Predicting aboveground biomass carbon sequestration potential in hybrid poplar clones under afforestation plantation management in southern Ontario, Canada

by Amir Behzad Bazrgar[1], Derek Sidders[2] and Naresh Thevathasan[1*]

ABSTRACT

Afforestation systems as a pathway for natural climate solutions contributing to terrestrial C sequestration are influenced by agroclimatic conditions, tree species and clones. This study validated a regression equation to predict aboveground biomass C (AGBC) sequestration potentials of hybrid poplar clones under afforestation plantation and compared these clones' adaptability to three levels of land suitability in four afforestation sites in southern Ontario, Canada. Results validated the proven ability of the GenOnBio model to reasonably predict AGBC content in all tested clones. This research suggests that DN154 and FFC1 having C sequestration rates of 2.19 and 2.13 Mg C ha^{-1} y^{-1}, respectively, are suitable for marginal lands having high land suitability condition. In contrast, DTAC29, and DTAC26 (0.56 and 0.88 Mg C ha^{-1} y^{-1}, respectively) should not be selected for the above land suitability. On marginal lands with severe limitations, NM6 (1.53 Mg C ha^{-1} y^{-1}) showed the highest adaptability for AGBC sequestration. Our findings confirm that poplar afforestation on marginal lands in southern Ontario, at least up to the age of 15 years, can significantly contribute to AGBC sequestration, which in turn can have significant positive influence on the current 2 billion tree planting program initiated by the federal government.

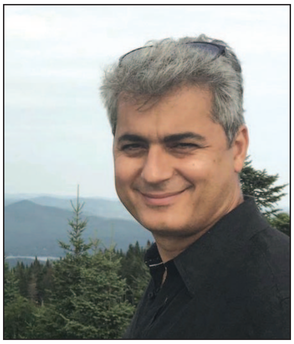
Keywords: regression equation; allometric models; carbon stock estimation; climate change mitigation; woody cropping systems

RÉSUMÉ

Le boisement en tant que voie de solution naturelle d'atténuation des changements climatiques par séquestration terrestre du carbone dépend des conditions agroclimatiques, des espèces d'arbres et des clones utilisés. Cette étude cherchait à valider une équation de régression prédisant le potentiel de séquestration du carbone de la biomasse aérienne (CBA) de clones de peupliers hybrides utilisés dans des plantations de boisement et à comparer le rendement de ces clones selon trois niveaux d'aptitude écologique de quatre sites du sud de l'Ontario au Canada. Les résultats ont validé la capacité du modèle GenOnBio de prédire de façon raisonnable le contenu en CBA issus de tous les clones testés. Cette étude indique que les clones DN154 et FFC1 affichant des taux respectifs de séquestration de 2,19 et de 2,13 Mg C ha^{-1} an^{-1}, sont performants dans le cas des terres marginales ayant un haut niveau d'aptitude. Par contre, le DTAC29 et le DTAC26 (affichant respectivement 0,56 et 0,88 Mg C ha^{-1} an^{-1}) ne devraient pas être sélectionnés pour ce niveau d'aptitude. Dans le cas de terres marginales ayant des aptitudes très limitées, le NM6 (1,53 Mg C ha^{-1} an^{-1}) a affiché la plus forte capacité de séquestration en CBA. Nos observations confirment que le boisement avec du peuplier sur les terres marginales dans le sud de l'Ontario, du moins jusqu'à l'âge de 15 ans, peut significativement contribuer à la séquestration en CBA, ce qui en retour peut avoir une influence positive sur le programme actuel de plantation de 2 milliards d'arbres soutenu par le gouvernement fédéral.

Mots clés : équation de régression, modèles allométriques, estimation des stocks de carbone, atténuation des changements climatiques, systèmes de culture ligneuse

[1]School of Environmental Sciences, University of Guelph, Guelph, N1G 2W1, ON, Canada; *Corresponding author: nthevath@uoguelph.ca
[2]Canadian Wood Fibre Centre, Natural Resources Canada, Edmonton, T6H 3S5, AB, Canada



Amir Behzad Bazrgar

Derek Sidders

Naresh Thevathasan

Introduction

Hybrid poplar (*Populus* spp.) is a woody crop with an extensive biomass productivity potential for pulp and bioenergy industries and at the same time can enhance system level carbon (C) sequestration (Jassal *et al.* 2013; Georgiadis *et al.* 2017). C sequestration in afforestation plantations is now considered as a pathway for natural climate solutions (NCS) that could provide additional climate mitigation and other ecosystem services beyond business as usual (BAU) scenario (Drever *et al.* 2021). Aboveground biomass (AGB) carbon sequestration through woody cropping systems in Canada is also considered as one of the promising land-uses to achieve Canada's climate change mitigation goals as outlined in the United Nations Framework Convention on Climate Change (UNFCCC) (ECCC 2020). Afforestation initiatives can also help growers economically by providing valuable feedstock (Bazrgar *et al.* 2020) to further enhance green technologies in Canada. Growth and biomass yield in hybrid poplar cropping systems can significantly differ based on genotypes, agroclimatic conditions, and site characterisation (Jassal *et al.* 2013; Fortier *et al.* 2010; Pinno *et al.* 2010; Truax *et al.* 2012). For poplar plantation as short rotation woody crop production system, Bazrgar *et al.* (2020) reported 4.01 and 7.01 Mg C ha^{-1} in cycle 3 year 2 and cycle 3 year 3 in Guelph, Ontario. Coleman *et al.* (2018) also indicated that the aboveground biomass for eight poplar clones in a concentrated short-rotation woody crop production system in southern Ontario varied between 3.96 to 13.40 Mg ha^{-1} and 0.35 to 1.59 Mg ha^{-1} in cycle 2 year 3 and cycle year 1 respectively. Teruax *et al.* (2014) developed clone-specific allometric relationships, with the objective of calculating volume and biomass production after 13 years in 8 poplar plantations in southern Quebec, Canada and reported variations in eight study sites (2.1 to 78.7 and 5 to 148 Mg ha^{-1} in 8- and 13- year-old plantations, respectively). Understanding long-term biomass accumulation by promising local and native clones in each geographic areas in Canada and the adaptability of these clones to the different agroclimatic conditions is essential for assessing system level biomass productivity and to track C stocks at a spatial and temporal scales across Canada (Chambers *et al.* 2001). This could lead to accurately measure and quantify sequestration of C in AGB (Cooper 1983; Specht and West 2003; Kebede and Soromessa 2018). The use of regression models is a common and cost-effective method for prediction of AGB, and biomass C stock non-destructively, in various woody crop production systems (Ravindranath and Ostwald 2008; Youkhana *et al.* 2017). Different site specific allometric equations have been developed for estimating aboveground biomass in specific genomic groups and different clones in North America and Europe (Jenkins *et al.* 2003; Johansson and Karačić 2011; Chojnacky *et al.* 2014; Rathore *et al.* 2021) and specifically in Canada (Lambert *et al.* 2005; Zabek and Prescott 2006; Teruax *et al.* 2012, 2014). However, there are limited predictive biomass models currently available to accomplish the above task for hybrid poplar clones under large-scale afforestation programs on marginal lands in southern Ontario, Canada. Meanwhile, allometric equations used for biomass estimation in this region (southern Ontario) has been related to older hybrid poplar clones, it is unclear whether these equations can precisely estimate AGB for newly developed clones (Headlee and Zalesny, 2019). These equations mainly use tree growth characteristics as regressors such as diameter at breast height (DBH), height, and collar diameter (Guiabao 2016; Naik *et al.* 2019). However, the reliability and predictability of biomass calculation through regression (allometric) models is an issue (Packard and Birchard 2008). Although many researchers have used DBH and height as regressors for predicting biomass, others have reported that they are not realistic with other trees such as fruit trees because of canopy management practices (Ganeshamurthy *et al.* 2016, 2019). Therefore, in order to accurately predict carbon sequestration in afforestation plantations in southern Ontario, this study focused on 1) evaluating regression equations (best model) for predicting C sequestration in AGB in hybrid poplar clones, and 2) using the developed best predictive model to quantify carbon sequestration in AGB of hybrid poplar clones.

Materials and methods

Evaluation of the best regression equation for predicting aboveground biomass carbon

Site descriptions

To evaluate and validate a regression equation for predicting C sequestration in AGB in hybrid poplar clones under afforestation plantation management, a study was conducted in two high-yield hybrid poplar afforestation sites at the University of Guelph Agroforestry Research Station (GARS), Guelph, Ontario, Canada (latitude 4332028" N, 8012032" W) (Fig. 1). The average annual precipitation for GARS is 904 mm of which 338 mm is received during the growing season (May to September). There are 144 frost-free days. The hybrid poplar afforestation sites were established in 2005 and 2009. Most of the land is Class 3-4 agricultural land based on the Canadian Land Inventory (CLI) classification. Class 3 lands have moderate limitations that reduce the choice of crops or require special conservation practices and Class 4 lands have severe limitations that restrict the choice of crops or require special conservation practices and very careful

Fig. 1 Hybrid poplar afforestation sites (established in 2005 and 2009), University of Guelph Agroforestry Research Station in Guelph, Ontario, Canada (Google Earth Pro 2021).

management, or both (Bazrgar *et al.* 2020). Soils are classified as Gray Brown Luvisols, with fine sandy loam texture. High yield poplar afforestation plantations were established on 2.4-ha in 2005 (clones of DN-34, DN-182, NM-6) and on a 13-ha plot in 2009 (clones of NM-6, DN-136, DN-154, 2293-19, DN-74, DN-2) on three replicated blocks at the research station (1100 stems ha^{-1}). Prior to establishment, soils were cultivated with deep tillage to a depth of 25 cm followed by shallow tillage, and plantings were 3 m x 3 m spacing. All the hybrid poplar clones, and parents grown at study sites are shown in Table 1.

Aboveground biomass sampling and measurements

The 63 representative poplar trees (36 trees from the 2009 planted site [2 trees × 3 replications × 6 clones] and 27 trees from the 2005 planted site [3 trees × 3 replications × 3 clones]) were selectively harvested to capture varying DBH and heights, and materials weighed, including the bark, branches, and twigs, using a compact truck loader, Kubota CTL Model SVL75-2, and a Digital Crane Hanging Scale, Vevor 1000 kg. Heights and DBH for all the harvested trees were recorded.

Table 1. Hybrid poplar clones, and parents grown at in studied afforestation management systems in southern Ontario, Canada

Clone	Parents	
DN-2	*P. deltoides*	*P. euramericana*
DN-34	*P. deltoides*	*P. euramericana*
DN-74	*P. deltoides*	*P. nigra*
D-136	*P. deltoides*	*P. nigra*
DN-154	*P. deltoides*	*P. nigra*
NM-6	*P. nigra*	*P. maximowiczil*
DN-182	*P. deltoides*	*P. euramericana*
FFC-1 (AKA 2293-19)	*P. deltoides*	*P. trichocarpao*
DTACs	*P. deltoides*	*P. trichocarpa*

Quantification of carbon in aboveground biomass

Moisture content at time of harvest was determined using sub-sample cookies from each harvested tree. The sub-sampled cookies were weighed in the field and sent to the lab for the determination of moisture content using the method outlined by Bazrgar *et al.* (2020). These values were used to convert the whole-tree green weights to oven-dry weights.

Carbon content in each sample was also quantified by the dried combustion method (LECO CR412) (Table 2), and actual C content calculated using equation 1.

1) $$AGBC = AGB \times (MCC/100)$$

Table 2. Mean carbon content of studied poplar clones in afforestation management systems

Poplar clones	Mean Carbon Concentration (MCC) %
DN-154	47.63 (±0.72)
DN-182	45.71 (±0.62)
DN-34	47.19 (±1.58)
NM-6	48.02 (±0.63)
DN-74	46.75 (±0.89)
DN-2	47.32 (±0.28)
DN-136	45.82 (±0.59)
2293-19	46.38 (±0.57)

Table 3. Predictive equations for C sequestration estimation in aboveground biomass in hybrid poplar clones

Equation	Fitted equation	Reference
Ter-Mikaelian	$B=0.0687\times DBH^{2.5153}$	Ter-Mikaelian & Korzukhin1997
GenOn	$V=\exp(-1.06+1.56\times\ln(DBH)+0.10*H)) \times (1.01)/1000$	OMNR, 1991
GenOnBio	$B=\exp(2.97+1.33\times\ln(DBH)+0.18\times\ln(H)+0.19\times\ln(DBH)*\ln(H)))*0.01)$	OMNR, 1991

B - Oven-dry weight of the biomass component of a tree (kg), DBH - Diameter at breast height (DBH) (cm), H - Height (m), V - Volume (m3)

Where, AGBC – aboveground biomass carbon (kg C), AGB – aboveground dry biomass (Kg) and MCC – mean C concentration in associated clone.

Evaluation of regression equations

Three commonly used predictive equations (Table 3) were fitted and compared in order to validate and select the most accurate predictive equation for C sequestration in AGB in hybrid poplar clones. Height and DBH were used as regressors for fitting in various statistical equations and predicted AGB was calculated using these two parameters. The predicted C sequestration in AGB was calculated by multiplying the predicted AGB by the respective C concentration in AGB associated with each clone.

Scatter plots of predicted and observed values were plotted (Fig. 2), followed by the regression analysis of predicted vs. observed values. The slope and intercept parameters against the 1:1 line were compared. The best-fitted equation was selected using four standard criteria as follows: (1). Coefficient of determination (adjusted-R^2) which is a measure of the proportion of the variance in observed values explained by the predicted values; (2). Root mean square error (RMSE), which indicates the bias (deviation of the actual slope value from the 1:1 line) in a particular model (Savage 1993); (3). Testing the significance of slope =1 and intercept =0 which shows the significant deviation of the linear regression of predicted vs. observed values from the 1:1 line in a particular model; and (4). Mean absolute percentage error (MAPE) as a measure of prediction accuracy of the particular model is given by Equation 2:

$$2) \quad MAPE = 1/n \sum_{i=1}^{n} \left| \frac{Observed\ i - Predicted\ i}{Observed\ i} \right| \times 100$$

Over/under estimation (MOUE) (%) was also calculated based on Equation 3 and used to evaluate the predictive equations.

$$3) \quad MOUE = \frac{Mean\ observed - Mean\ predicted}{Mean\ observed} \times 100$$

Statistical analysis for equation evaluation and selection

All regression analysis was carried out using SAS 9.4 (SAS Institute Inc. Cary, NC, USA), applying the NLIN and REG procedure to perform statistical analyses, fitting and evaluating the equations. Normality of the standardized residuals and variance homogeneity were verified with plots of standardized residuals for all equations using SAS.

Predicting carbon sequestration potential in aboveground biomass

Site descriptions

To predict and assess the C sequestration in AGB in hybrid poplar clones under afforestation plantation management using the selected equation, a second study was conducted in four high-yield hybrid poplar afforestation sites in three different locations (University of Guelph Agroforestry Research Station (GARS), Guelph, Ontario; Claremont, Ontario; and Kemptville, Ontario) in southern Ontario. Description of each research site is shown in Table 4, and the geographical locations are shown in Fig. 3.

Parameter measurements

Heights and DBH were recorded for the 111 representative sub-plots from 11 hybrid clones (2293-19, DN-136, DN-154, DN-182, DN-2, DN-34, DN-74, DTAC26, DTAC29, FFC1, NM-6) in Guelph-2005 research site [2 sub plot × 3 replications × 3 clones=18], Guelph-2009 research site [1 sub plot × 3 replications × 6 clones=18], Claremont research site [1 sub plot × 3 replications × 5 clones=15], and Kemptville research site [2 sub plot × 5 replications × 6 clones=60] (Table 4). Average area of each experimental plot in Guelph-2005 and Kemptville was 3600 m^2 (30 m x 120 m) and in Guelph-2009 and Claremont was 2500 m^2 (50 m x 50 m). In Guelph-2005 and Kemptville, two sub- plots were marked and measured from east to west or north to south, depending on the plot direction. In Guelph 2009 site and Claremont one sub-plot was marked and measured in the centre of each plot. The experimental sub-plots were 200 m^2 (a circle with 7.98 m radius) in Guelph 2009 and in Claremont. This area was 100 m^2 (a circle with 5.64 m radius) in Guelph 2005 and in Kemptville. The number of trees varied among sub-plots as there were some missing or dead stems. Therefore, the number of trees in each 100 m^2 circular sub-plot was up to nine trees and in each 200 m^2 circular sub-plot was up to 25.

Biomass C simulation

Aboveground biomass C (AGBC) was simulated for each tree in each sub-plot using the selected nonlinear predictive equation with DBH and height as regressors. Total AGBC in any given sub-plot was calculated by the summation of AGBC of all trees. Finally, total C sequestration in AGB in one hectare of hybrid poplar afforestation plantation for all 11 clones and in four different research sites were calculated based on the area of associated experimental plots.

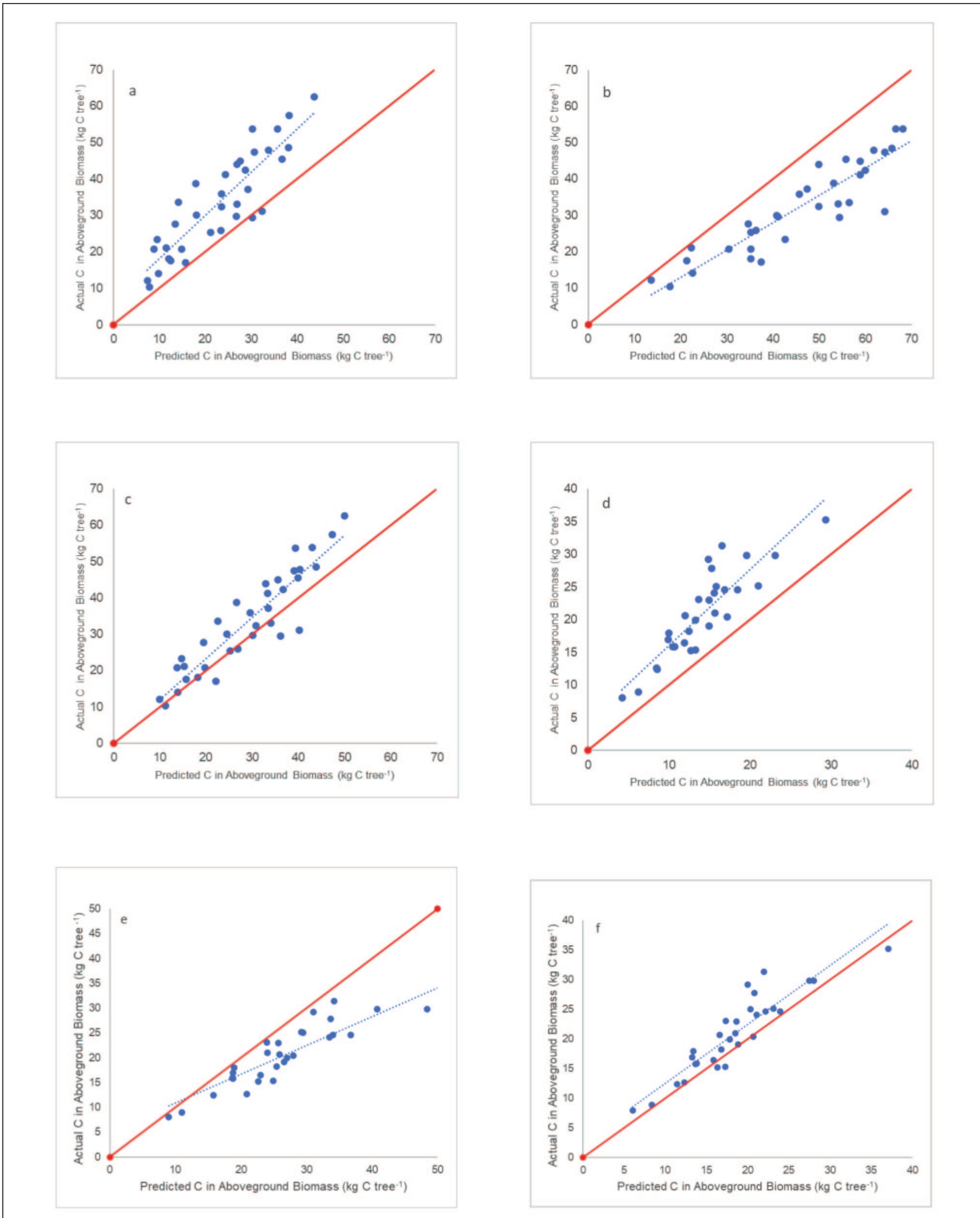


Fig. 2 Comparison of predicted C sequestration by Eq. Gen Ontario **(a)**; Eq. Ter-Mikaelian and Korzukhin **(b)**; and Eq. GenOnBio **(c)** in afforestation site planted in 2005; and Gen Ontario **(d)**; Eq. Ter-Mikaelian and Korzukhin **(e)**; and Eq. GenOnBio **(f)** in afforestation site planted in 2009 and observed C sequestration in aboveground biomass hybrid poplar in afforestation management systems in southern Ontario. (Blue line: linear regression of predicted and observed data, red line: 1:1 line).

Table 4. Description of study area and site characteristics

Location	Geographical Coordinates	Planting year	Soil Type	No. of studied sub-plots	Clones
Guelph	4332028″ N, 80 12032″ W	2005	Fine/Medium Sand	18	NM-06, DN-34, DN-182
Guelph	4332028″ N, 80 12032″ W	2009	Fine sand /Sandy Loam	18	NM-6, DN-136, DN-154, 2293-19, DN-74, DN-2
Claremont	4358101″ N, 7909049″ W	2006	Clay Loam/Loam	15	DN-154, DN-74, DTAC29, DTAC26, FFC1
Kemptville	4500186″ N, 7538179″ W	2013	Sand Loam/Fine Medium Sand	60	DN-154, DN-136, DN-74, NM-6, DN-2, FFC1

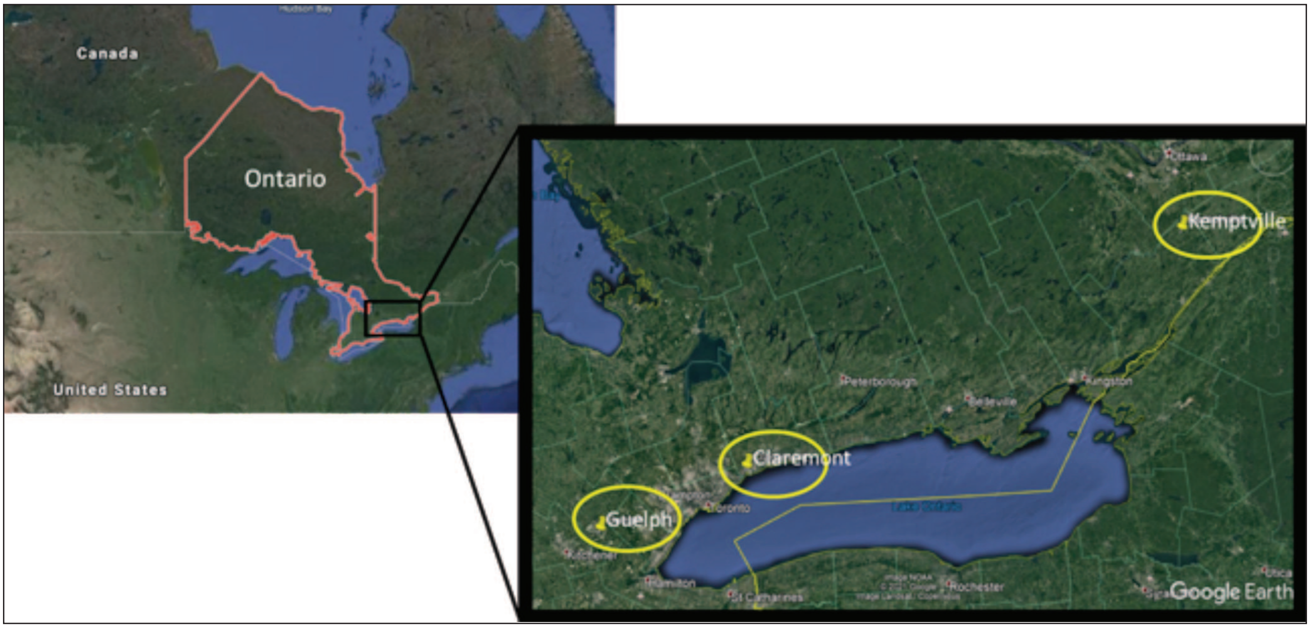


Fig. 3 Geographical location of the hybrid poplar afforestation research sites (Guelph, Claremont, and Kemptville) in southern Ontario, Canada (Google Earth Pro 2021).

Poplar afforestation site suitability classification

To compare hybrid poplar clone AGBC sequestration potential under afforestation systems in different agroclimatic conditions, four research sites were classified into three site suitability groups (SSG) (Table 5). This classification was done based on Canada Land Inventory (CLI) (Agronomic Interpretation Working Group 1995; Ashiq *et al.* 2018) and Site Suitability Classification (SSC) based on Joss *et al.* (2008).

Statistical analysis

All treatments were tested for statistical parameters using SAS 9.4 (SAS Institute Inc. Cary, NC). General Linear Model, Glimmix, Regression and Correlation Procedures in SAS (PROC GLM, PROC GLIMMIX, PROC REG and PROC CORR) were used to perform statistical analyses. The Shapiro–Wilk test ($\alpha = 0.05$) was used to determine whether residuals followed a normal distribution, and variance homogeneity was verified with plots of standardized residuals for all equations using SAS. Where necessary, log transformations were used to normalize residuals.

Table 5. Research site suitability grouping based on Canada Land Inventory (CLI) and Site Suitability Classification (SSC) in poplar afforestation systems

Group	CLI*	SSC**	Studied Sites
1	2	0.9 - 1.1	Clairmont, Kemptville
2	3	0.81 - 0.87	Guelph-2009
3	4	0.69	Guelph-2005

* Canada Land Inventory, ** Site Suitability Classification (Joss *et al.* 2008)

Results

Best regression equation for predicting aboveground biomass carbon

Figure 2 depicts the predicted and observed C sequestration in AGB of hybrid poplar. Comparison of predicted and observed data shows that, among the tested equations, GenOnBio equation had the best predictions of C sequestra-

Table 6. Estimated parameters and evaluation statistics (adjusted R^2, root mean square error (RMSE) and parameter estimations [interception (a), coefficient of regression (b)] of observed/predicted (OP) linear regression; mean absolute percentage error (MAPE) of the three predictive equations for C sequestration in aboveground biomass in hybrid poplar clones planted in 2005 and 2009

Equation	a		b		Adjusted R^2		RMSE		MAPE	
Afforestation System	2005	2009	2005	2005	2005	2009	2005	2009	2005	2009
Ter-Mikaelian	-2.090 ^{ns}	5.058**	0.754**	0.581**	0.850**	0.800**	5.28	2.99	45.4	30
GenOn	6.110 *	4.358*	1.190**	1.164**	0.772**	0.769**	6.52	3.21	31.4	31.9
GenOnBio	0.630 ^{ns}	2.557 ^{ns}	1.135**	0.996**	0.835**	0.821**	5.54	2.83	16.9	13

ns=non-significant, *=significant (p<0.05), **= significant (p<0.01)

Table 7. Mean observed and predicted C sequestration in aboveground biomass and mean over/under estimation in percent (MOUE) of three predictive equations in hybrid poplar clones planted in 2005 and 2009

Afforestation System	2005			2009		
Equation	Mean Predicted (Kg C tree^{-1})	Mean Observed (Kg C tree^{-1})	MOUE (%)[1]	Mean Predicted (Kg C tree^{-1})	Mean Observed (Kg C tree^{-1})	MOUE (%)[1]
Ter-Mikaelian	47.3	33.6	-41.0	27.3	20.9	-30.5
GenOn	23.0	33.6	31.4	14.2	20.9	32.0
GenOnBio	29.0	33.6	13.5	18.4	20.9	11.9

[1]Positive value shows underestimation and negative values shows overestimation.

tion of biomass. Observed biomass C in harvested poplar from five different clones in both 2005 and 2009 afforestation systems, and predicted biomass C by GenOnBio equation had a significant linear relationship (yield adjusted R^2 = 0.835** and 0.821**, respectively) and the coefficient of determination showed that observed values are significantly well explained by the predicted values using GenOnBio equation (Table 6).

RMSE was lowest in GenOnBio equation for the 2009 afforestation system (2.83); however, for 2005, Ter-Mikaelian had the minimum RMSE (5.28) (Table 6).

Regression analysis of predicted vs. observed values and comparing the slope and intercept parameters against the 1:1 line show that the GenOnBio equation had no significant difference among the three predictive equations. In this study, testing the significance of slope coefficient of regression, $b = 1$ and intercept $a = 0$ showed that, in both 2005 and 2009 planted systems, a was insignificant and b had the closest value to 1 (Table 6).

The results show that the GenOn and GenOnBio equations underestimated, and Ter-Mikaelian equation overestimated the AGBC (Table 7). However, in both 2005 and 2009 afforestation systems, the GenOnBio equation had the least deviation of predictions (13.5% and 11.9%, respectively) compared to the other equations and produced very similar C sequestration predictions of the AGB.

Aboveground biomass C sequestration potential in different hybrid poplar clones

AGBC sequestration was significantly different between clones in all sites, except for the Guelph-2009. Aboveground biomass C sequestration among all clones across all afforestation plantation systems ranged from 31.5 Mg C ha^{-1} (in DN-154, Claremont) to 4.8 Mg C ha^{-1} (in DN-182, Guelph-2005) (Fig. 4). In Guelph-2005, NM-6 (23.0 Mg C ha^{-1}) and in Guelph-2009, DN-74 and DN-154 (12.9 and 12.0 Mg C ha^{-1}, respectively) showed the highest C sequestration. The results from this study show that DN-154 was one of the two best clones in Kemptville after FFC-1 (15.1 and 16.3 Mg C ha^{-1}, respectively).

The average AGBC accumulation rate (AGBCRate) in 11 hybrid poplar clones in the afforestation plantation system ranged from 1.8 Mg C ha^{-1} y^{-1} for DN154 to 0.3 Mg C ha^{-1} y^{-1} for DN182 (Fig. 5). DN154 and FFC1 showed the maximum and significantly, the highest accumulation potential compared to DN182. However, their annual accumulation rate was not significantly different from other clones (Fig. 5).

Aboveground biomass C sequestration potential on different sites

The results show that there is no significant difference between the four afforestation sites in terms of AGBC sequestration. The Claremont and Guelph-2009 sites had the highest and lowest AGBC sequestration (19.1 and 10.6 Mg C ha^{-1}, respectively) from the established year (2006 and 2009 respectively) to 2020 (Fig. 6). However, the annual AGBCRate was significantly different between sites. The Kemptville and Guelph-2005 sites had the highest and lowest rates of AGBC accumulation in each year from the established date to 2020 (1.7 and 0.9 Mg C ha^{-1} y^{-1}, respectively) (Fig. 6).

Aboveground biomass C sequestration potential in different site suitability groups

The estimated AGBC sequestration and annual AGBCRate were compared among three different SSGs (Table 8). The

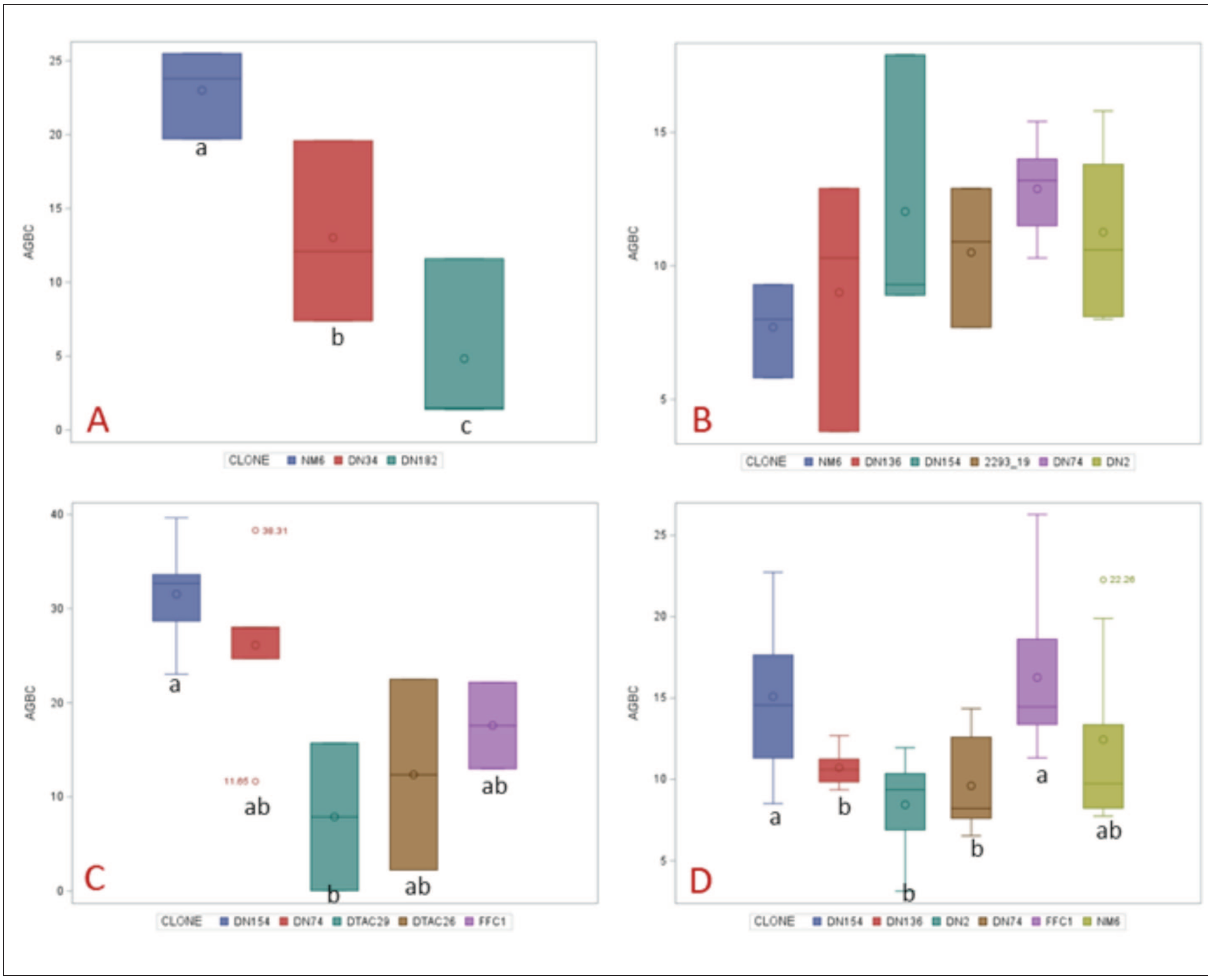


Fig. 4 Boxplots of aboveground biomass C sequestration (AGBC) (from establishment year to 2020) (Mg C ha^{-1}) in different hybrid poplar clones planted in Guelph-2005 **(A)**, Guelph-2009 **(B)**, Claremont **(C)**, and Kemptville **(D)** afforestation site in southern Ontario. The y-axis units are Mg C ha^{-1}. (Means in each clone labelled with the same letter(s) are not significantly different as determined by the least significant difference at α = 0.05).

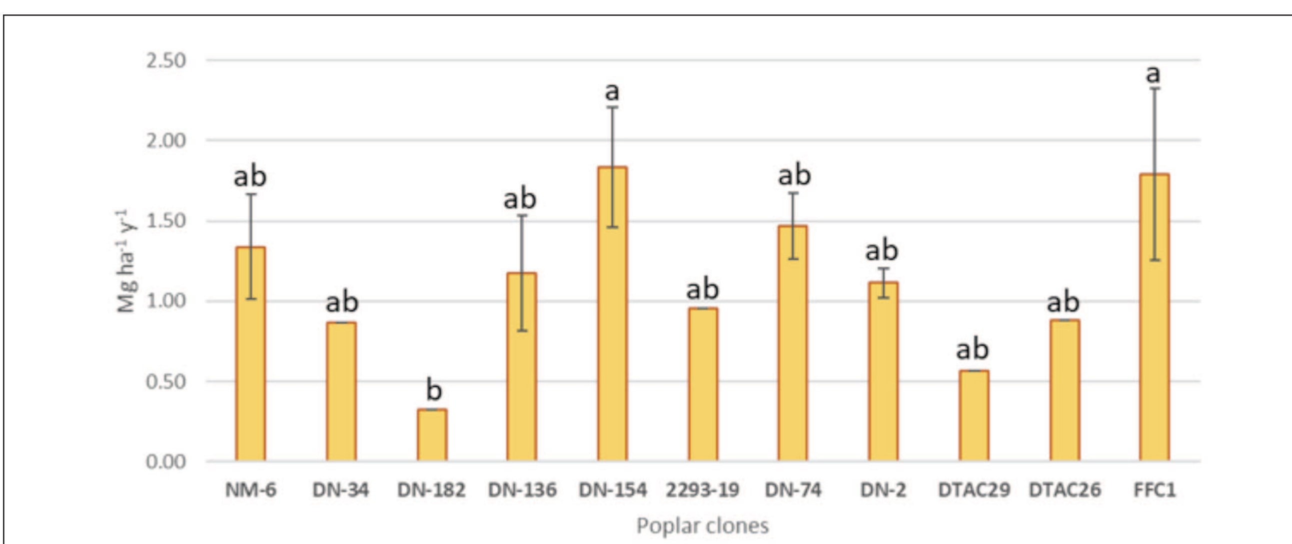


Fig. 5 Average aboveground biomass C accumulation rate in different hybrid poplar clones across all afforestation test sites in southern Ontario. (Means in each clone labelled with the same letter(s) are not significantly different as determined by least significant difference at α = 0.05).

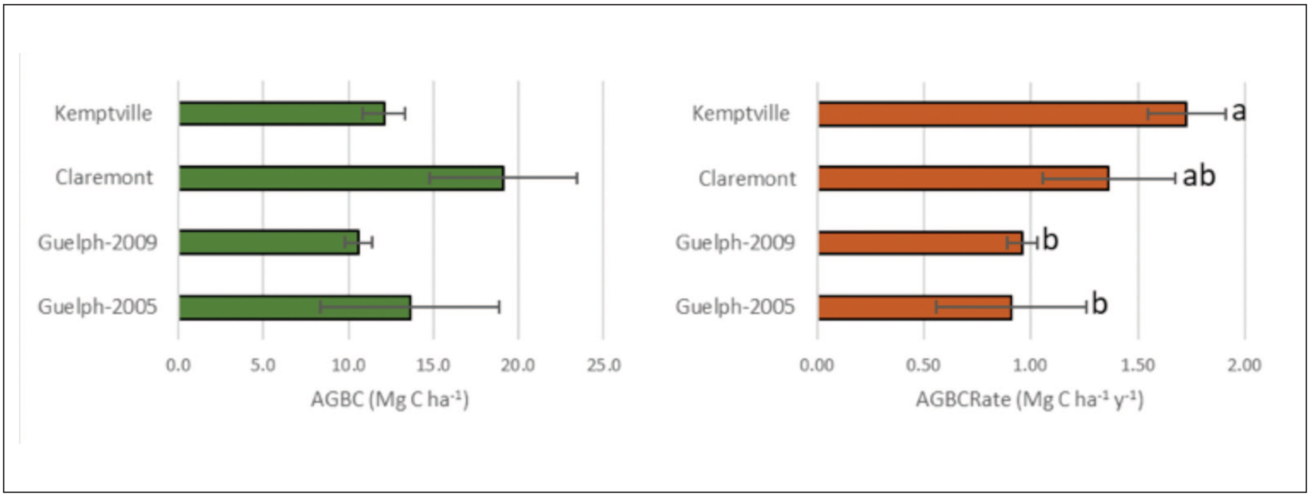


Fig. 6 Average aboveground biomass carbon sequestration (AGBC) (from establishment to 2020) (left) and annual aboveground biomass carbon accumulation rate (AGBCRate)(right) across all afforestation test sites in southern Ontario.

Table 8. Average aboveground biomass carbon sequestration (AGBC) (establish to 2020) and annual aboveground biomass carbon accumulation rate (AGBCRate) in hybrid poplar clones under afforestation plantations management in different site suitability groups (standard errors in brackets)

Site Suitability Group	AGBC (Mg C ha^{-1})	AGBCRate (Mg C ha^{-1} y^{-1})
SSG1	15.60 (±2.25)^a	1.55 (±0.17)^a
SSG2	10.57 (±0.79)^a	0.96 (±0.07)^a
SSG3	13.63 (±5.25)^a	0.91 (±0.35)^a

results show that SSG1 had the highest AGBC sequestration and the highest annual C accumulation in aboveground biomass. However, from a statistical point of view, there was no significant differences in AGBC sequestration and annual AGBCRate among all three SSGs (Table 8).

Aboveground biomass C sequestration potential by different clones per SSG

The results for AGBC sequestration and annual AGBCRate by different hybrid poplar clones planted in three SSGs are shown in Figs. 7 and 8. These results show that differences between AGBC sequestration and AGBCRate across planted clones in SSG1 and SSG3 are statistically significant but comparable in SSG2. In SSG1, both AGBC sequestration and AGBCRate were highest in DN154 (21.0 Mg C ha^{-1} and 2.2 Mg C ha^{-1} y^{-1}, respectively), followed by FFC1 (16.5 Mg C ha^{-1} and 2.1 Mg C ha^{-1} y^{-1}, respectively); DTAC29 had the lowest (7.9 Mg C ha^{-1} and 0.6 Mg C ha^{-1} y^{-1}, respectively). In SSG2, there were no significant differences between poplar clones; however, DN74 and DN154 had the highest AGBC (12.9 and 12.0 Mg C ha^{-1}, respectively), and the highest rate of C accumulation in AGB (1.2 and 1.1 Mg C ha^{-1} y^{-1}, respectively). The results indicate that, in SSG3, NM6 had significantly the highest AGBC sequestration and AGBCRate (23.0 Mg C ha^{-1} and 1.5 Mg C ha^{-1} y^{-1}, respectively) and DN182 significantly the lowest (4.8 Mg C ha^{-1} and 0.3 Mg C ha^{-1} y^{-1}, respectively).

Discussion

Best regression equation for predicting AGBC in hybrid poplar clones

A comparison of predicted and observed C sequestration in aboveground biomass showed the capability of the GenOnBio equation to estimate C content in AGB of hybrid poplars grown in plantations in southern Ontario. All four standard criteria that validate a model, such as coefficient of determination, RMSE, the significance of slope =1 and intercept =0, and MAPE, showed that the observed AGBC in five poplar clones and predicted values by the GenOnBio equation had a clear linear relationship. Further, the values are well-explained by the predicted values with statistical rigor using GenOnBio equation. Although for the RMSE the Ter-Mikaelian equation showed the minimum value for the Guelph-2005 research site, it should be recognized that the Ter-Mikaelian equation uses only DBH as a predictor component. In this context, some researchers (Basuki *et al.* 2009) have reported it is an acceptable biomass predictor at local or regional scales. However, others have recommended that both DBH and height must be used (Jenkins *et al.* 2003; Lambert *et al.* 2005). Therefore, the GenOnBio equation has been chosen to be used in subsequent analysis of carbon sequestration potential in AGB of hybrid poplar clones under plantation management.

Aboveground biomass C sequestration potential by different clones

The concept of biomass production by hybrid poplar plantations is more attractive for waste disposal sites (Laureysens *et al.* 2004) and marginal agricultural lands (Ashiq *et al.* 2018; Bazrgar *et al.* 2020) where additional benefits from biomass production could support rural landowners financially (Jassal *et al.* 2013). AGB growth and productivity in hybrid poplar cropping systems is significantly affected by a combination of genetics (clones) and environmental conditions, including soil type and fertility. Hybrid poplar biomass yield varied with various studies. Hansen *et al.* (1988) reported the mean annual increment (MAI) of aboveground biomass in high density hybrid poplar plantations with irrigation and fertilization as 6.7 Mg ha^{-1} y^{-1} at five years of age. This showed that

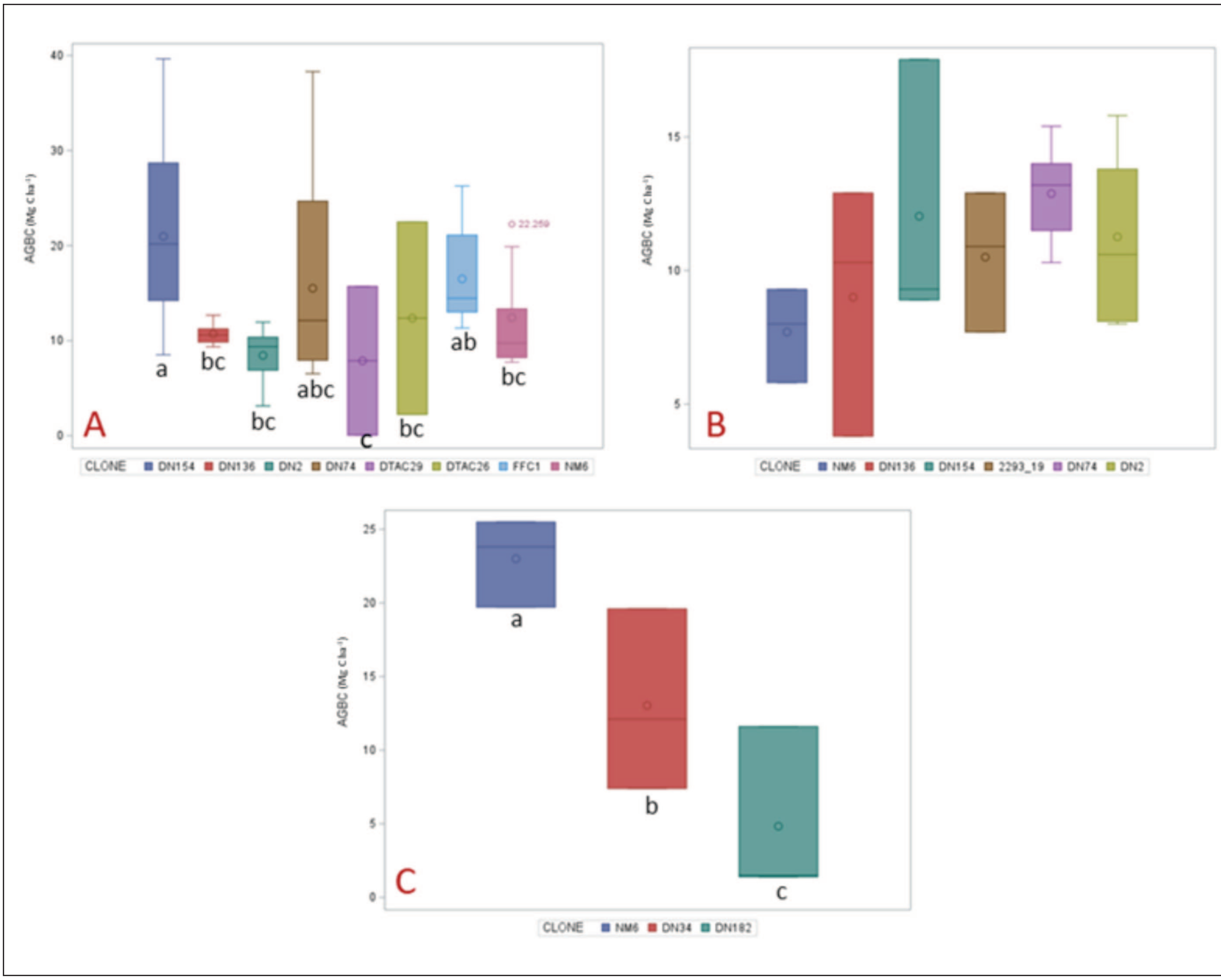


Fig. 7 Boxplots of aboveground biomass C sequestration (AGBC) (from establishment year to 2020) (Mg C ha^{-1}) in different hybrid poplar clones planted under afforestation plantations management in different site suitability groups (SSG) [SSG1 **(A)**, SSG2 **(B)**, SSG3 **(C)**], in southern Ontario, Canada. (Means in each clone labelled with the same letter(s) are not significantly different in associated SSG as determined by the least significant difference at α = 0.05).

AGBC sequestration was equal to 3.1 Mg C ha^{-1} y^{-1}, considering a mean C concentration of 46.9 % (Table 2). Cannell and Smith (1980) reviewed the maximum biomass productivity of stands of poplar clones and found that MAI of aboveground biomass was 10.0-12.0 Mg ha^{-1} y^{-1} (equal to 4.7-5.6 Mg C ha^{-1} y^{-1}) for both 4–5– and 11–26-year-old plantations. However, in this study, poplar AGB was quantified and estimated for marginal soils and lower biomass production was expected.

Findings from this study show that clone DN154, on average, had the best performance on all sites in sequestering AGBC (31.5, 12.0, and 15.1 Mg C ha^{-1} for the Guelph-2009, Claremont, and Kemptville sites, respectively). This clone also showed the highest average C accumulation rate (1.8 Mg C ha^{-1} y^{-1}) across all sites. Therefore, overall, DN154 had the best performance followed by FFC1.

In this study, DN182, DTAC26 and DTAC29 performed poorly and showed that they are not appropriate for this part of the province, possibly due to higher humidity conditions. However, these clones might produce better yields in western parts of Ontario with dryer conditions (Coleman *et al.* 2018). Therefore, to obtain the optimum AGBC sequestration from hybrid poplar afforestation systems, site specific clonal selection should be considered in combination with management technics (Fortier *et al.* 2010).

Aboveground biomass C sequestration potential on different research sites

Hybrid poplar afforestation systems on different test sites did not show significant C sequestration in aboveground biomass. The clones associated with different test sites were different ages. Since the ages were not equal, the AGBRate as a normalized index shows the appropriate and comparable capability of different sites for AGBC sequestration. Our findings show a significant difference in the functionality of research sites. Comparing this index among the four sites showed that the AGBCRate is associated with the age of the system. In this context, the youngest site, (Kemptville established in 2013), had the highest (1.7 Mg C ha^{-1} y^{-1}) AGBCRate, and the oldest site, (Guelph established in 2005),

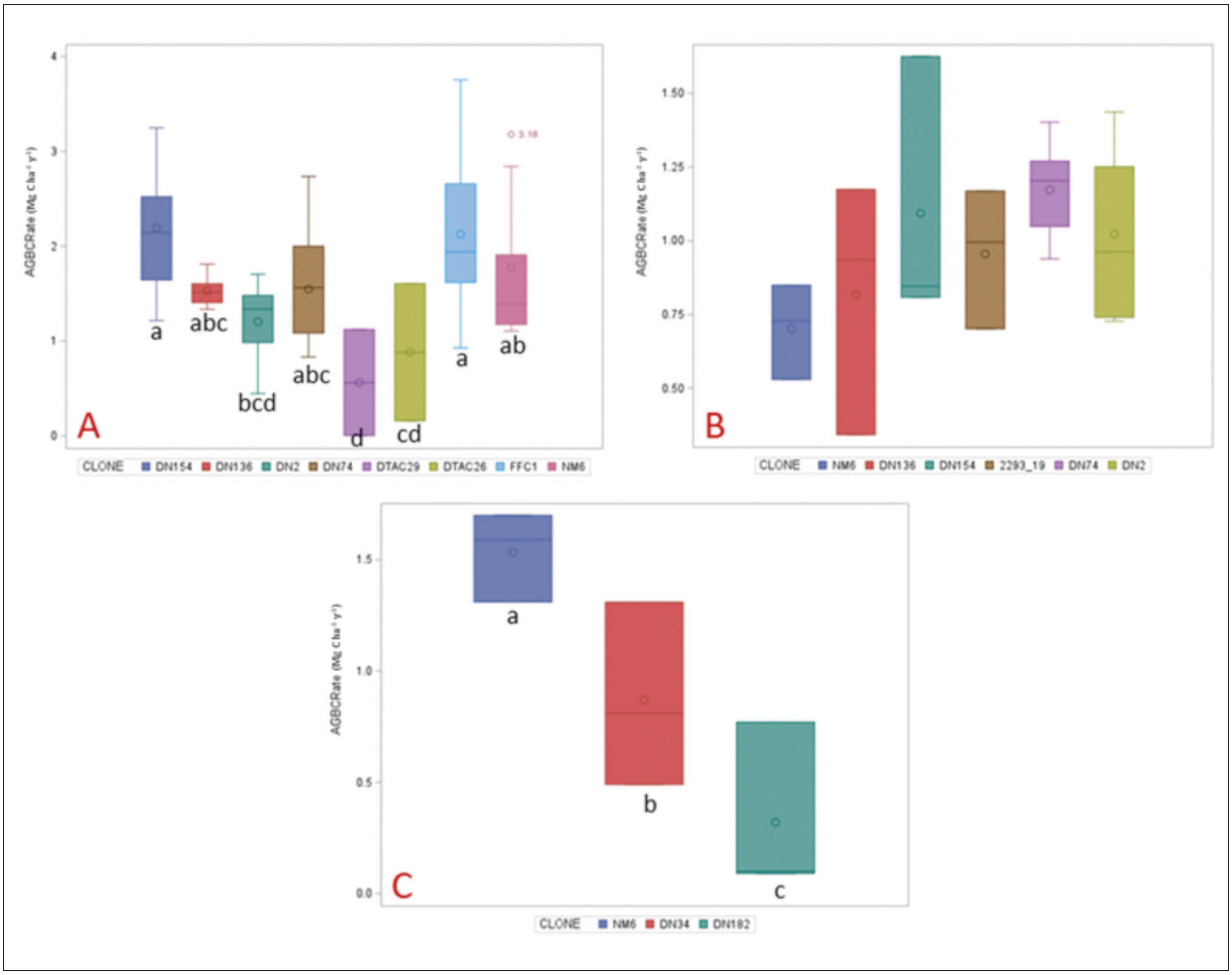


Fig. 8 Boxplots of annual aboveground biomass carbon accumulation rate (AGBCRate) in different hybrid poplar clones planted under afforestation plantations management in different site suitability groups (SSG)[SSG1 **(A)**, SSG2 **(B)**, SSG3 **(C)**], in southern Ontario, Canada. (Means in each clone labelled with the same letter(s) are not significantly different in associated SSG as determined by least significant difference at $\alpha = 0.05$).

had the lowest (0.9 Mg C ha^{-1} y^{-1}). However, this was not valid for the Claremont site, i.e., although the Guelph site, (established in 2009), was younger than the Claremont site (established in 2006), the AGBCRate in Claremont was higher (1.0 Mg C ha^{-1} y^{-1} 2009 Guelph vs. 1.4 Mg C ha^{-1} y^{-1} 2006 Claremont). Differences in agroclimatic conditions associated with the Guelph and Claremont sites may have resulted in this difference in the AGBCRate, even though the Guelph site poplars were three years younger. In addition, significantly lower C accumulation by the 15-year-old poplars (Guelph site -2009) suggests that these poplars have started to decline and therefore future net carbon gain is doubtful. Such sites should be harvested and replanted to enhance AGBCRate. However, the end use of harvested wood is also important to consider in order to obtain net C sequestration in the long-term. The conclusion is that site suitability classification should be considered for poplar afforestation plantation comparisons on different sites and that the optimal poplar maturity should be less than 15 years in order to maintain a high AGBCRate.

Aboveground biomass C sequestration potential in different site suitability groups

The identification of land suitable for plant production began with the dawn of arable agriculture (Ahrens *et al.* 2002). Recently, several land suitability classification methods have attempted to integrate soil, climate, and landscape variables to calculate and classify the suitability of land to support commercial production systems (Bock *et al.* 2018). Establishing large-scale afforestation plantations by the Government of Canada also requires this information so that maximum productivity with appropriate poplar clones can be achieved. To address this requirement, this study used the results from a fuzzy-logic modeling approach to assess land suitability for afforestation of hybrid poplar (Joss *et al.* 2008).

Although the AGBC sequestration in different site suitability groups depends on the age of the system, the AGBCRate represents the standardized annual accumulation of C during the life cycle of a site. The AGBCRate was highest on the most suitable site (SSG1, 1.6 Mg C ha^{-1} y^{-1}) and decreased as the site suitably reduced (1.0 and 0.9 Mg C ha^{-1}

y^{-1} in SSG2 and SSG3, respectively). This implies that along with the importance of clone selection, it is also crucial to carefully choose sites that are suitable for afforestation (Hodgman and Munger 2009; Mangus *et al.* 2021).

Aboveground biomass C sequestration potential by different hybrid clones in SSG

Several researchers have indicated that a number of factors need to be considered when selecting suitable sites and clones to establish a plantation, including soil type and characterization, site productivity and history, natural disturbance regimes, plant growth-rates, and genetic diversity (Mansuy *et al.* 2013; Bashir *et al.* 2019; Isabel *et al.* 2019; Mangus *et al.* 2021). Analyzing the aboveground biomass C sequestration capability of different poplar clones in three land suitability classes showed that in SSG1, sites with the highest land suitability for biomass production, DN154 and FFC1 (21.0 and 16.5 Mg C ha^{-1} AGBC and 2.2 and 2.1 Mg C ha^{-1} y^{-1} AGBCRate, respectively) had the best performance and can be recommended as the most suitable clones for establishing poplar management systems on good quality, marginal lands of southern Ontario. However, DTAC29, DTAC26 and DN2 did not show good performance and therefore, cannot be considered as the recommended clones for SSG1. On land with moderate soil fertility and average agroclimatic suitability (SSG2), all the clones showed comparable AGBC sequestration and annual C accumulation rates; however, DN74 and DN154 (12.9 and 12.0 Mg C ha^{-1} AGBC and 1.2 and 1.1 Mg C ha^{-1} y^{-1} AGBCRate, respectively) had the best performance, which shows their high adaptation to this type of land (SSG2). Our findings show that on the poorest marginal lands (SSG3), where the oldest poplar plantation was established, NM6 (23.0 Mg C ha^{-1} AGBC and 1.5 Mg C ha^{-1} y^{-1} AGBCRate) had the best performance and showed the highest adaptability to overcome severe limitations. However, DN182 demonstrated that it was not the right clone for SSG3 sites. Coleman *et al.* (2018) reported AGB accumulations of 1.3 Mg C ha^{-1} y^{-1} for NM6 during its second growing cycle in a short-rotation crop production system in Guelph, comparable to the results in this study.

Conclusion

Afforestation is being promoted by the Canadian Wood Fibre Centre, NRCan as a land management practice to enhance fibre and renewable energy production in Canada, while creating medium-term carbon sinks for mitigating the effects of global climate change (Richards and Stokes 2004; Ramlal *et al.* 2009). However, large scale afforestation projects are not always feasible. The potential for an afforestation system for C sequestration and C offset vary considerably between locations, climate, soil types, and growth rates and adaptability of species and clones (Yemshanov *et al.* 2005; Laganière *et al.* 2010; Mansuy *et al.* 2013). Furthermore, to understand the C sequestration capability of an afforestation system, it is important for long-term monitoring as the C sink associated with these systems will increase gradually over time (Mangus *et al.* 2021). This study analyzed and validated a regression equation to predict the AGBC sequestration potentials of different hybrid poplar clones in long-term afforestation plantations and looked at their adaptability to three land suitability classes in southern Ontario.

Overall, the analyses showed the ability of the GenOnBio equation to provide a reasonable estimation of aboveground biomass carbon content in hybrid poplar. Therefore, this equation was used for analyzing southern Ontario poplar plantations established by the Canadian Wood Fibre Centre (CWFC), NRCan since 2005.

Results from this study suggest that site suitability classification should be considered when establishing hybrid poplar plantations. They show that, although the rate of carbon accumulation in the aboveground biomass was highest on the most suitable sites and decreased as the site suitably decreased, hybrid poplar plantations maintained an average C accumulation rate without significant differences among all three SSGs in southern Ontario.

This research suggests that poplar clones DN154 and FFC1 are suitable for growing on marginal lands having high land suitability (SSG1) conditions for biomass production. However, clones DTAC29, DTAC26 and DN2 were inferior under the SSG1 conditions. On lands with medium condition agroclimatic suitability (SSG2), DN74 and DN154 had the best performance and NM6 the highest adaptability for sites with severe limitations (SSG3). DN182 was not suitable for severely limited lands (SSG3). This study also found that, in the oldest poplar plantation at 15 years as the trees were degrading, net carbon gain might not be achieved. Therefore, hybrid poplars 15 years of age or more should be harvested and the site replanted. However, our findings confirms that poplar afforestation in southern Ontario, at least up to 15 years of age, will create a carbon sink through aboveground biomass that could make contribute to mitigating carbon dioxide emissions in southern Ontario.

Acknowledgement

The authors are thankful to Mr. Andrew Alphons for his untiring contributions in the field and assistance in collecting tree data. The authors also express their gratitude for the funding for this study from the Canadian Wood Fibre Centre, NRCan, and to the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) for funding this research.

References

Agronomic Interpretation Working Group. 1995. Land Suitability Rating System for Agricultural Crops: 1. Spring-seeded small grains. W.W. Pettapiece (ed.). Tech. Bull. 1995-6E. Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada, Ottawa. 90 pages, 2 maps. Cat. No. A54-8/1995-6E. ISBN 0-662-23005-1

Ahrens, J.R., T.J. Rice and H. Eswaran. 2002. Soil Classification: Past and present. NCSS newsletter 19: 1–5.

Ashiq, M.W., A.B. Bazrgar, H. Fei, B. Coleman, K. Vessey, A. Gordon, D. Sidders, T. Keddy and N. Thevathasan. 2018. A nutrient-based sustainability assessment of purpose-grown poplar and switchgrass biomass production systems established on marginal lands in Canada. Can. J. Plant Sci. 98: 255–266. doi.org/10.1139/cjps-2017-0220.

Bashir, A., D.A. MacLean and C.R. Hennigar. 2019. Growth-mortality attributes and species composition determine carbon sequestration and dynamics of old stand types in the Acadian Forest of New Brunswick, Canada. Ann. For. Sci. 76(35): 1–12. doi:10.1007/s13595-019-0821-3.

Basuki, T.M., P.E. van Laake, A.K. Skidmore and Y.A. Hussin. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. For. Ecol. Manag. 257:1684–1694.

Bazrgar, A.B., A. Ng, B. Coleman, M.W. Ashiq, A. Gordon and N. Thevathasan. 2020. Long-term monitoring of soil carbon sequestration in woody and herbaceous bioenergy crop production systems on marginal lands in southern Ontario, Canada. Sustainability 12: 3901. doi.org/10.3390/su12093901

Bock, M., P-Y. Gasser W.W. Pettapiece, A.J. Brierley, A. Bootsma, P. Schut, D. Neilsen and C.A.S. Smith. 2018. The land suitability rating system is a spatial planning tool to assess crop suitability in Canada. Front. Environ. Sci. 6: 77. doi:10.3389/fenvs.2018.00077

Cannell, M.G.R. and R.I. Smith. 1980. Yields of mini-rotation closely spaced hardwoods in temperate regions: Review and appraisal. For. Sci. 26: 415–428.

Chambers, P.A., M. Guy, E.S. Roberts, M.N. Charlton, R. Kent, C. Gagnon, G. Grove and N. Foster. 2001. Nutrients and their impact on the Canadian environment. Agriculture and Agri-Food Canada, Environment Canada, Fisheries and Oceans Canada, Health Canada, and Natural Resources Canada, Ottawa, ON.

Chojnacky, D.C., L.S. Heath and J.C. Jenkins. 2014. Updated generalized biomass equations for North American tree species. Forestry 87: 129–151. https://doi.org/10.1093/forestry/cpt053

Coleman, B., K. Bruce, Q. Chang, L. Frey, S. Guo, M.S. Tarannum, A. Bazrgar, D. Sidders, T. Keddy, A. Gordon and N. Thevathasan. 2018. Quantifying C stocks in high-yield, short-rotation woody crop production systems for forest and bioenergy values and CO_2 emission reduction. For. Chron. 94: 260–268.

Cooper, C. 1983. Carbon storage in managed forests. Can. J. For. Res. 13: 155–166. doi:10.1139/x83-022.

Drever, R.C., S.C. Cook-Patton, F. Akhter, *et al.* 2021. Natural climate solutions for Canada. Sci. Adv. 7(23): 1–3. doi: 10.1126/sciadv.abd6034

ECCC. 2020. [Environment and Climate Change Canada] National Inventory Report 1990–2018: Greenhouse gas sources and sinks in Canada: Executive summary. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions.html [accessed 17 September 2021].

Fortier, J., D. Gagnon, B. Truax and F. Lambert. 2010. Biomass and volume yield after 6 years in multiclonal hybrid poplar riparian buffer strips. Biomass Bioenergy. 34:1028–1040.

Ganeshamurthy, A.N., V. Ravindra, T. Rupa and R.M. Bhat. 2019. Carbon sequestration potential of mango orchards in the tropical hot and humid climate of Konkan region, India. Curr Sci 116(8):1417–1423.

Ganeshamurthy, A.N., V. Ravindra, R. Venugopalan M. Mathiazhagan and R.M. Bhat. 2016. Biomass distribution and development of allometric equations for non-destructive estimation of carbon sequestration in grafted mango trees. J. Agric. Sci. 8:201–211. DOI:10.5539/jas.v8n8p201

Georgiadis, P., l. Vesterdal, I. Stupak and K. Raulund-Rasmussen. 2017. Accumulation of soil organic carbon after cropland conversion to short-rotation willow and poplar, GCB Bioenergy 9(8): 1390–1401 DOI: 10.1111/gcbb.12416

Guiabao, E.G. 2016. Above-ground carbon stock assessment of mango-based agroforestry in Bulbul, Rizal, Kalinga, Philippines. Int. J. Interdisci. Res. Inno. 4(2):19–25

Hansen, E.A., R.A. McLaughlin and P.E. Pope. 1988. Biomass and nitrogen dynamics of hybrid poplar on two different soils: Implications for fertilization strategy. Can. J. For. Res. 18:223–230.

Headlee, W.L. and R.S. Zalesny. 2019. Allometric relationships for aboveground woody biomass differ among hybrid poplar genomic groups and clones in the North-Central USA. BioEnergy Res. 12: 966–976.

Hodgman, T. and J. Munger. 2009. Managing afforestation and reforestation projects for carbon sequestration: key considerations for land managers and policymakers. *In*: M.L Tyrrell, M.S. Ashton, D. Spalding, and B. Gentry (Eds). Forests and carbon: A synthesis of science, management, and policy for carbon sequestration in forests. pp. 313–346. Bull. Yale Univ., Sch. For. Environ. Stud. 42. Available from: https://elischolar.library.yale.edu/fes-pubs/42 [accessed 22 September 2021].

Isabel, N., J.A. Holliday and S.N. Aitken. 2019. Forest genomics: Advancing climate adaptation, forest health, productivity, and conservation. Evol. Appl. 13: 3–10. doi:10.1111/eva.12902.

Jassal, R.S., T.A. Black, C. Arevalo, H. Jones, J.S. Bhatti and D. Sidders. 2013. Carbon sequestration and water use of a young hybrid poplar plantation in north-central Alberta. Biom. Bioener. 56: 323–333, doi.org/10.1016/j.biombioe.2013.05.023

Jenkins, J.C., D.C. Chojnacky, L.S. Heath and R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. For. Sci. 49: 12–35.

Johansson, T. and A. Karačić. 2011. Increment and biomass in hybrid poplar and some practical implications. Biom. Bioen. 35: 1925–1934. https://doi.org/10.1016/j.biombioe.2011.01.040

Joss, B.N., R.J. Hall, D.M. Sidders and T.J. Keddy. 2008. Fuzzy-logic modeling of land scuitability for hybrid poplar across the Prairie Provinces of Canada. Environ. Monit. Assess 141: 79–96.

Kebede, B. and T. Soromessa. 2018. Allometric equations for aboveground biomass estimation of *Olea europaea* L. subsp. *cuspidata* in Mana Angetu Forest. Ecosy. Heal. Sustain. 4:1 1–12, DOI: 10.1080/20964129.2018.1433951

Laganière, J., D.A. Angers and D. Paré. 2010. Carbon accumulation in agricultural soils after afforestation: A metaanalysis. Global Change Biol. 16: 439–453

Lambert, M.C., C.H. Ung and F. Raulier. 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35: 1996–2018, doi: 10.1139/X05-112

Laureysens, I., J. Bogaert, R. Blust and R. Ceulemans. 2004. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. For. Ecol. Manag. 187: 295–309.

Magnus, G.K., E. Celanowicz, M. Voicu, M. Hafer, J.M. Metsaranta, A. Dyk and W.A. Kurz. 2021. Growing our future: Assessing the outcome of afforestation programs in Ontario, Canada. For. Chron. 97(02) 179–190 doi.org/10.5558/tfc2021-019

Mansuy, N., S. Gauthier and Y. Bergeron. 2013. Afforestation opportunities when stand productivity is driven by a high risk of natural disturbance: A review of the open lichen woodland in the eastern boreal forest of Canada. Mitig. Adapt Strateg. Glob. Change 18: 245–264 DOI 10.1007/s11027-012-9362-x

Naik, S.K., P.K. Sarkar and B. Das, A.K. Singh and B.P. Bhatt. 2019. Biomass production and carbon stocks estimate in mango orchards of hot and subhumid climates in eastern region, India. Car. Manag. 10(5):477–487

Ontario Ministry of Natural Resources (OMNR). 1991. A grower's guide to hybrid poplar. Ontario Ministry of Natural Resources, Queen's Printer, Toronto, Ontario, 148 p.

Packard, G.C. and G.F. Birchard. 2008. Traditional allometric analysis fails to provide a valid predictive 334 model for mammalian metabolic rates. J. Exp. Biol. 211: 3581–3587.

Pinno, B., B. Thomas and N. Belanger. 2010. Predicting the productivity of a young hybrid poplar clone under intensive plantation management in northern Alberta, Canada using soil and site characteristics. New For. 39: 89–103.

Ramlal, E., D. Yemshanov, G. Fox and D. McKenney. 2009. A bioeconomic model of afforestation in southern Ontario: Integration of fiber, carbon and municipal biosolids values. J. Environ. Manage. 90: 1833–1843

Rathore, A.C., H. Mehta, S. Islam, P.L. Saroj, N.K. Sharma, J. Jayaprakash, A.K. Gupta, R.K. Dubey, B.N. Ghosh, R. Prasad, D. Kumar and A. Raizada. 2021. Biomass, carbon stocks estimation and predictive modeling in mango-based land uses on degraded lands in Indian Sub-Himalayas. Agroforest. Syst. doi.org/10.1007/s10457-021-00660-4

Ravindranath, N.H. and M. Ostwald. 2008. Carbon inventory methods: Handbook for greenhouse gas inventory. Carbon Mitigation and Round Wood Production Projects, Springer Science. Delft: Advances in Global Change Research, Springer.

Richards, K.R. and C. Stokes. 2004. A review of forest carbon sequestration cost studies: A dozen years of research. Clim. Chan. 63: 1–48. doi.org/10.1023/B:CLIM.0000018503.10080.89

Savage, M.J. 1993. Statistical aspects of model validation. At Workshop on the field water balance in the modelling of cropping systems, University of Pretoria, South Africa.

Specht, A. and P.W. West. 2003. Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia. Biom. Bioen. 25: 363–379. doi:10.1016/S0961-9534(03)00050-3

Ter-Mikaelian, M.T. and M.D. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manag. 97: 1–24. https://doi.org/ 10.1016/S0378-1127(97)00019-4.

Truax, B., D. Gagnon, J. Fortier and F. Lamber. 2012. Yield in 8-year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients. For. Ecol. Manag. 267: 228–239.

Truax, B., D. Gagnon, J. Fortier and F. Lamber. 2014. Biomass and volume yield in mature hybrid poplar plantations on temperate abandoned farmland. Forests 5 (12): 3107–3130. https://doi.org/10.3390/f5123107

Yemshanov, D., D.W. McKenney, T. Hatton and G. Fox. 2005. Investment attractiveness of afforestation in Canada inclusive of carbon sequestration benefits. Can. J. Agric. Econ. 53: 307–323

Youkhana, A.H., R.M. Ogoshi, J.R. Kiniry, M.N. Meki, M.H. Nakahata and S.E. Crow. 2017. Allometric models for predicting aboveground biomass and carbon stock of tropical perennial C4 grasses in Hawaii. Front. Plant Sci. 8:650. doi: 10.3389/fpls.2017.00650

Zabek, L.M. and C.E. Prescott. 2006. Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia. For. Ecol. Manag. 223: 291–302. https://doi.org/ 10.1016/j.foreco.2005.11.009