to select the stems to measure (e.g., three largest stems or average stem?) and determine how many diameter and height values should be measured, given the fact that measuring all the stems in a plant is impractical. Various authors have indicated that clone-specific equations were needed for accurate predictions of biomass, but there are still few equations for short-rotation plantations of willows or poplars [11–15], and even fewer for Canadian conditions [3,16–19]. A recent study has presented clone-specific equations for stem biomass in SRIC systems and used these to estimate plant biomass by summing the weights of all the individual stems [3]. To predict biomass yield (t ha^{-1}) for a few willow clones planted in SRIC systems in eastern Canada, Mosseler et al. [19] presented simple linear models based on selected stem characteristics (e.g., diameter (or stem length) of the largest (or longest) stem or of the three largest (or three longest) stems). This approach had the advantage of reducing the number of stem measurements required and may be refined via more flexible nonlinear models combining multiple variables.

The present study has two objectives. First, developing plant allometric equations for various commercial clones of willow and poplar using data from Québec, Ontario and Alberta, the three Canadian provinces in which SRIC systems are predicted to develop the most by 2021 [1]. The issue of multi-stemmed plants (coppice) was addressed by stem selection. Second, sampling methodologies were tested to determine which sampling strategy results in the most accurate estimates of biomass at the level of the plantation with the smallest number of field measurements. Indeed, this question has rarely been explicitly addressed for SRIC (e.g., [20,21]).

2. Material and methods

2.1. Plot descriptions

Sampling of willows and poplars was conducted at six sites in Québec, Ontario and Alberta. Site and plantation characteristics, as well as the name of each clone and the number of plants sampled, are reported in Table 1. For willows, the age of the stems and of the number of coppicing differed substantially between Guelph (GU; 9-year-old plantation, already harvested twice, with 2-year-old stems), Boisbriand (BB; 3-year-old plantation, not yet harvested) and Beaverlodge (BL; 4-year-old plantation, not yet harvested). For poplars, we had a more complex situation. All the stems were 2 years old, even if at GU the rooting system was 9 years old (three rotations) and at Saint-Augustin-de-Desmaures (SA) it was 5 years old (one rotation), but initial plantation density varied a lot, from around 5000 plants per hectare at SA to around 10,000 plants per hectare at Cacouna (CA) and Saint-Paul-de-la-Croix (SP) and, finally, more than 15,000 plants per hectare at GU (Table 1).

2.2. Sampling for allometric equations

Sampling was performed at the end of summer or during autumn 2014, when the peak of growth was already passed. An approximately equal number of plants were harvested for small, medium and large plants to ensure a balanced range of sizes and morphology to develop allometric equations for the estimation of aboveground dry leafless biomass of the plant. Prior to harvesting, a mark was made at 15 cm from the base of each stem of a plant (measured on the upper side from the stem insertion), and each stem was numbered. Diameter at the 15-cm mark and at 115 cm above the mark (the equivalent of diameter at breast height, usually measured at 1.3 m from the ground) of each stem was measured in millimeters (mm) with a digital caliper (D15 and DBH, respectively). DBH was measured only for stems with D15 greater than or equal to 20 mm (a minority of stems in these young plantations). Stem length from the 15-cm mark to the top of the stem (without leaves) was recorded in centimeters (cm), allowing the calculation of total stem height by adding 15 cm (H). The plants were cut at the ground level. Once the stems were removed, there usually remained a piece between the cut at ground level and the insertion of each stem, which was identified as the main stump and represented the plant stump, not pertaining to any individual stem in particular. This allowed us to estimate the contribution of the main stump to plant biomass. It should be noted that harvesting machines in commercial plantations usually cannot cut below 10–15 cm from the ground level, and thus the main stump and part of each individual stem base generally remains in the field after harvesting, allowing the coppicing of the aboveground part for the next harvest, without the need to plant new cuttings at each harvesting cycle.

Once the plant was cut, leaves were manually removed if sampling took place before complete leaf fall. Individual stems and the main stump were weighed separately in the field with an electronic kitchen scale (±1 g) to obtain fresh weight of the different components. Subsamples were taken if the original sample was heavier than 400 g and the fresh weight of the subsample was recorded. Subsamples contained roughly the same number of equal-length pieces from the basal (first third of the stem), central and top part of the stem. In the laboratory, samples were oven-dried at 70 °C for 72 h and dry weights were recorded. For those parts for which subsamples were taken, the ratio between the dry and fresh weight of the subsample multiplied by the fresh weight of the original sample was used to calculate the total dry weight.