
Evaluating Different Techniques for Estimating Biomass in Short-Rotation Willow Plantations

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Abstract

The hallmark of any successful purpose-grown willow production system involves regular monitoring of willow growth to apply timely management techniques for supporting increased productivity, but also timing harvest for maximizing profit. The objective of this study was to compare a conventional allometric technique (i.e., defined by a simple empirical relationship between stem size and mass) with a novel alternative method measuring light attenuation through the willow crop canopy (i.e., Stem Area Index; using a LAI-2000 Plant Canopy Analyzer) and relate these data to harvested willow biomass. Two different hybrid willow clones with contrasting growth form, either single stem (Charlie) or multi-stem (SV1), were studied. The observed allometric models were stronger for multi-stemmed SV1 ($R^2 = 0.81$) compared to the single-stemmed Charlie ($R^2 = 0.67$); however, the allometric relationships in this study were not as robust as those typically reported in the literature for willow and is probably due to the uncoppiced management of the study plantation. Given the strong correlations ($R^2 > 0.98$) between Stem Area Index and harvested willow biomass, regardless of growth form, it appears that this novel mensurative technique is a promising alternative to conventional allometry. It is prudent to develop a rapid, cost-effective, and non-destructive mensurative technique yielding reliable biomass estimates, for supporting effective management decisions in a timely manner.

Introduction

Considering that harvesting operations are the greatest single cost incurred with short-rotation willow production systems (Heller et al., 2003, 2004; Keoleian and Volk, 2005; Spitzley and Keoleian, 2005; Tharakan et al., 2005), it is imperative for farmers to optimize the timing of harvest, based on accurate estimations of current yield, for supporting the greatest economical return on investment. Additionally, monitoring annual production rates will be invaluable in terms of making effectual management decisions prior to harvest, such as prompting fertilizer amendments to increase productivity, for meeting both economic objectives and/or contractual obligations with industrial partners relying on feedstock commitments. The conventional non-destructive technique is allometry – defined by a simple empirical relationship between size and mass, which involves calibrating measured stem diameter (at a specified height) with subsequently harvested biomass (Figure 1a; Heinsoo et al., 2002; Nordh and Verwijst, 2004; Arevalo et al., 2007). Currently, this is the industry standard with which all other approaches should be compared. However, manually collecting above-ground samples for biomass estimates can be time consuming, costly, susceptible to subjective errors, and inherently destructive. As such, there remains a need to develop a mensurative technique for estimating willow biomass, having not only the accuracy of allometry, but also non-destructively yielding quick and economical data.



Figure 1. Estimating above-ground willow biomass using an allometric technique (a) and a LAI-2000 Plant Canopy Analyzer to measure the ‘gap fraction’ (i.e., fraction of the sky visible from beneath the canopy) corresponding to five sensor rings centred on different zenithal angles (b).

A novel alternative approach to allometry proposed in this study involves using the LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE; Figure 1b) to measure the ‘gap fraction’, which is the fraction of the sky visible from beneath the canopy, by quantifying the fraction of sky that is blocked by foliage, branches, or stems (i.e., degree of canopy openness; Welles and Norman, 1991; LI-COR, 1992; Machado and Reich, 1999). The Plant Canopy Analyzer is the foremost research instrument for measuring light attenuation (i.e., reduction in amplitude and intensity) as it passes through a vegetative canopy and its utility has been reported in hundreds of articles covering a range of vegetation types, including: shrubs and grasses (Welles and Norman 1991; Hanan and Bégué, 1995; White et al., 1997; Sonnentag et al., 2007); coniferous, deciduous, and mixedwood forests (Gower and Norman, 1991; Deblonde et al., 1994; Vertessy et al., 1995; Strachan and McCaughey, 1996; Comeau et al., 1998); annual crops (Welles and Norman 1991; Dobermann et al., 1995; Hicks and Lascano, 1995; Rudorff et al., 1996); vineyards (Ollat et al., 1998; Johnson and Pierce, 2004.); turfgrass (Yuen et al., 2002); and even non-crop species (Thevathasan et al., 2000). Gap fraction is synonymous with canopy openness, canopy transmittance, and diffuse non-interceptance (Machado and Reich, 1999; Engelbrecht and Herz, 2001; Comeau et al., 2003; Voicu and Comeau, 2006; Kobe and Hogarth, 2007) and is determined by measuring the difference between the diffuse incident radiation at the top of the canopy with the diffuse transmitted radiation under the canopy, assessed at five different angles relative to the zenith concurrently, using a “fish-eye” 148° field-of-view optical sensor (LI-COR, 1992; Figure 1b). The Plant Canopy Analyzer uses all five zenithal angle gap fraction measures to simultaneously calculate leaf area index (LAI; ratio of the canopy foliage area to ground area; Watson, 1947), using well established inversion and integration models describing radiation transfer through vegetation canopies (Welles and Norman, 1991; Leblanc and Chen, 2001; Breda, 2003; Broadhead et al., 2003; Jonckheere et al., 2004).

Notwithstanding its popularity, a common criticism of the Plant Canopy Analyzer is that its measured LAI values are not ‘true’ LAI values, because of its 490 nm filter, it cannot distinguish between radiation intercepted by photosynthetic leaves vs. non-photosynthetic woody stems and branches within the canopy (i.e., leads to LAI overestimation; Welles, 1990; Chen et al., 1997; Whitford et al., 1995; Weiss et al., 2004). The intention of this study, however, is to use the Plant Canopy Analyzer to measure ‘leaf area index’ after leaf fall, in order to test its utility as a surrogate measure of leafless above-ground biomass within willow plantations. By measuring the gap fraction of non-photosynthetic woody material, the Plant Canopy Analyzer is, therefore, essentially providing a measure of ‘Stem Area Index’ (SAI), which can be calibrated with harvested biomass. The objective of this study was to compare a conventional allometric technique with a novel alternative estimation of SAI, measured using the Plant Canopy Analyzer, and relate these data to harvested above-ground biomass of two different hybrid willow clones having contrasting growth forms. Given that *in situ* observations clearly indicating the effect of variable above-ground willow biomass on variances in transmitted radiation at ground level (Figure 2), it is hypothesized that the Plant Canopy Analyzer will provide an accurate and precise estimates of harvestable willow biomass and, thus, serve as an effective alternative to conventional allometry for providing a fast and reliable indirect measure of willow plantation productivity.



Figure 2. The effect of willow canopy light interception on the fraction of transmitted radiation to the snow surface. Note the marked difference in light levels within rows and between rows, despite the relatively sparse one-year-old willow stems.

Materials and Methods

Study site

The data for this study were collected in the spring of 2008 from a two-year-old hybrid willow plantation located on the University of Saskatchewan campus in Saskatoon (Figure 3; UTM coordinates: 13U 389970 5776342). The plantation was established on June 14, 2006 and

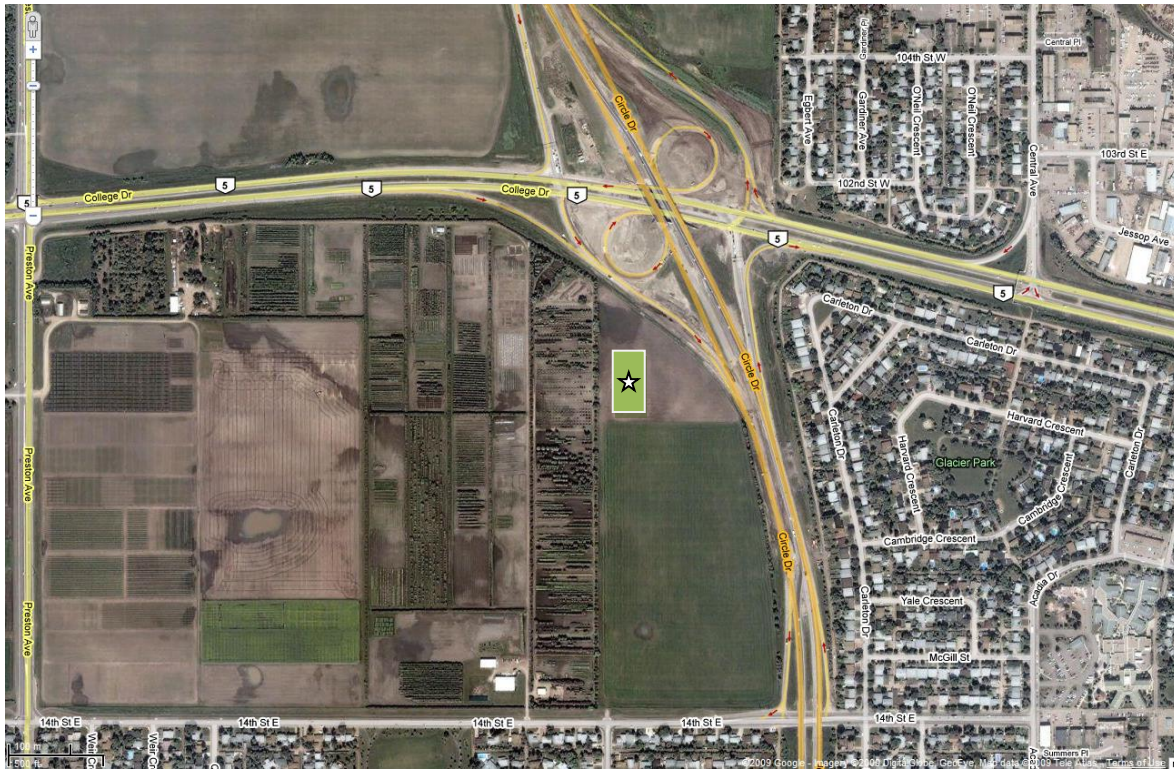


Figure 3. Location of willow plantation on the University of Saskatchewan campus.

Table 1. Selected Characteristics of hybrid willow study site located in central Saskatchewan.

Soil Characteristics			Site Characteristics					Weed Control Practices			
Association	Soil Type	Texture	Prior Crop	ACC*	MAP†	MAT‡	FFD§	Pre-planting		Post-planting	
								Mechanical	Chemical	Mechanical	Chemical
Sutherland**	Orthic Vertisol	heavy clay	barley/oats	2-3	375	2	112	Deep till, Light cultivation, and Tandem disc (x 2)	Linnuron (1.7 L ha ⁻¹)	Between-row tillage, mowing, and hand weeding	Glyphosate (2 L ha ⁻¹)

* Agriculture capability classification (Class 2-3: moderate to moderately severe limitations due to lack of precipitation).

† Mean Annual Precipitation (mm).

‡ Mean Annual Temperature (°C).

§ Frost-free days.

** For a complete description (i.e., map unit, parent material, stoniness, drainage, etc.) see SCSR (1978).

selected characteristics of the site are reported in Table 1. The willow plantation is a clonal trial arranged in a randomized complete block design, replicated three times, using a 60 x 60 cm grid spacing within each triple-row bed and 200 cm spacing between beds (approximate density of 15,625 stems/ha). Two hybrid willow clones, having contrasting growth forms, were studied: Charlie (*Salix alba* x *Salix glauca*; single-stem) and SV1 (*Salix dasyclados*; multi-stem). Charlie and SV1 are the standard clones for comparison within Canada and the U.S., respectively.

Developing Allometric Models for Estimating Willow Biomass

Conventional allometric equations for estimating above-ground willow biomass were developed by calibrating measured stem diameter (at 30 cm height; Figure 1a) with harvested leafless biomass from 30 systematically sampled plants within the plantation for each clone (Arevalo et al., 2007). The harvested stems (including branches) were cut approximately 3 cm above the soil surface using hand clippers, dried at 65 °C to a constant weight, and weighed. Typically, these allometric models are then coupled with stem density and diameter measurements from each of the respective clonal beds to estimate biomass per bed and then extrapolated to a stand level (i.e., total biomass per hectare). In this study, however, the objective was simply to determine the strength of the allometric relationship between stem diameter and harvested stem biomass, so stand level biomass estimates were not necessary. **[Note: I have done the stand level calculations based on the allometric estimates and will include these in the MS, because it will help facilitate the comparison of the two methods. Ken, this may have been what you were talking about when you asked about a ‘common factor’ when reviewing the poster.]**

Development of Stem Area Index as Surrogate for Estimating Willow Biomass

A LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE) was used to measure the gap fraction and subsequently calculate the SAI for leafless willow within each block for each clone for correlation with harvested above-ground willow biomass (Figure 1b). Briefly, three different sampling scales (between-row, within-row, and single plant) were used to collect SAI measurements using the Plant Canopy Analyzer (Figure 4). Each of these sampling scales has been successfully used to measure gap fraction for a variety of plant crops with either discontinuous or heterogeneous canopies (Welles and Norman, 1991; LI-COR, 1992; Welles and Cohen, 1996; López-Serrano et al., 2000; Wilhelm et al., 2000; Malone et al., 2002; Johnson and Pierce, 2004; Weiss et al., 2004); however, given the exceptional growth form of coppiced willow, all three approaches will be assessed to determine which provides the most reliable estimate of SAI for routine use within the short-rotation willow plantation context. All three sampling schemes will involve: placing the sensor near the soil surface; using both a 45° and 90° view cap (consisting of a 315° and 270° opaque mask, respectively) to restrict the azimuthal range of the sensor – necessary to not only prevent light not transmitted through the canopy from influencing the measurements (common concern with discontinuous row crops), but also to obscure the operator from the sensor; one above-canopy measurement will be taken for every four below-canopy measurements (in the same azimuthal direction) to allow the Plant Canopy Analyzer to determine the fraction of diffuse incident radiation passing through the willow canopy – required for calculating the SAI of the plot; and finally, taking measurements under diffuse sky conditions (i.e., overcast, before sunrise, or after sunset) in order to avoid direct sunlight and/or light scattering within the canopy from influencing the readings. If these were operational-scale plantations, then these sampling schemes would be randomly located within the plantation; however, in view of its small research-scale plot size, each sampling scheme was systematically set up to sample the entire triple-row bed, while avoiding possible edge effects (Figure 4). For each sampling scheme, SAI was calculated based on a total of 16 below-canopy and four corresponding above-canopy measurements within each plot, and the SAI values were correlated with the corresponding willow biomass that was subsequently harvested, dried at 65 °C to a constant weight, and weighed.

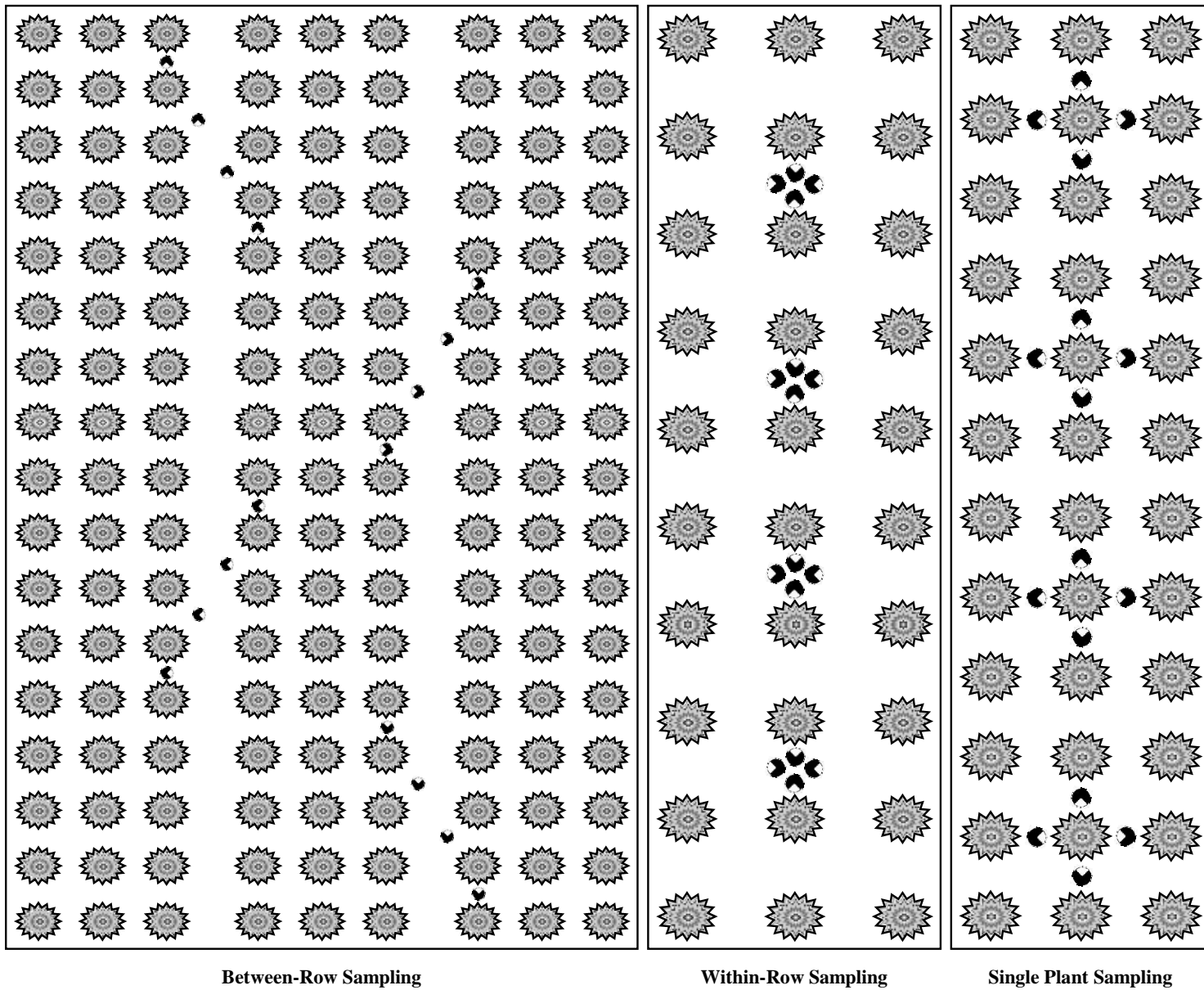


Figure 4. Placement of LI-COR Plant Canopy Analyzer (with 90° view cap indicated by white fraction of circle), at varying sampling scales, to measure gap fraction for correlation with harvested biomass within short-rotation willow plantations.

Statistical Analyses

Simple linear regressions were performed using the REG procedure in SAS (Version 9.1, SAS Institute Inc. Cary, NC).

Results and Discussion

Allometric Relationship Between Stem Diameter and Harvested Above-ground Willow Biomass

The allometric relationships in this study, for either the single-stemmed Charlie or multi-stemmed SV1 clones (Figures 5a and b), were not as robust as those typically reported in the literature for willow (i.e., R^2 values ~ 0.95 ; Arevalo et al., 2007; Bond-Lamberty et al., 2002; Hytönen and Kaunisto, 1999). These relatively poor correlations are probably due to the uncoppiced management of the study plantation. Along with adopting a triple-row bed design, the Canadian Forest Service production system also differs from conventional purpose-grown willow plantation protocols by harvesting after four years of growth without coppicing after the first year. Coppicing promotes the production of larger numbers of uniformly-shaped stems (i.e., relatively homogeneous diameter:mass), which also helps to explain the observed larger R^2 value of the multi-stemmed SV1 clone allometric model compared to the single-stemmed Charlie model. Specifically, unlike the shrub growth form of SV1, the tree growth form of Charlie is inherently more variable within a plantation due to inconsistent branching and, therefore, results in relatively weaker correlations between stem diameter and biomass, which can occur among trees having a relatively heterogeneous structure (Lambert et al., 2005; Ter-Mikaelian and Korzukhin, 1997). Likewise with the uncoppiced management of the multi-stemmed SV1, where the marked presence of varying degrees of sylleptic branching (i.e., branching along the upper part of the stem) was evident in this plantation, whereas this is uncharacteristic of coppiced SV1 plantations.

Relationship Between Measured Stem Area Index and Harvested Above-ground Willow Biomass

There was a much stronger correlation between SAI, measured using the Plant Canopy Analyzer, and above-ground biomass of the two hybrid willow clones compared to the observed allometric relationships (Figures 5c and d). For the multi-stemmed SV1 clone, the within-row sampling scheme (using the 90° view cap) provided the best estimates of willow biomass, whereas the single-tree sampling scheme (using the 45° view cap) was superior for the single-stemmed Charlie (data not shown). Presumably, these differences in efficacy among the sampling scheme/view cap combinations used to measure the SAI of the two clones is due to the effect of growth form on gap fraction distributions within the clonal plots. Specifically, when measuring SAI of the single-stemmed Charlie, evidently it is prudent to use the single-tree sample approach with a narrower view cap in order to sample more of the woody material and less interplant area, otherwise the Plant Canopy Analyzer will measure a larger gap fraction, thereby underestimating the SAI. Conversely with the multi-stemmed SV1, where the within-row sample approach with the wider view cap samples a larger area of these relatively dense beds, or else the Plant Canopy Analyzer measures a smaller gap fraction, in so doing overestimating the SAI. The relationship between SAI and harvested biomass, using pooled data from both willow clones, remained significant although was not as strong ($R^2 = 0.56$; $P < 0.05$), and is not surprising considering the marked differences in growth form and concomitant

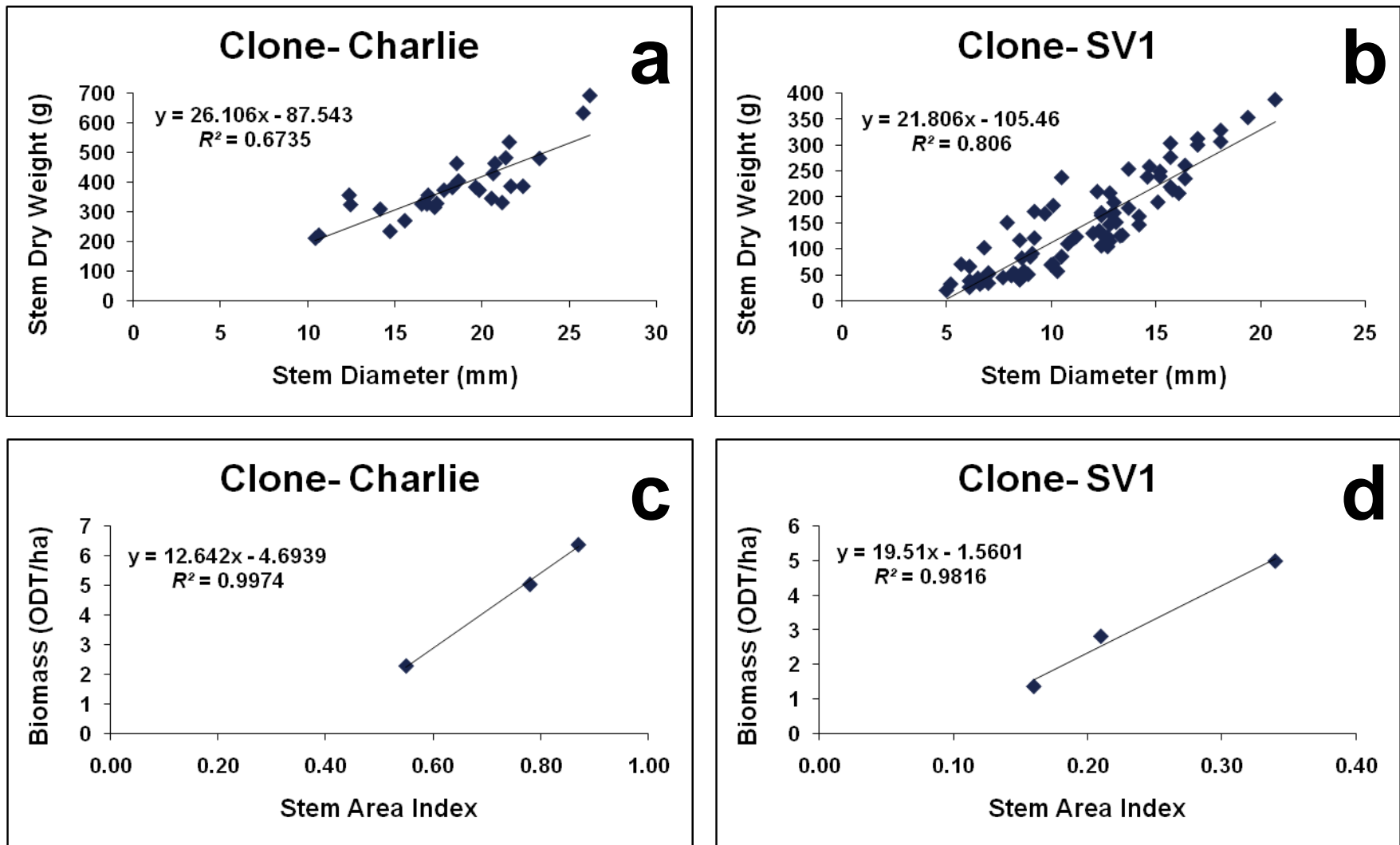


Figure 5. Modelling above-ground biomass of different two-year-old willow clones using an allometric relationship between stem diameter (at 30 cm height) and leafless stem weight of 30 systematically sampled plants (a and b) or relating Stem Area Index, measured using a LAI-2000 Plant Canopy Analyzer, with harvested bed biomass (c and d). Note: single-tree (45° view cap) and within-row (90° view cap) sampling schemes were used to measure the Stem Area Index for Charlie and SV1 clones, respectively.

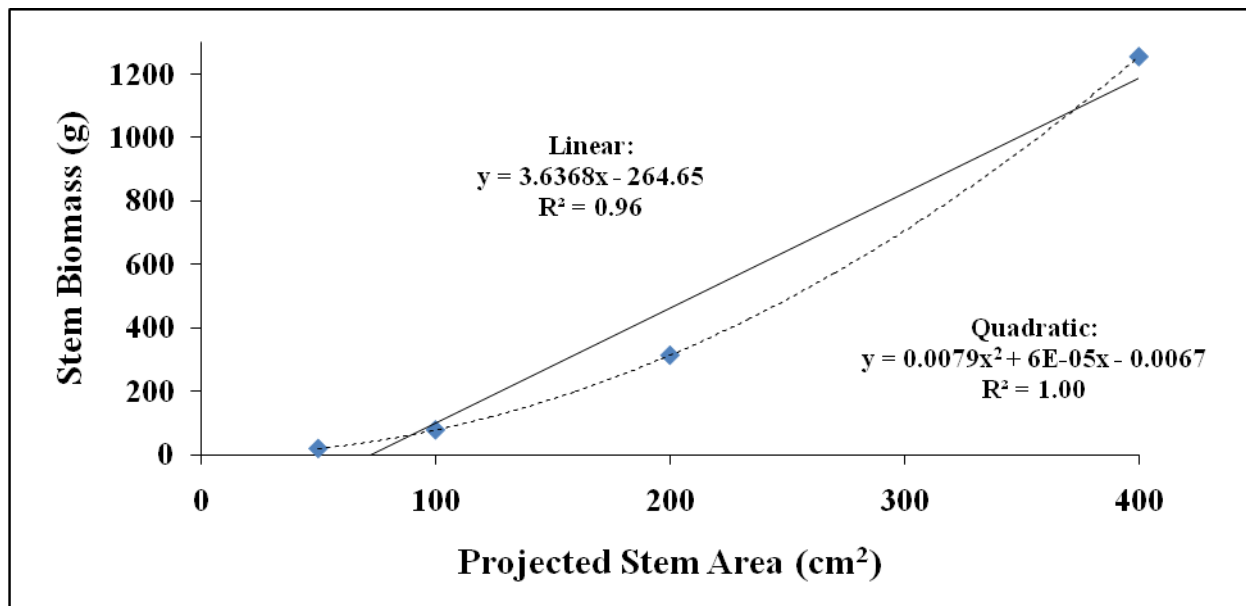


Figure 6. Theoretical dataset illustrating the effect of increasing willow stem diameter (0.5, 1, 2, and 4 cm) on the linear and quadratic relationships between projected stem area and stem biomass (assuming a constant height of 100 cm, cylindrical stem shape, and wood density of 1 g cm⁻³).

variation in light attenuation characteristics between the two canopy types. Considering that the Plant Canopy Analyzer is designed to estimate two-dimensional leaf shading area, it can be argued that the instrument will be insensitive to variations in plant morphology, in particular, stem diameter. For instance, a stem with a radius of 0.5 cm and height of 100 cm will have a projected area of 50 cm² (i.e., 0.5 x 100 cm) and a volume of 19.6 cm³ (i.e., $\Pi \times 0.25^2 \times 100$ cm), while another stem having an identical height but double the diameter, has a projected area of 100 cm² and volume of 78.5 cm³. Thus, a doubling of stem diameter results in a doubling of projected stem area (i.e., SAI), but the volume (and presumably biomass too – assuming similar wood density) will be *four times* larger (Figure 6). Consequently, thicker stems will have a smaller SAI to mass ratio than thinner stems of similar height. Such a relationship is inherently non-linear and helps to explain the negative intercept in the observed linear models in this study, compared to using a polynomial equation that allows for the possibility of a zero intercept using a quadratic fit instead of a linear fit (Figure 6). This apparent shortcoming is also inherent to photogrammetric methods used to estimate willow biomass, but like this study, evidently has a negligible effect on the resultant empirical linear or quadratic models predicting willow biomass (Ens et al., 2009).

Conclusion

Notwithstanding the apparent influence of the uncoppiced management of the study plantation on the observed allometric relationships, the strong relationship between SAI, measured using the Plant Canopy Analyzer, and harvested willow biomass compares very well with the robust allometric models often reported in the literature. Although very accurate, traditional methods of estimating willow plantation productivity by developing allometric

relationships for these multi-stemmed species can be time consuming, costly, and susceptible to subjective errors. Consequently, it appears that this novel mensurative technique is a promising alternative to conventional allometry, thereby supporting effective management decisions throughout the rotation of purpose-grown hybrid willow plantations. Further research is needed, however, to determine if the observed relationships between SAI and above-ground willow biomass remains consistent with different clones growing across a geoclimatic gradient, on a variety of soil types, under a coppiced management system typically used in the U.S. and Europe.

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