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Simple height and volume equations for on-the-fly estimation of productivity in hybrid poplar (*Populus* x *euroamericana*) plantations in the Duero Basin (northwestern Spain) †

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Abstract: Hybrid poplar plantations are becoming increasingly important as a source of income for farmers in the Duero Basin (northwestern Spain), as rural depopulation and farmers aging prevent them from planting other labor-intensive crops. However, forest owners, usually elderly and without formal forestry backgrounds, lack of simple tools to estimate the size and volume of their plantations by themselves. Therefore, farmers are usually forced to rely on the estimates made by the timber companies that are buying their trees. With the objective of provide a simple but empowering tool for these forest owners, simple equations based only on diameter to estimate individual tree height, and volume were developed for the region. To do so, growth in height, diameter and volume were measured for 10 years (2009-2019) in 404 trees planted in three poplar plantations in Leon province. An average growth per tree of 1.66 cm year^{-1} in diameter, 1.52 m year^{-1} in height, and 0.03 m^3 year^{-1} in volume was estimated, which translated into annual volume growth of 13.02 m^3 ha^{-1} year^{-1}. However, annual volume growth was different among plots due to their fertility, with two plots reaching maximum growth around 13 years of tree age and another at 15 years, encompassing the typical productivity range in plantations in this region. Such data allowed developing simple lineal, polynomic and power equations to estimate height and volume explaining 84% to 97% of the observed variability. Such equations can be easily implemented in any cellphone with a calculator, allowing forest owners to accurately estimate their timber existences by using only a regular measuring tape to measure tree diameter.

Keywords: Tree plantations; growth equations; rotation length; growth rates; poplar productivity

1. Introduction

Poplar plantations, usually considered as short-term silviculture, are usually established in former agricultural lands or in fertile forestlands with little or non-degradation [1]. Such short-term plantations cover 7% of planted areas but provide 50% of wood volume used in the industry.

In Spain, and particularly in the Duero and Ebro river basins poplar plantations are under expansion, due to its rapid growth and timber quality [3]. In 2016, poplar stands accounted in Spain for 145,000 ha, being one-third natural stands and two-thirds plantations. Such plantations have been traditionally used for pulp and unrolling for plywood or veneers. Socially, such plantations have an important function, as they provide additional income from low-productive croplands to farmers or for urban owners not willing to work their farmlands. In addition, the current ageing process in the rural countryside and particularly among farmers makes poplar plantations increasingly popular as a production system that only requires a few days labor in a typical ~15-year rotation.

However, due to the lack of formal training in forestry, most owner do not know how much volume their plantations have, and when selling the timber to sawmills they have to accept the price that are offered. Such lack of negotiation power reduces the profits for the forest owners and creates an unbalanced market in which timber companies and sawmills impose their economic objectives over the plantation owners´. A simple way to empower forest owners (mostly senior) is by providing simple, easy-to-use tools to assess standing timber volume on-the-fly. Simple volume equations that can be implemented in a cellphone (ubiquitous nowadays even in rural areas) can be used for this proposed if they use as inputs a single, easy to measure variable, such as tree diameter, which can be estimated with a simple measuring tape.

Therefore, the objective of this research was to develop such simple volume equations for poplar plantations in northwestern Spain, one of the European regions with the highest production of poplar timber but at the same time one of the regions with the highest level of rural abandonment and aging population.

2. Material and Methods

3.1. Trees and management

Three research plots, located in the town of Villarejo de Órbigo (León province, northwest Spain) were used for this research. Placed in former agricultural lands, in a flat surface about 3 km from the Órbigo River, the plots were planted with 2-year old saplings of Popolus x euroamericana (Dode) Guinier, clonal variety I-214. In March 2006, trees were planted in a 5 x 5 m spacing, for a total of 404 trees planted. Trees were tended as usual in the region (localized fertilization in plantation year 2 combined with chemical herbicide and pesticide, followed by manual removal of weeds with scythe each summer, irrigation in June and August each summer. Trees were pruned in plantations year 3 and 5.

3.2. Measurements and data analysis

Diameters at breast height (1.30 m, DBH) were measured annually in August for each tree every year using a tree caliper and estimated as the average of two perpendicular measurements. Tree heights were measured for each tree annually in August using an ultrasonic hypsometer (Vertex IV, - Haglöf, Sweden), and estimated as the average of six measurements. Individual tree volume was estimated using the volume equation by [3]

Data were tested for normality with the Shapiro-Wilk and Kolmogorov-Smirnov tests. Homoscedasticity was tested with the Levene and Bartlett tests. As data passed both tests, regressions between tree height and DBH, and between DBH and tree volume were carried out using linear, polynomial and power functions [4].

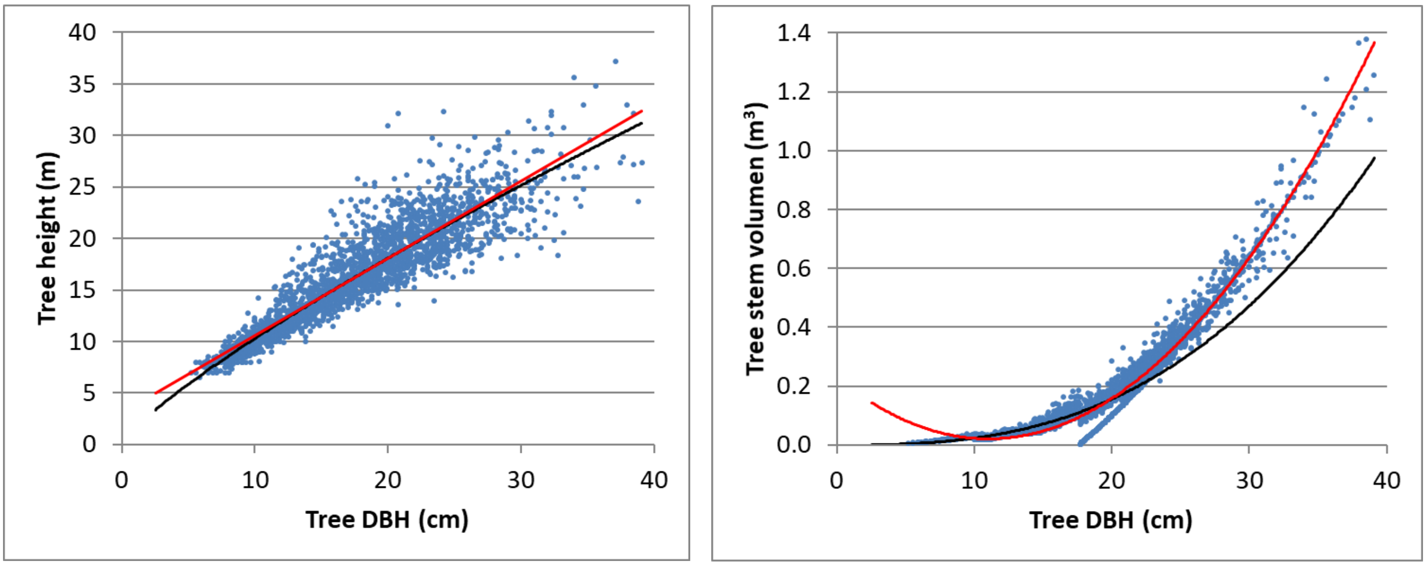
3. Results

Tree diameter in 2019 (at plantation age 13 years) ranged from 12.8 to 39.1 cm, but most of trees were close to an average diameter of ~25 cm (Table 1). Tree heights ranged from 11.93 to 37.17 m, with an average of ~22 m. As a consequence, trees were quite slender, with slender indexes (height/diameter) close to 1. Tree volume was very variable (ranging from 0.038 to 1.343 m^3) with an average value close of 0.458 m^3 (Table 1). For stand-level variables, basal area was approximately 23 m^2 ha^{-1}, whereas volume reached 233.840 m^3 ha^{-1} (Table 1).

An average growth per tree of 1.66 cm $year^{-1}$ in diameter, 1.52 m $year^{-1}$ in height, and 0.03 m^3 $year^{-1}$ in volume was estimated, which translated into annual volume growth of 13.02 m^3 ha^{-1} $year^{-1}$. However, annual volume growth was different among plots due to their fertility, with two plots reaching maximum growth around 13 years of tree age and another at 15 years, encompassing the typical productivity range in plantations in this region. Such data allowed developing simple lineal, power and polynomic equations (Eq 1 to 4) to estimate height and volume explaining 84% to 97% of the observed variability (Figure 1).

Table 1. Summary data for the measured trees in 2019 (n=404, averages ± error standard).

Variable	Value
DBH (cm)	24.78 ± 0.605
Height (m)	21.67 ± 0.423
Slenderness index (m/cm)	0.888 ± 0.014
Tree volume (m^3)	0.458 ± 0.029
Basal area (m^2 ha^{-1})	23.004 ± 0.855
Volume with bark (m3/ha)	233.840 ± 17.698



(**a**) (**b**)

Figure 1. Regressions among tree attributes. Panel a) Estimation of tree height with tree DBH as predictor (red line: power function, Equation 1; black line: linear function, Equation 2). Panel b) Estimation of tree volume with tree DBH as predictor (red line: power function, Equation 3; black line: polynomic function, Equation 4).

$$H(m) = 1{,}5769 \times D(cm)^{0{,}8143} \quad R^2 = 0{,}8889 \tag{1}$$

$$H(m) = 3{,}0407 + 0{,}7493\, D(cm) \quad R^2 = 0{,}8409 \tag{2}$$

$$V(m^3) = 0{,}000043 \times D(cm)^{2{,}734005} \quad R^2 = 0{,}8471 \tag{3}$$

$$V(m^3) = 0{,}2291 + 0{,}0377 \times D(cm) + 0{,}0017 \times D^2(cm) \quad R^2 = 0{,}9654 \tag{4}$$

4. Discussion

Relationships among tree attributes are determined by tree architecture and growing conditions. As seen in this work, some poplar trees planted in the Duero Basic can reach commercial (harvesting) sizes (DBH > 30 cm) 13 years after planting, but the stand as whole may need closer to 16-17 years to reach such size in average. Such long rotation times for a fast-growing species such as hybrid poplar are typical for this region, reaching an annual productivity considered as good [5]. However, the lengthy plantation time and dense plantation spacing can make trees quite susceptible to windthrow, as indicated by the slender index close to 1 [6] Trees broken or fallen by wind are clear economic losses that may cancel the benefit of extending rotation times. Therefore, after passing 13-14 years since plantation, owners in this region must evaluate the potential benefit of letting trees grow another year (about 1.5 cm potential DBH increase) versus losses by wind.

To make such decisions it is crucial for the forest owner to know how much the timber price stands at the time of harvest but even more important is to know how much standing volume is present in the plantation. There are several volume equations for poplar plantations in Spain [7-11], but they all use two or more tree attributes (e.g. diameter and height). As tree height is difficult to be precisely measured without specific (and usually expensive) equipment such hypsometers, two-variable equations are out of reach in practical terms for forest owners (most of the seniors).

In contrast, the equations provided here showed a very high predictive capacity (R^2 values in the 84-97% range), more than enough to provide volume estimations adequate to make such decisions. In addition, the equations provided here are simple enough that can be written in any smart phone equipped with a calculator app. This allows the forest owner to measure the tree with a regular measuring tape, introduce the circumference in the calculator and just converting it into diameter and then into tree volume. Such simple calculation will provide a forest owner with the capacity to initiate negotiations with timber companies on the time and cost of plantation harvesting from a much stronger position than if the volume estimation is left into the hands of the same company that has to harvest the trees.

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