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Abstract: Forests and forestry can contribute to climate change mitigation through the removal of atmospheric carbon dioxide (CO_2) by forest vegetation and long-term storage in forest ecosystems and harvested wood products. Woodland owners, researchers and educators, Indigenous communities, industry, and the general public alike require information and decision-support tools to assist in integrating carbon into their approaches to forest management/land stewardship. The purpose of this research report is to describe a forest carbon web application called the Nova Scotia Forest Carbon Calculator (NSFCC; https://ns-resource-analysis.shinyapps.io/nsfcc/) that was developed in response to these needs. The tool synthesizes many peer-reviewed studies and models, including the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), to calculate forest carbon from user-provided data or existing Department inventory data. The app provides carbon estimates for living trees and saplings, standing dead trees (i.e., snags), and coarse woody material, as well as stand/plot-level basal area and merchantable volume, all based on external data uploaded by users or by user-specific parameters in the app interface. Moreover, NSFCC can generate carbon estimates from the Department's publicly available photo-interpreted forest inventory data and from the Nova Scotia Growth and Yield model. Lastly, NSFCC has a carbon yield curve viewer, which provides carbon yield curves for natural stands. Permanent sample plot data and photo-interpreted inventory data were used to test and demonstrate NSFCC functionality. The results of this testing are described in this report. A critical aspect of carbon estimation in general and the application of NSFCC specifically is the embedded error and uncertainty involved along with the sensitivity of estimation to different methodologies. NSFCC users should be aware of these issues as they develop their own carbon objectives. It is hoped that the different NSFCC features make it useful to a variety of forest managers and stakeholders with differing needs. A particular need has been identified among woodland owners to better understand and manage their forest carbon and ideally access carbon markets, with which NSFCC might bring some utility. A necessary starting point for mitigation action in forestry is building carbon literacy and quantitative tools like NSFCC to enable a variety of forest stakeholders to estimate and model their forest carbon.

Keywords: Carbon, climate change, mitigation, forest planning

1. Introduction

Global climate change threatens ecosystems and society alike. Nova Scotia is expected to experience climate warming between 2 ºC and 4 ºC with more frequent extreme heat events and drought (IPCC, 2014; Bush & Lemmen, 2019). The province is also expected to experience increasing levels of annual precipitation from 100 mm to 300 mm, though more of this will be in winter months and will fall as rain, not snow, with the potential for drier conditions during the growing season (IPCC, 2014; Bush & Lemmen, 2019). The increasing frequency and severity of natural disturbance events, especially hurricanes and windstorms, and more favourable conditions for native and invasive forest pests, are already having adverse impacts on forests and their management in Nova Scotia (Taylor et al., 2020; MacLean et al., 2022).

Adaptation in the forest sector will be necessary to address these impacts and build resilience. However, forests and forestry can also contribute to climate change mitigation through the removal of atmospheric carbon dioxide (CO_2) by forest vegetation and long-term storage in forest ecosystems and harvested wood products (IPCC, 2019; Smyth et al., 2020). Moreover, there is increasing research and development of the forest bioeconomy, where more novel forest products (e.g., fuels, plastics) are substituting higher-emission alternatives derived from fossil fuels (CCFM, 2022; Steenberg et al., 2023). The Canadian forest sector is the lowest emitting economic sector in the country and had net negative emissions in the most recent national inventory of greenhouse gases (ECCC, 2022).

The growing importance of understanding and managing carbon in forestry coupled with the potential for forest ecosystems to be nature-based solutions to climate change (Griscom et al., 2017) has spurred a demand for carbon literacy. Woodland owners, researchers and educators, Indigenous communities, industry, and the general public alike require information and decision-support tools to assist in integrating carbon into their approaches to forest management/land stewardship (Zald et al., 2016). Moreover, the emergence carbon offset credits for forest projects (e.g., improved forest management, afforestation) has added significantly to this demand among forest landowners for understanding and in particular for skills in quantifying forest carbon (Vail et al., 2022). This latter trend is reflected in a recent independent review of forest practices (i.e., the Lahey Report) and its recommendation to support woodland owners in accessing carbon markets (Lahey, 2018).

The purpose of this research report is to describe a forest carbon web application developed by the Nova Scotia Department of Natural Resources and Renewables (NSDNRR). The Nova Scotia Forest Carbon Calculator (NSFCC; https://ns-resource-analysis.shinyapps.io/nsfcc/) was developed in response to the above needs and values and to support Nova Scotians in integrating carbon into their forest planning and management. The tool synthesizes many peer-reviewed studies and models to calculate forest carbon from user-provided data or existing NSDNRR inventory data. Climate change is complex and uncertain and a diversity of strategies and tools are needed to address it. The NSFCC will hopefully provide one such tool to empower Nova Scotians to mitigate climatic change.

2. Methods

NSFCC is a web-based application (a.k.a., app) developed using R and the shiny and shinydashboard packages (R Core Team, 2022). Other key R libraries used in app development included the dplyr, ggplot2, and data.table packages. It utilizes equations and models available in the peer-reviewed literature for estimating forest biomass/carbon based on existing data as well as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al., 2009) and Nova Scotia Growth and Yield Model (NSGNY; O'Keefe & McGrath, 2006; Steenberg et al., 2023). The app provides carbon estimates based on external data uploaded by users or by user-specific parameters in the app interface.

2.1. Living Trees and Saplings

To estimate carbon in living trees and saplings, NSFCC uses the Canadian national tree aboveground biomass equations (Lambert et al., 2005) to calculate dry biomass in wood, bark, branches, and foliage, which is converted to carbon by multiplying by a factor of 0.5. These biomass equations were developed from 8,636 sampled trees across Canada, including 445 trees from Nova Scotia, that were harvested, oven-dried, and weighed. Non-linear regression models were developed to predict biomass (kg) using either diameter at breast height (DBH) or DBH along with height as a second predictor at the species level, for hardwoods and softwoods, and for all species combined (Lambert et al., 2005). Belowground biomass and carbon in fine and coarse roots are calculated using equations from CBM-CFS3 (Li et al., 2003). The equations predict total root biomass for either hardwood or softwood species and from root biomass predictions for the proportion of belowground biomass that is fine roots.

The app uses these equations for tree carbon estimation in several ways. Carbon storage in wood, bark, branches, foliage, fine roots, and coarse roots is calculated and visualized for individual trees using simple drop-down menus for DBH and species. Carbon can also be calculated from external data containing a tree list so that multiple trees and/or plots can be used. Calculations for sapling data are derived from the same equations but enables the input of tallied data; often in forest inventory saplings are not measured individually but are tallied by diameter classes and species.

2.2. Standing Dead Trees

Estimating carbon in standing dead trees (i.e., snags) uses the same equations as for living trees and saplings (Lambert et al., 2005; Li et al., 2003). These carbon estimates then account for declines in carbon storage due to decomposition and due to the physical loss of material (e.g., bark, branches) from the snag over time. Accounting for carbon loss from decay is done using wood density reduction factors (Harmon et al., 2011) and accounting for the loss of tree material is done using structural loss adjustment factors (Domke et al., 2011). NSFCC uses five decay classes for standing dead trees as defined by Harmon et al. (2011, p. 4):

- Class 1: All limbs and branches are present, the top of the crown is still present, all bark remains, sapwood is intact with minimal decay, heartwood is sound and hard.
- Class 2: There are few limbs and no fine branches, the top may be broken, a variable amount of bark remains, sapwood is sloughing with advanced decay, heartwood is sound at base but beginning to decay in the outer part of the upper bole.
- Class 3: Only limb stubs exist, the top is broken, a variable amount of bark remains, sapwood is sloughing, heartwood has advanced decay in upper bole and is beginning at the base.
- Class 4: Few or no limb stubs remain, the top is broken, a variable amount of bark remains, sapwood is sloughing, heartwood has advanced decay at the base and is sloughing in the upper bole.
- Class 5: No evidence of branches remains, the top is broken, <20 percent of the bark remains, sapwood is gone, heartwood is sloughing throughout.

As with living trees, snag carbon may be calculated entirely within the app using simple drop-down menus for DBH, species, and decay class or from external user data containing a tree list with multiple trees and plots.

2.3. Coarse Woody Material

To estimate carbon storage in downed coarse woody material (CWM), the NSFCC requires plot-level line-intersect sampling (LIS) data. The LIS method relies on one or more transects within a plot, where any intersection with a piece of CWM is recorded along with its diameter, decay class, and species. A typical transect orientation used in research is a triangle with three 20-m transects at 60° angles (Stewart et al., 2009). Following Nova Scotia inventory specifications, CWM must be at an angle of 45° or less from horizontal and greater than 9 cm in diameter (NSDNRR, 2004). The LIS data are converted to volume using equations from Marshall et al. (2000) and biomass and carbon are calculated using wood density reduction factors and bulk density factors (Harmon et al., 2011). NSFCC uses five decay classes for CWM, as defined by Harmon et al. (2011, p. 5):

- Class 1: Sound, freshly fallen, intact logs with no rot, no conks present indicating a lack of decay, original colour of wood, no invading roots, fine twigs attached with tight bark.

- Class 2: Sound log sapwood partly soft but cannot be pulled apart by hand, original colour of wood, no invading roots, many fine twigs are gone and remaining fine twigs have peeling bark.
- Class 3: Heartwood is still sound with piece supporting its own weight, sapwood can be pulled apart by hand or is missing, wood colour is reddish-brown or original colour, roots may be invading sapwood, only branch stubs are remaining which cannot be pulled out of log.
- Class 4: Heartwood is rotten with piece unable to support own weight, rotten portions of piece are soft and/or blocky in appearance, a metal pin can be pushed into heartwood, wood colour is reddish or light brown, invading roots may be found throughout the log, branch stubs can be pulled out.
- Class 5: There is no remaining structural integrity to the piece with a lack of circular shape as rot spreads out across ground, rotten texture is soft and can become powder when dry, wood colour is red-brown to dark brown, invading roots are present throughout, branch stubs and pitch pockets are usually rotten down.

2.4. Plot-Level Basal Area

Often forest managers do not have the detailed inventory data describing individual trees (e.g., fixed-area plots) that are used more in research and monitoring. Timber cruising and other types of rapid assessment are typically comprised of plot-level estimates of forest attributes like basal area (e.g., variable-radius plots) using a prism. Where users have plot-level basal area measurements, NSFCC estimates carbon storage in living forest biomass using aboveground biomass equations (Paré et al., 2013) to calculate dry biomass in wood, bark, branches, and foliage, which is converted to carbon by multiplying by a factor of 0.5. The Paré equations were developed using the Lambert individual tree equations, whereby the original plot data used by Lambert et al. (2005) were used to calculate plot-level basal area, biomass data were estimated using the lambert equations, and new regression models were fit to predict biomass. Only basal area and leading species for each plot are used in these equations. Belowground biomass and carbon in fine and coarse roots are calculated using equations from CBM-CFS3 (Li et al., 2003).

2.5. Plot-Level Merchantable Volume

Merchantable volume is an important variable in growth and yield modelling and traditional forest management planning. While it likely would have been derived from one of the above inventory variables, which could also have been used to calculate carbon, the NSFCC still calculates estimates from merchantable volume for users. Moreover, users may input their own growth and yield curves in this section of the calculator to generate carbon yields for living forest biomass. NSFCC estimates carbon storage in living forest biomass using aboveground biomass equations (Boudewyn et al., 2007) to calculate dry biomass in wood, bark, branches, and foliage, which is converted to carbon by multiplying by a factor of 0.5. These biomass equations, also called biomass expansion factors, are a core set of equations used by CBM-CFS3 to generate its carbon estimates from growth and yield data. Belowground biomass and carbon in fine and coarse roots are again calculated using the CBM-CFS3 equations (Li et al., 2003).

2.6. Carbon Yield Curves

Carbon yields for Nova Scotia's natural stands were developed using CBM-CFS3, which is a peer-reviewed and internationally adopted scientific model for forest carbon accounting developed by the Canadian Forest Service (Kurz et al., 2009). CBM-CFS3 is a freely available, stand-alone model that is an aspatial, stand- and landscape-level simulator of forest carbon pools, including above- and below-ground living biomass, dead organic matter, and soil carbon (Table 1). The model relies on local and user-supplied growth and yield data, inventory data describing current conditions, and landscape classifiers (also called strata). The core assumptions of the model rely on conversion factors to convert merchantable volume yields to aboveground biomass (Boudewyn et al., 2007; see Section 2.5), belowground biomass (Li et al., 2003), and dead organic matter turnover and decay dynamics (Kurz et al., 2009).

NSDNRR maintains a database of growth and yield curves for natural (i.e., unmanaged, not planted or treated with any silviculture) stands in Nova Scotia. These strata yields were developed using non-linear least squares regression fit to inventory permanent sample plot (PSP) data (NSDNRR, 2016). The yield curves predict merchantable volume (m^3/ha) from stump age (yr). During the curve fitting procedures, PSPs that sustained any kind of moderate-to-severe disturbance (i.e., 30% reduction in basal area or greater) were omitted from yields. Conversely, low-severity disturbances like small gaps or individual tree mortality would be imbedded in these strata yields. The PSP data were stratified by five landbase themes for model fitting to incorporate key site and stand variables influencing growth and yield so that separate functions and coefficients were created for each strata combination.

Table 1. Carbon pools modelled by CBM-CFS3, quoted and/or adapted from Kurz et al. (2009, p. 486).

Carbon Pool	Description
Living forest biomass	All carbon pools associated with living trees in a forested stand
Merchantable wood + bark	Live stemwood of merchantable size (i.e., > 9 cm DBH) plus bark
Other wood + bark	Live branches, stumps, and small trees including bark
Foliage	Live foliage
Fine roots	Live roots, approximately < 5 mm diameter
Coarse roots	Live roots, approximately >= 5 mm diameter
Dead organic matter	All carbon pools comprised of dead organic matter in a forested stand; Most dead organic matter pools are named after their relative decay rates
Snag stems	Dead standing stemwood of merchantable size (i.e., > 9 cm DBH) including bark
Snag branches	Dead branches, stumps, and small trees including bark
Medium	Coarse woody material on the ground
Aboveground fast	Fine and small woody material plus dead coarse roots in the forest floor
Aboveground very fast	The litter horizon, comprised of foliar litter plus dead fine roots
Aboveground slow	Forest floor (i.e., F, H, and O horizons)
Belowground fast	Dead coarse roots in the mineral soil
Belowground very fast	Dead fine roots in the mineral soil
Belowground slow	Humified organic matter in the mineral soil

The first theme is ecoregion (Neily et al., 2017), with ecoregions 100 (Northern Plateau), 200 (Cape Breton Highlands), and 800 (Atlantic Coastal) being the least productive strata grouping, 600 (Valley and Central Lowlands), 700 (Western), and 900 (Fundy Shore) being the more productive strata grouping, and 300 (Nova Scotia Uplands), 400 (Eastern), and 500 (Northumberland/Bras d'Or) being of average productivity. The second theme is forest community (Table 2), which includes a set of 12 communities for natural stands based on classification rules of photo-interpreted species composition.

Table 2. Forest communities currently used in strategic forest modelling.

Forest Community	Classification
Hardwood	Softwood species cover less than or equal to 20% of all species
Tolerant hardwood	Tolerant hardwood species greater than or equal to 60% of all hardwood species
Mixed intolerant/tolerant hardwood	Tolerant hardwood species between 30% and 59% of all hardwood species
Intolerant hardwood	Tolerant hardwood species less than 30% of all hardwood species
Mixedwood	Softwood species cover between 21% and 79% of all species
Mixedwood – tolerant	Tolerant hardwood species greater than or equal to 50% of all hardwood species
Mixedwood – intolerant with softwood leading	Tolerant hardwood species less than 50% of all hardwood species and softwood species cover exceeds hardwood species cover
Mixedwood – intolerant with hardwood leading	Tolerant hardwood species less than 50% of all hardwood species and hardwood species cover exceeds softwood species cover
Softwood	Softwood species cover greater than or equal to 80% of all species
Balsam fir dominant	Balsam fir is greater than or equal to 60% of all softwood species
Red/black spruce dominant[1]	Spruce species are greater than or equal to 60% of all softwood species and red or black spruce are greater than or equal to 50% of all spruce species
White spruce dominant	Spruce species are greater than or equal to 60% of all softwood species and red or black spruce are less than 50% of all spruce species
Spruce/balsam fir dominant	Balsam fir and spruce species are greater than or equal to 60% of all softwood species
Pine dominant	Pine species are greater than or equal to 60% of all softwood species
Mixed hemlock/pine/spruce	All other softwood stands not included in the above

[1] Red and black spruce are grouped in this community despite their different silvics and ecology because early photo-interpreted inventory data often grouped them together when they could not be distinguished.

The third theme is stocking class, which is derived from photo-interpreted crown closure. Stand-level stocking classes include class A with a crown closure between 0 and 30%, class B with a crown closure between 31 and 50%, class C with a crown closure between 51 and 70%, and class D with a crown closure between 71 and 100%. The fourth theme is site class, which is derived from mapped land capability (LC) for forestry (m^3/ha/yr). See NSDNRR (1993a) and NSDNRR (2006) for further details on land capability and its estimation. Site class ranges from 3 to 7. For softwood LC, site class 3 includes LC of 1-3 m^3/ha/yr and site class 7 includes softwood LC of 7 m^3/ha/yr and higher, while site class 4, 5, and 6 equate to the softwood LC values. For hardwood LC, a site class of 4 includes LC of 1 m^3/ha/yr, site class 5 includes LC of 2 m^3/ha/yr, site class 6 includes LC of 3 m^3/ha/yr, and site class 7 includes LC values of 4 m^3/ha/yr and higher.

The fifth and final modelling theme for natural strata yields is management state. Natural stands that have not been treated by any silvicultural intervention must have a management state of natural even-aged, natural uneven-aged, or naturally regenerating (i.e., recently harvested). For the sake of reducing the tool complexity and the thousands of possible strata yield curve combinations, this modelling theme was averaged into one single option for natural stands within NSFCC. In other words, users must only select ecoregion, forest community, stocking, and site class options to view and download carbon yields. Carbon yields for stands in a managed state that have been treated with pre-commercial thinning or are a plantation can be generated from NSGNY (Section 2.8).

2.7. Photo-Interpreted Inventory

NSFCC provides estimates of forest carbon storage using Nova Scotia's publicly available photo-interpreted forest inventory. NSDNRR acquires aerial photos of the entire province on roughly a 10-year cycle. Stereoscopic interpretation allows for the assessment of leading species, average co-dominant height, crown closure, and land capability of every delineated stand (NSDNRR, 2006). These interpreted variables are subsequently used to derive other inventory variables like stand volume (NSDNRR, 2006). All inventory data are available in shapefile format.

The NSFCC tool for the forest inventory shapefiles relies on carbon yield curves developed using CBM-CFS3 (Kurz et al., 2009; Section 2.6). Consequently, the strategic landbase modelling themes of ecoregion, forest community (Table 1), stocking, and site class must be derived from the inventory data using location, interpreted species composition, crown closure, and land capability. Importantly, the NSFCC inventory shapefile tool does not account for management state (e.g., natural stands, plantations, pre-commercial thinning) and assumes all stands are natural. Carbon estimates will therefore likely be inaccurate and may overestimate carbon storage for some managed stands where partial harvesting has occurred (e.g., selection management, commercial thinning) and underestimate carbon where increased growth due to silviculture has occurred (e.g., plantations, pre-commercial thinning). The carbon estimates of NSGNY (Section 2.8) can provide more suitable estimates for managed stands.

The forest inventory data are joined to the carbon yield curves using a lookup function based on the above modelling themes and predicted stand age. Any interpreted stand that does not have a classified species will not receive any carbon estimates. For example, a stand may be forested (e.g., recently harvested or dead from pests) but because there is no species classification there will be no carbon estimates, even for dead organic matter. Stand age estimates for every stand within the photo-interpreted inventory data are derived as a function of average stand height and land capability (NSDNRR, 2006). Note that this age estimate has known accuracy issues and is an important source of uncertainty in carbon estimates. In addition to the propagated error from height and land capability prediction and their association with empirical age measurements, stand age has a high degree of variation within stands, especially natural stands, and a single estimate also does not account for multiple cohorts in uneven-aged stands. When using the app, a new attribute table (i.e., .dbf file) to replace the current inventory shapefile attribute table is generated by NSFCC that contains estimates for all living and dead carbon pools for every forested stand. No estimates are generated for non-forested polygons.

2.8. Nova Scotia Growth and Yield Model

The NSGNY model is a stand-level, single-species model. It is both site specific and focused on even-aged managed and natural stands in Nova Scotia. NSGNY has both softwood (NSDNRR, 1993b; Steenberg et al., 2023) and hardwood (O'Keefe & McGrath, 2006) models for natural stands and plantations and has the capacity to simulate pre-commercial thinning and commercial thinning treatments. The growth and yield model was developed using research PSP data from silviculture trials across Nova Scotia since the 1970s. See Steenberg et al. (2023) and O'Keefe and McGrath (2006) reports for the most recent detailed and updated descriptions of the softwood and hardwood model, respectively.

Carbon is calculated by NSGNY using the Lambert et al. (2005) individual tree functions and the functions of CBM-CFS3 for below-ground biomass and dead organic matter. Aboveground biomass of living trees is calculated from DBH and height, with below-ground (i.e., fine and coarse root) biomass then being calculated using the Li et al. (2003) functions. Note that NSGNY models the average tree in a stand; calculated biomass estimates for this tree are expanded to the stand level by multiplying average tree biomass estimates with NSGNY stand density (stems/ha) estimates. All predicted biomass estimates are converted to carbon by multiplying by a factor of 0.5. Stand-level estimates are then used to calculate dead organic matter using the CBM-CFS3 functions and routines (Kurz et al., 2009). NSFCC is a separate web app from the stand-alone, desktop NSGNY app, but it has a page that both directs users to the NSGNY download website and describes the NSGNY model processes and outputs relating to carbon.

2.9. Tool Application

A number of NSDNRR forest inventory datasets were used to test and demonstrate NSFCC functionality. Inventory PSP data were used with the living tree, sapling, snag, CWM, basal area, and merchantable volume calculators. All of these variables are measured within the 0.04 ha fixed-area PSPs on a five-year remeasurement cycle. The different methods of calculating carbon estimates are visualized and compared. Importantly, while the different methods can be compared to demonstrate which are yielding higher or lower estimates, it is not possible to discern which estimate is more accurate. Some measure of estimate error and variation can be gathered from the original publications describing each equation series (Li et al., 2003; Lambert et al., 2005; Boudewyn et al., 2007; Paré et al., 2013).

The photo-interpreted forest inventory data are used to calculate spatial estimates of forest carbon. These estimates and the forest inventory shapefile tool rely on the carbon yield curves generated by CBM-CFS3, which are also available through NSFCC. Estimates are mapped and summarized by county and by ecoregion for living forest biomass, dead organic matter excluding soil, and soil.

3. Results

3.1. Permanent Sample Plot Data

3.1.1. Living Trees

The PSP data were used to calculate carbon estimates for all NSFCC tools for stand/plot data (i.e., living trees from DBH, living trees from DBH and height, basal area, merchantable volume, saplings, snags, and CWM,). The Lambert et al. (2005) equations using DBH only are used as the reference estimates to compare against other estimates throughout the results section. Recall that it is not feasible to determine accuracy of the carbon estimates with the PSP data, as carbon cannot be measured in the field by inventory staff. Carbon estimates for validation would require destructive sampling, oven-drying samples, and weighing. However, these DBH-based equations tended to have the lowest error rates in the scientific literature (Lambert et al., 2005; Boudewyn et al., 2007; Paré et al., 2013) and require the fewest assumptions and additional sources of error (e.g., error in calculating merchantable volume prior to calculating carbon).

Carbon estimates show that on average, white pine, eastern hemlock, sugar maple, and yellow birch trees tended to store the most carbon (Fig. 1). The large majority of trees across all species store less than 100 kg of carbon per tree, which equates to DBH values of approximately 10 to 20 cm. The largest carbon storage value of 3,390 kg C currently measured within a PSP in Nova Scotia is a 104 cm DBH white pine located in Annapolis County. Conversely, across all of Nova Scotia, red maple stores the greatest total carbon of any species at 52.2 Mt, followed by balsam fir at 40.6 Mt, and red spruce at 32.3 Mt (Fig. 2). The data show an estimated total carbon storage of 250.1 Mt in living forest biomass in trees greater than 9 cm DBH. Note that outliers are removed in all boxplot figures to maintain visibility and comparability between medians and inner quartile ranges, and maximum values are provided in the text. Biomass equations are exponential and very large trees can be an order of magnitude larger than median values.

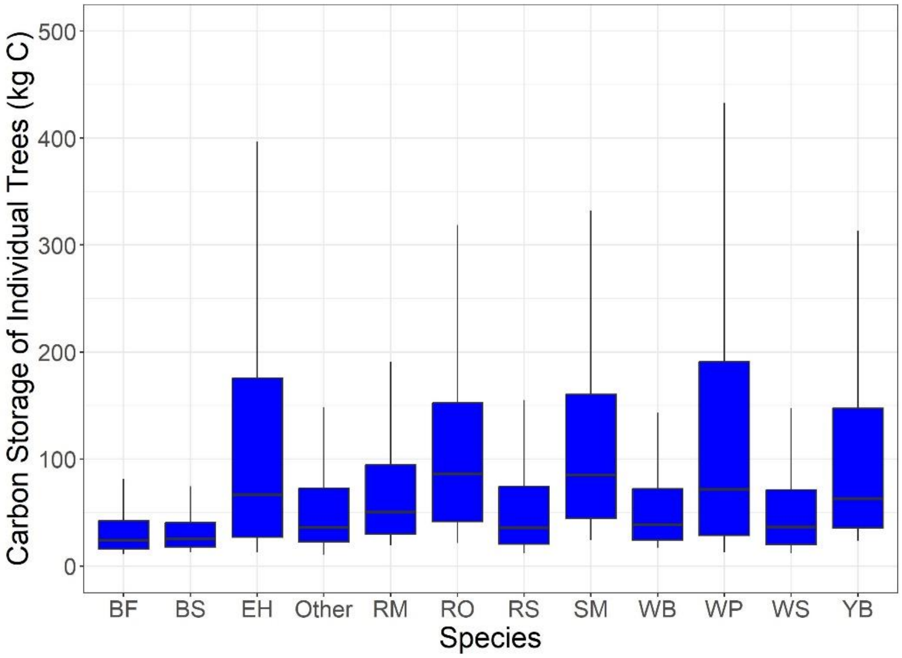

Fig 1. Distribution of carbon storage in individual living trees larger than 9 cm DBH. Note that outliers are removed for visualization but carbon values range up to 3,000 kg.

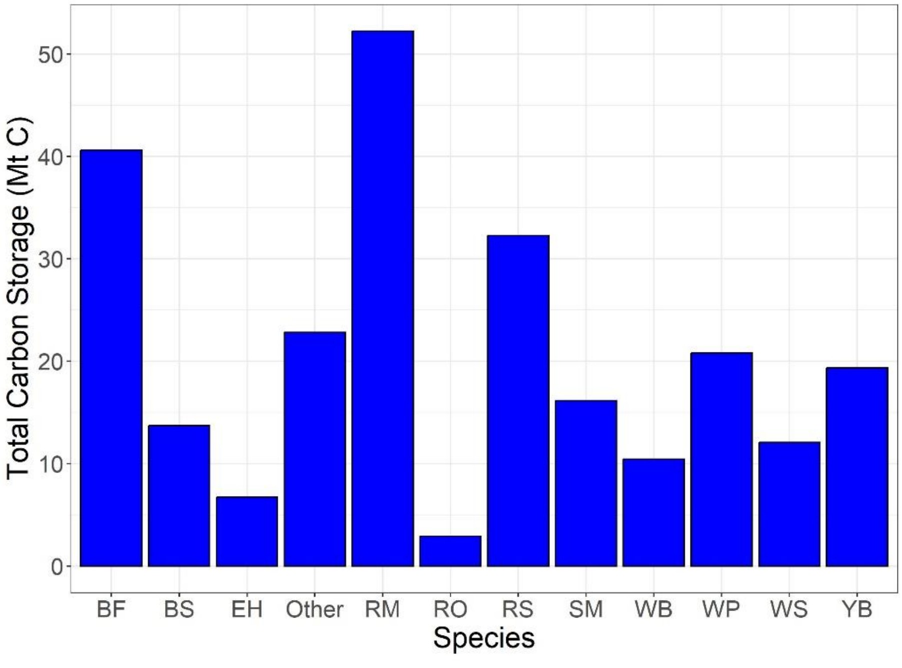

Fig. 2. Total carbon storage of living trees larger than 9 cm DBH in Nova Scotia.

Carbon estimates calculated using DBH compared to those calculated with DBH and height show fairly similar values, though the DBH-height method tended to predict lower values in larger trees compared to the DBH-only method (Fig. 3). A similar trend can be seen at the species level (Fig. 4), though not universally. For example, the DBH-height method tended to predict higher carbon estimates for balsam fir.

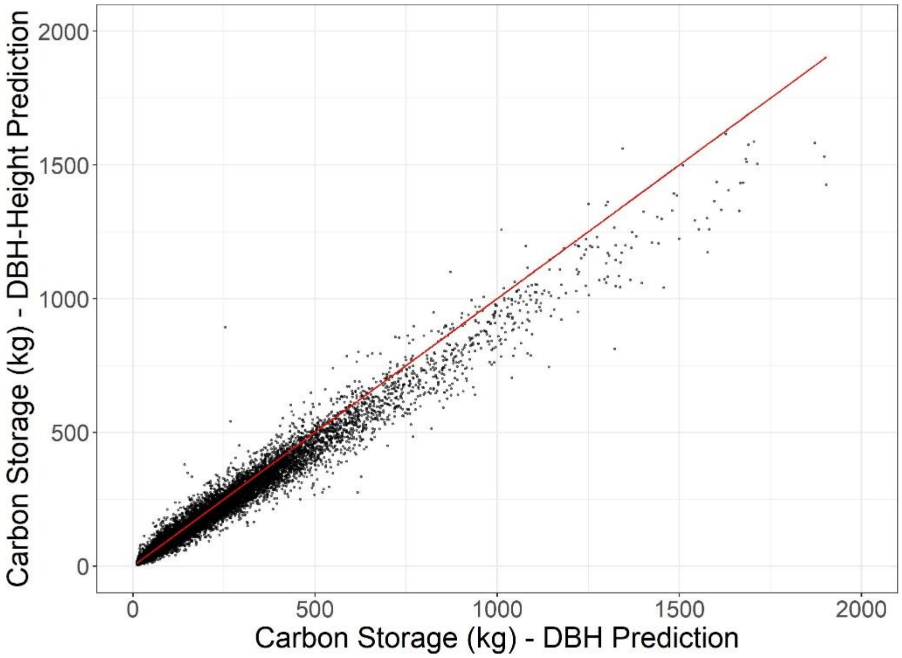

Fig. 3. Carbon storage of individual trees calculated using DBH only and calculated using DBH and height.

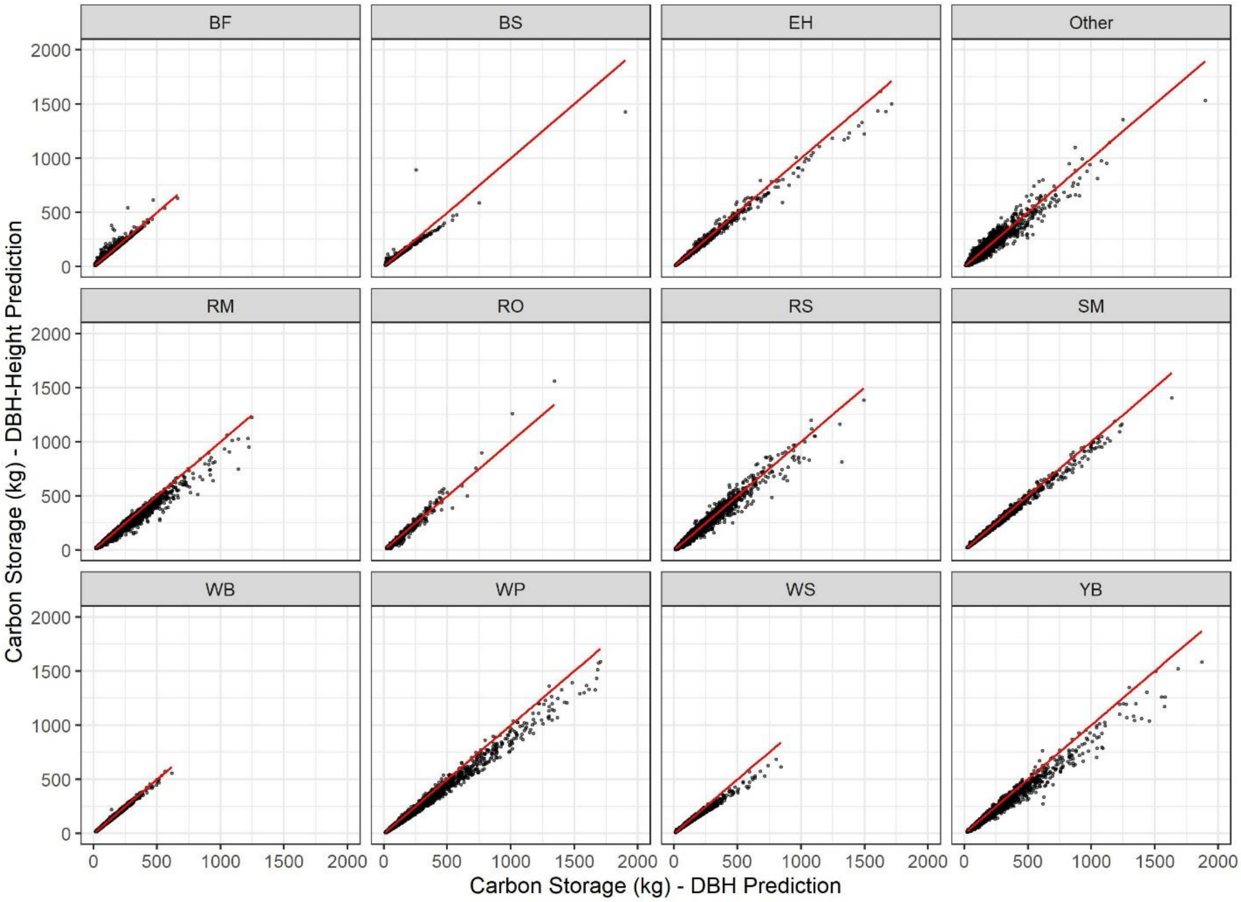

Fig. 4. Carbon storage of individual trees at the species level calculated using DBH only and calculated using DBH and height.

Carbon storage (DBH-only method), basal area (m^2), and merchantable volume (m^3) of individual trees were aggregated to the plot level in order to compare the individual tree carbon estimates to basal area (m^2/ha) and merchantable volume (m^3/ha). The comparison with basal area shows that basal-area-based calculations consistently estimated higher carbon storage than individual tree calculations (Fig. 5). This trend is again seen at the species level and quite pronounced for some species, such as yellow birch, sugar maple, and white pine (Fig. 6). Note that a limitation of calculating carbon estimates from basal area and merchantable volume is that only plot-level or stand-level leading species can be used. Therefore, unlike individual tree estimates these latter two methods do not account for variability in carbon storage attributable to mixed species.

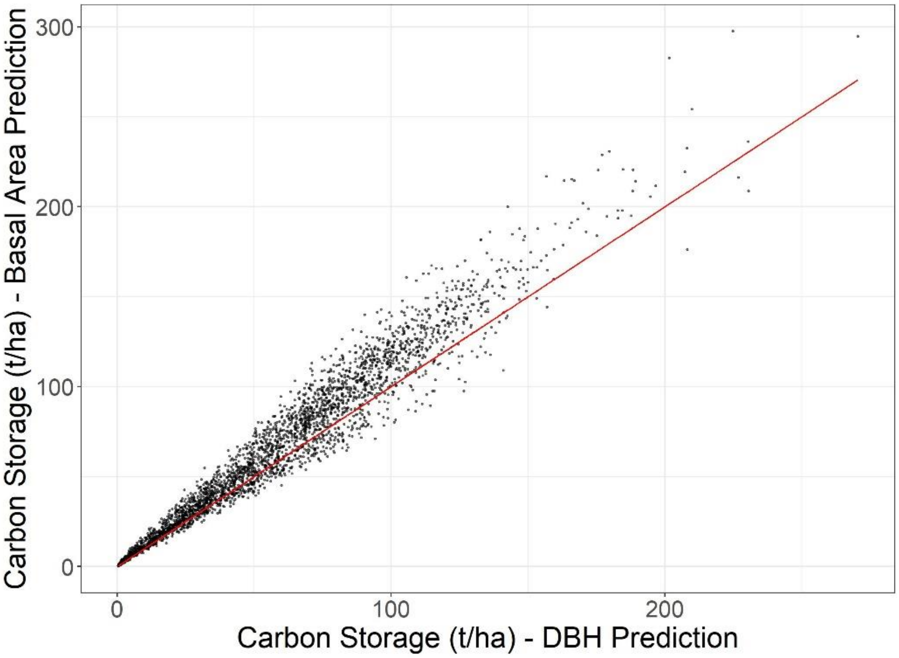

Fig. 5. Carbon storage of PSPs calculated using DBH only and calculated using basal area.

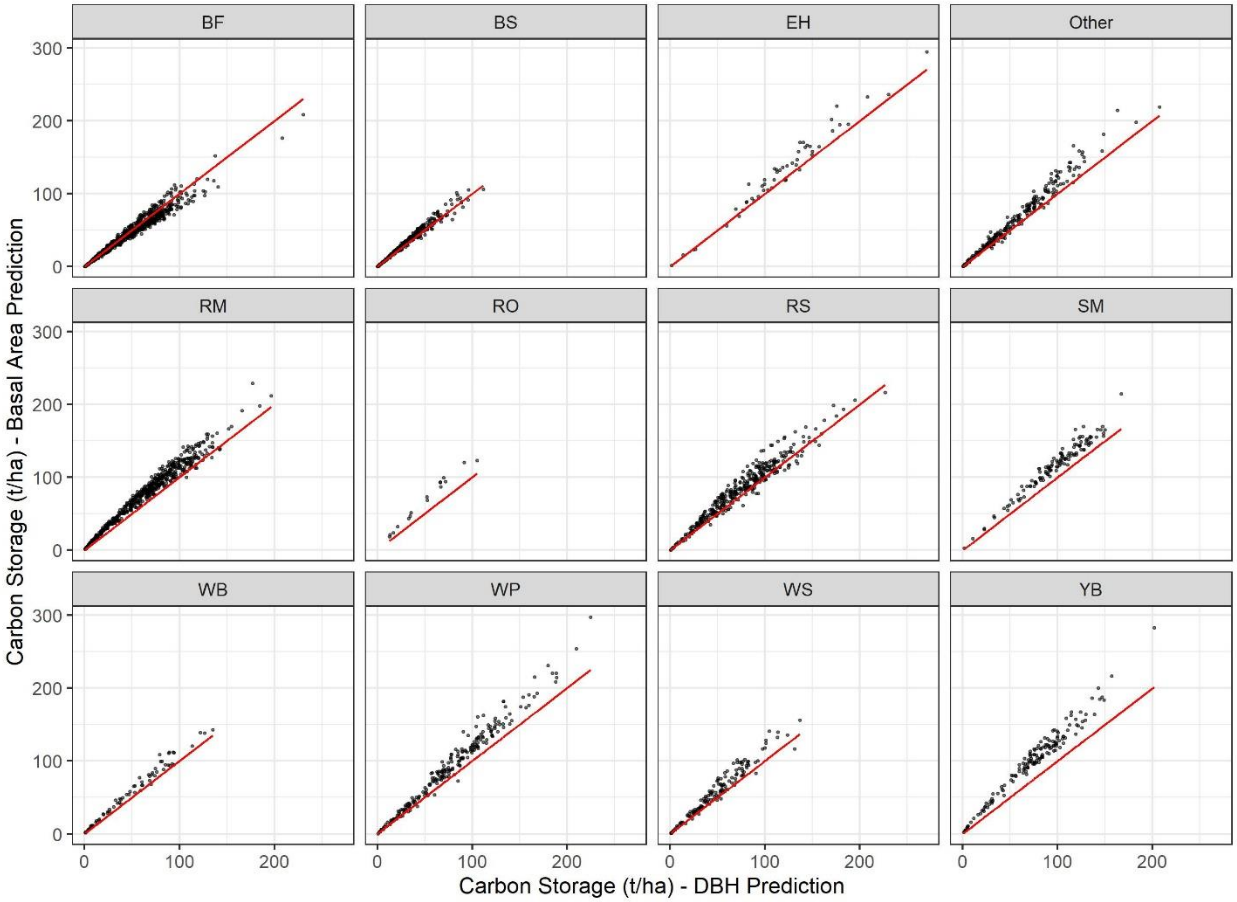

Fig. 6. Carbon storage of PSPs by leading species calculated using DBH only and calculated using basal area.

The comparison of DBH-based carbon estimates to those derived from merchantable volume also showed high variability but not consistently higher predictions like those derived from basal area (Fig. 7). The exception is for low-volume stands, where a sudden spike in carbon estimates is shown. This is likely contributable to the use of cap (i.e., maximum and minimum) values for different biomass components in the equations (Boudewyn et al., 2007). Calculated estimates for certain biomass compartments (e.g., branches, bark) tend to be unrealistically large in younger stands and cap values are used in their place. This artifact in carbon estimates is more visible with some species (e.g., red maple, balsam fir, yellow birch) than others (Fig. 8).

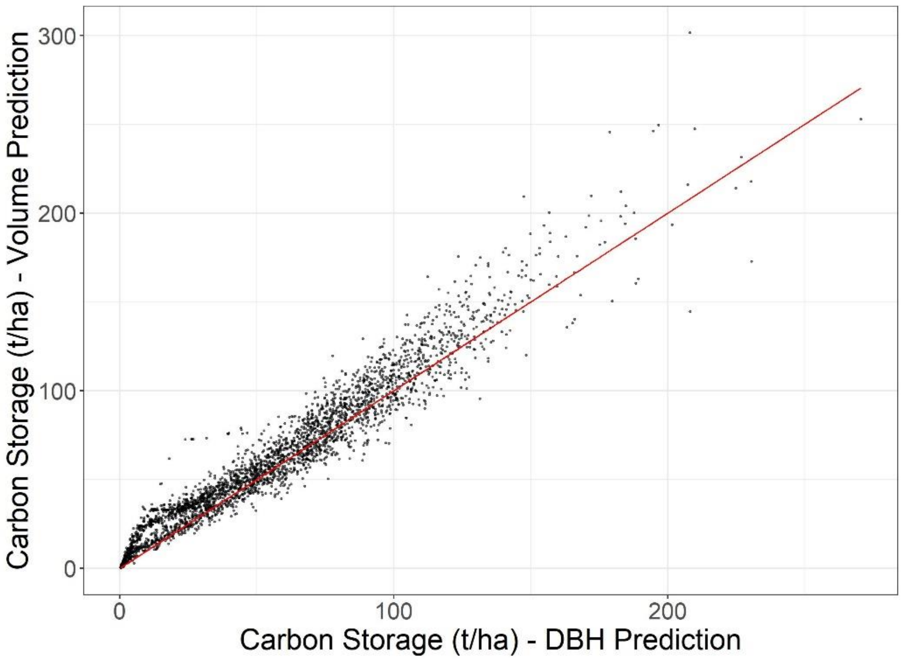

Fig. 5. Carbon storage of PSPs calculated using DBH only and calculated using merchantable volume.

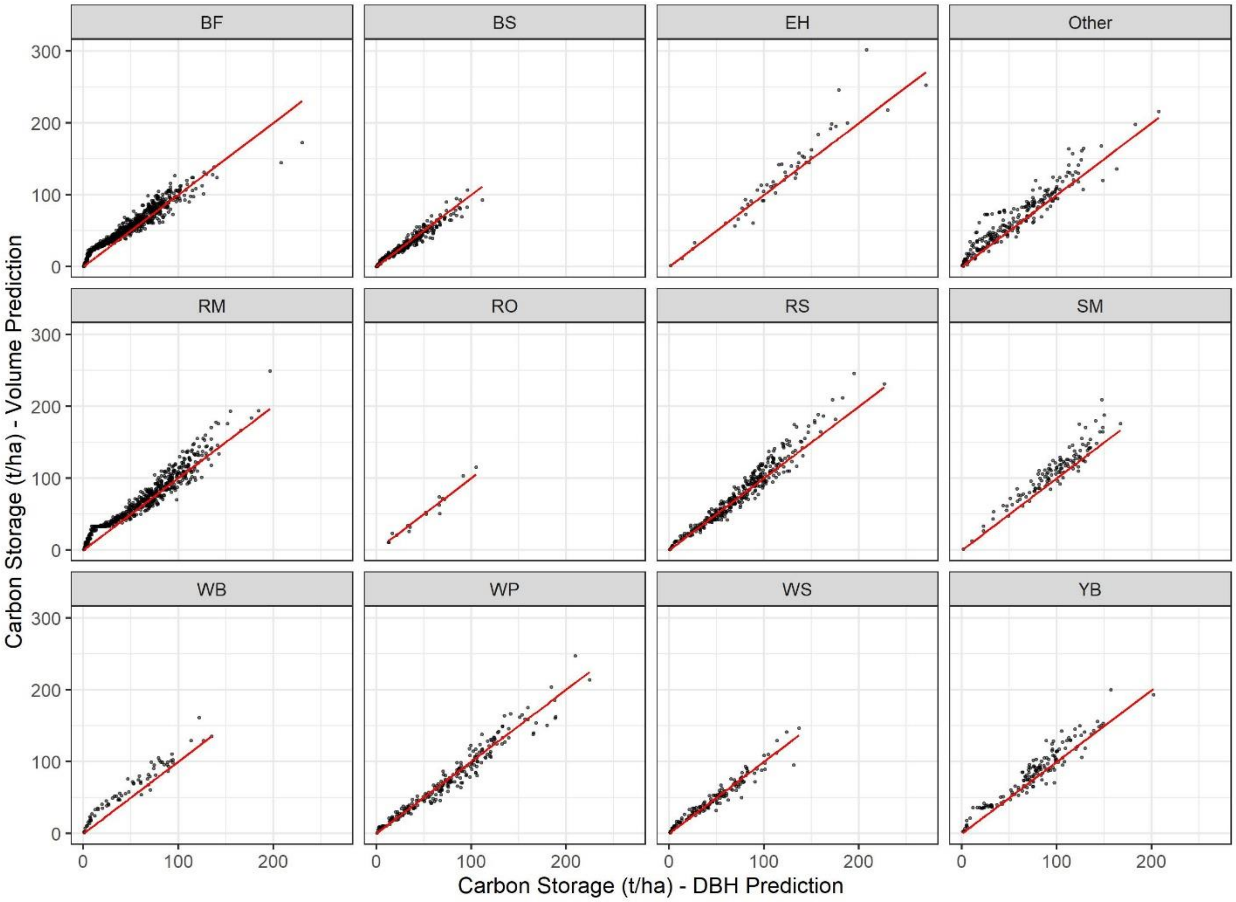

Fig. 6. Carbon storage of PSPs by leading species calculated using DBH only and calculated using merchantable volume.

Tracking an individual PSP helps to illustrate the potential variability in carbon estimates of these different methods. A mixedwood PSP established in 1965 in a forest stand that just reached merchantable size and subsequently measured every five years up to the most recent measurement in 2020 illustrates these differences (Fig. 7). The leading or dominant species in the PSP varied over the 65 years of measurement and at times included balsam fir, red spruce, red maple, and sugar maple. Recall that a stand- or plot-level leading species is required for carbon estimates from basal area and merchantable volume. Carbon estimates varied considerably – for example, in 2020 carbon storage was as low as 91.5 t/ha calculated from basal area with balsam fir as leading species and as high as 196.9 t/ha calculated from merchantable volume with sugar maple as leading species.

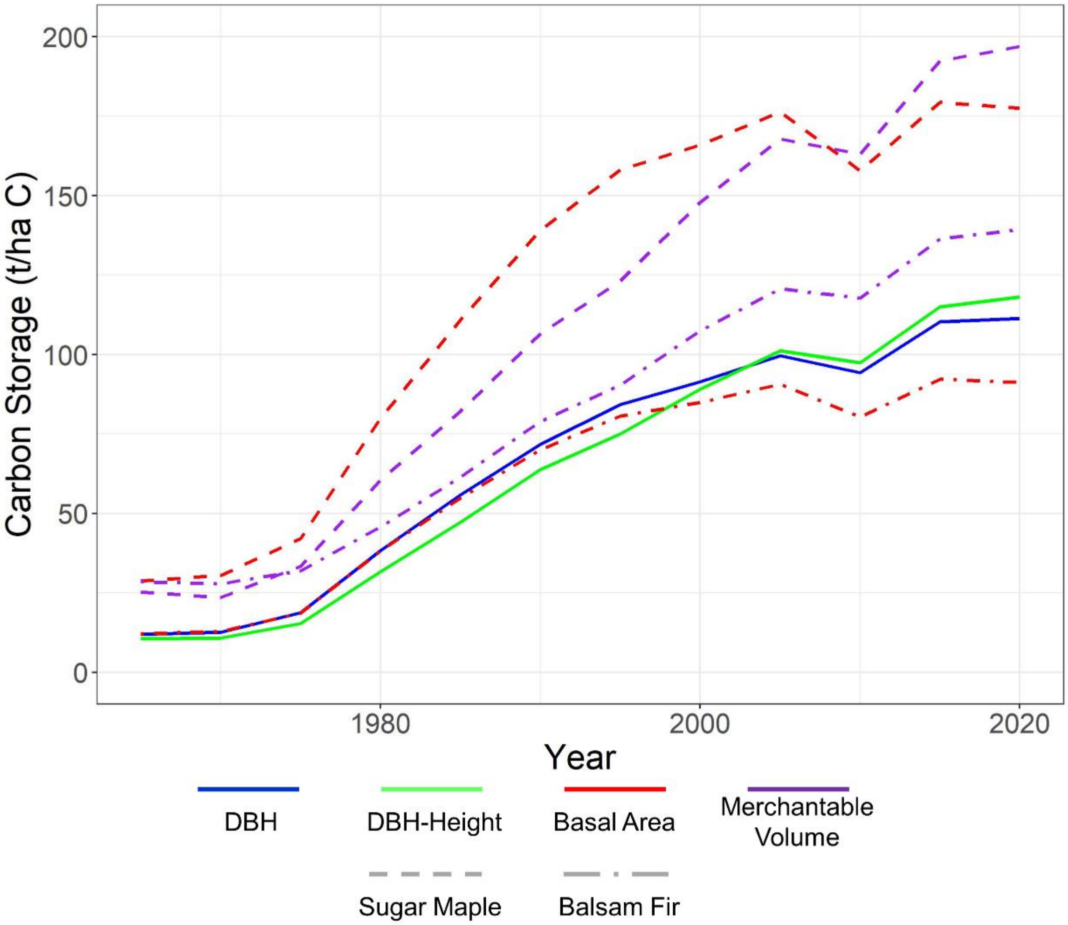

Fig. 7. Carbon estimates for a mixedwood PSP measured between 1965 and 2020 using the four different NSFCC methods for living trees (i.e., DBH, DBH and height, basal area, and merchantable volume). A leading species of balsam fir and sugar maple for basal area and merchantable volume estimates are shown. Colour shows the method of carbon estimation and line dashing shows leading species (basal area and merchantable volume only).

3.1.2. Saplings

Total carbon storage in saplings in the province is 40.6 Mt. Carbon storage in individual saplings cannot be counted because the input data requires a simplified sapling tally. However, when comparing average carbon storage of all saplings in individual plots it can be seen that there is not great variability among species (Fig. 8). Total carbon storage in the province by species shows that balsam fir has almost twice the amount of carbon storage (11.8 Mt) as any other species, followed by red maple, other species, and black spruce (Fig. 9).

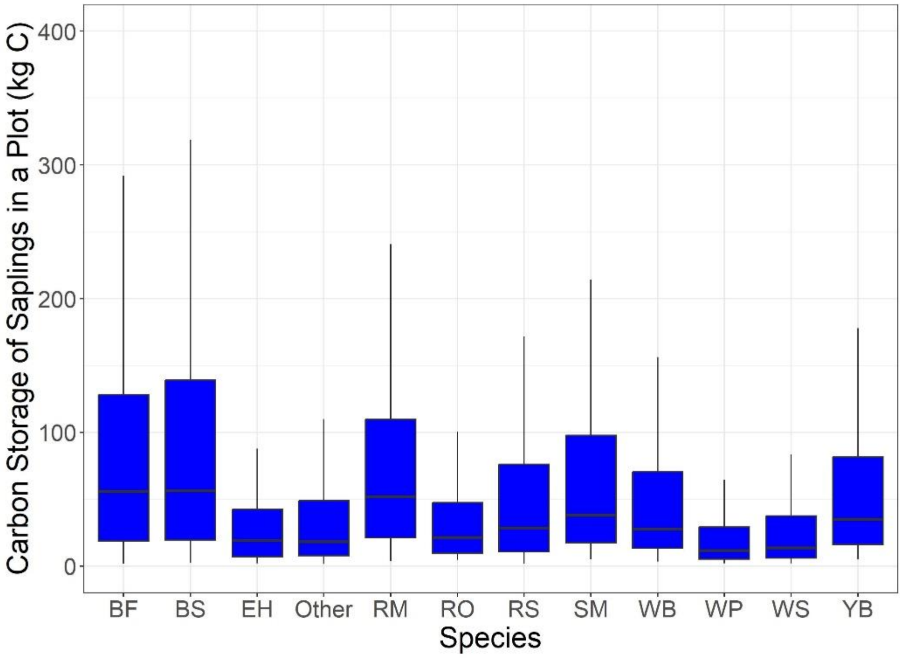

Fig. 8. Distribution of carbon storage in saplings at the plot level. Note that outliers are removed for visualization but carbon values range up to 2,000 kg.

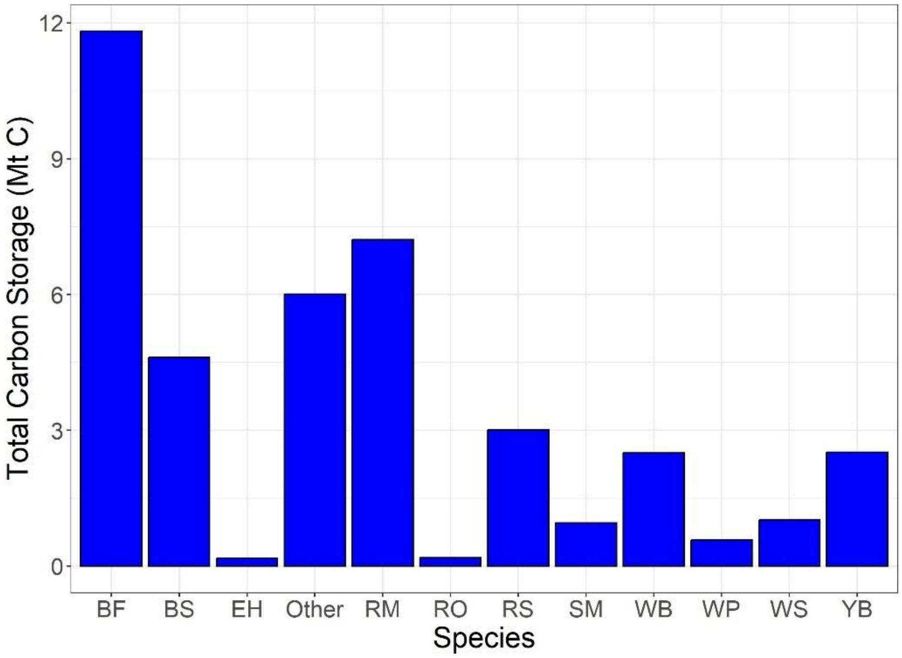

Fig. 9. Total carbon storage of saplings by species in Nova Scotia.

3.1.3. Snags

Total carbon storage in snags in the province is 27.2 Mt. Similar to the sapling results and in contrast to the living tree results, there is little variability across species in average carbon storage estimates in snags (Fig. 10). Again, total carbon storage in the province by species shows that balsam fir is dominant, having more than twice the amount of carbon storage (8.9 Mt) as any other species, followed by black spruce, red spruce, and white spruce (Fig. 11). The largest snag carbon storage value for a hardwood species is red maple at 1.5 Mt.

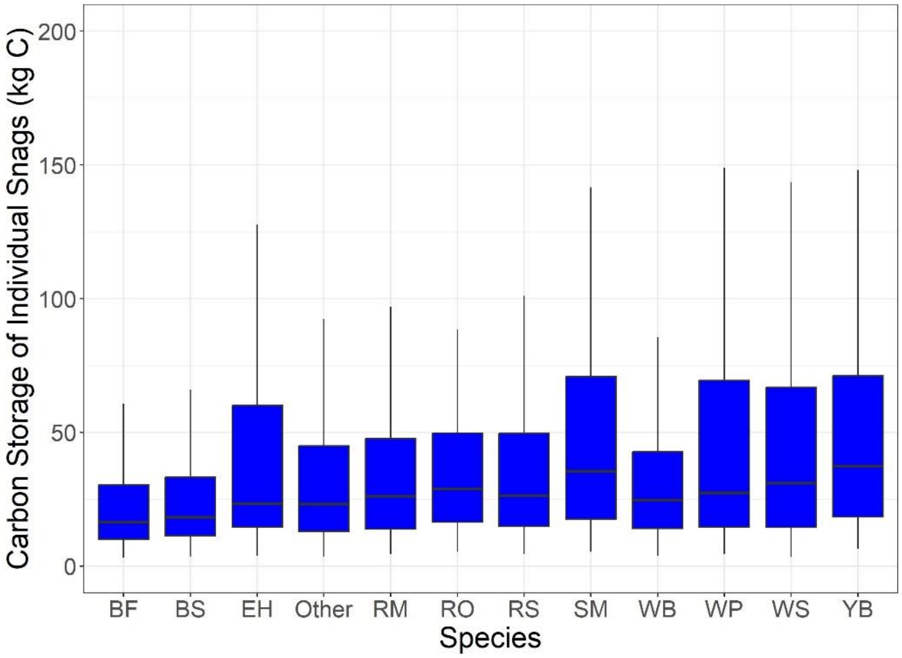

Fig. 10. Distribution of carbon storage in snags. Note that outliers are removed for visualization but carbon values range up to 1,600 kg.

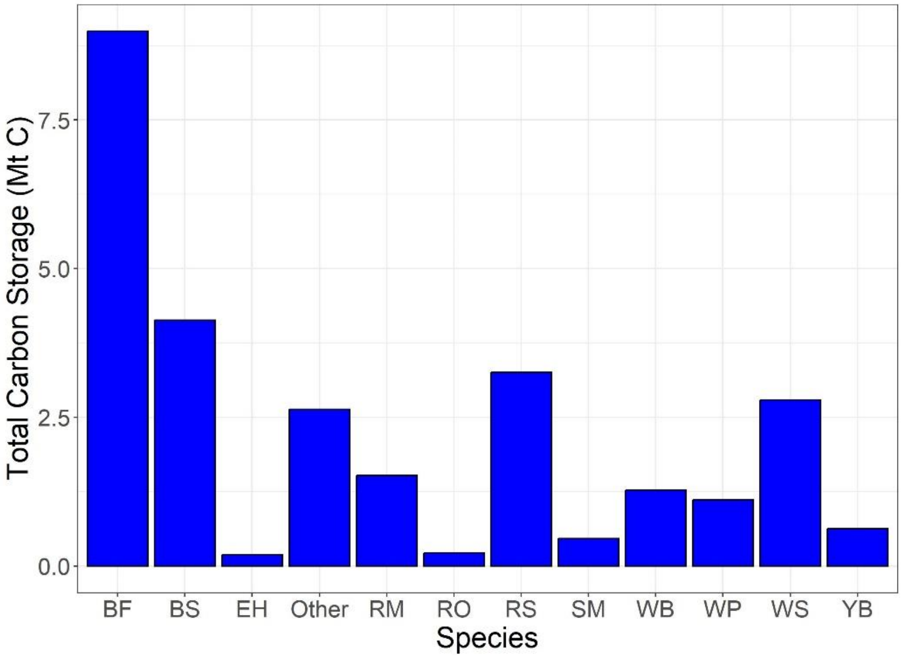

Fig. 11. Total carbon storage of snags by species in Nova Scotia.

3.1.4. Coarse Woody Material

Total carbon storage in CWM in the province is 10.4 Mt. White pine, eastern hemlock, and red spruce tended to comprise the larger CWM pieces, on average (Fig. 12). With the line-intersect sampling that is used for CWM, results provided are rated per-ha estimates and not estimates of individual pieces. Carbon storage values in individual CWM pieces was generally less than 10 t/ha, though the largest piece found in a PSP in Nova Scotia was a 70-cm diameter yellow birch with a decay class of 1 and represented 29 t/ha. As with snags, softwoods tended to comprise more of the carbon storage in CWM. The dominant species by far at 4.2 Mt was the other species group, which is to be expected given that species determination can be difficult in CWM with advanced decay (Fig. 13).

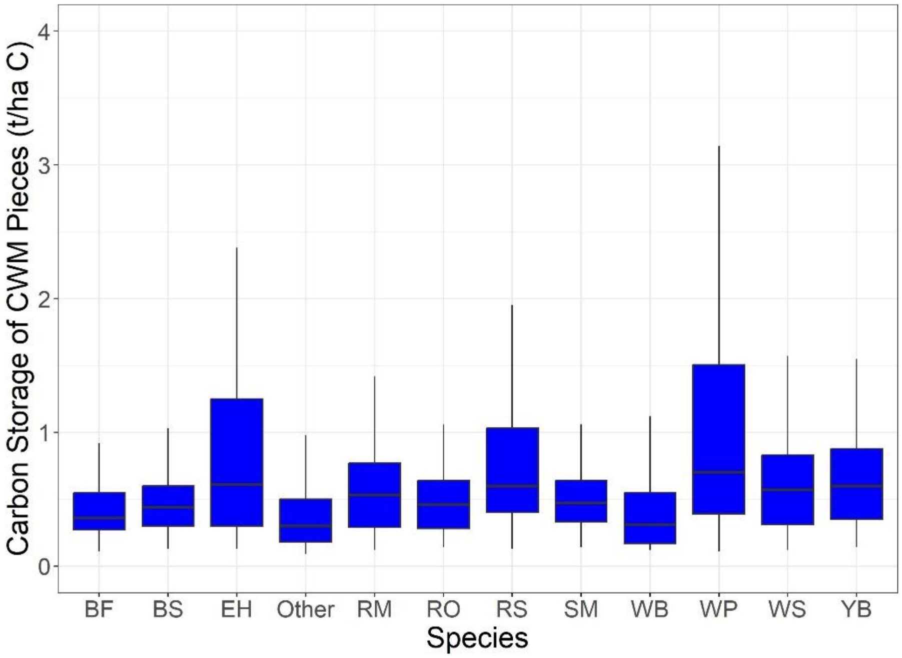

Fig. 12. Distribution of carbon storage in CWM. Note that outliers are removed for visualization but carbon values range up to 30 t/ha.

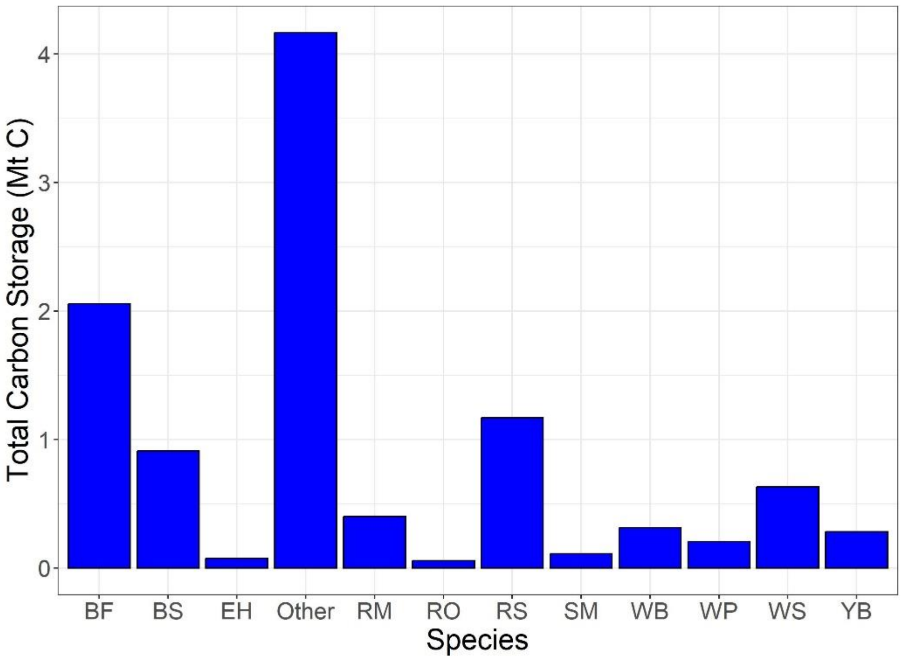

Fig. 13. Total carbon storage of CWM by species in Nova Scotia.

3.2. Carbon Yield Curves

Carbon yield curves were generated using CBM-CFS3 for all five living forest biomass pools and nine dead organic matter pools, including the two soil pools (Table 1) and are illustrated using the red/black spruce dominant community as an example (Fig. 14, 15, & 16). The NSFCC carbon yields for natural stands were stratified by ecoregion, forest community, stocking, and site class, giving at total of 540 possible strata yield combinations. Living forest biomass at stand maturity ranges from a maximum value of 130.1 t/ha for the mixedwood – tolerant forest community within Ecoregions 600, 700, or 900 in fully stocked conditions on the most productive possible site class to 19.9 t/ha in red/black spruce dominant stands (likely black spruce in this instance) within Ecoregions 100, 200, or 800 in poorly stocked conditions on the least productive site class.

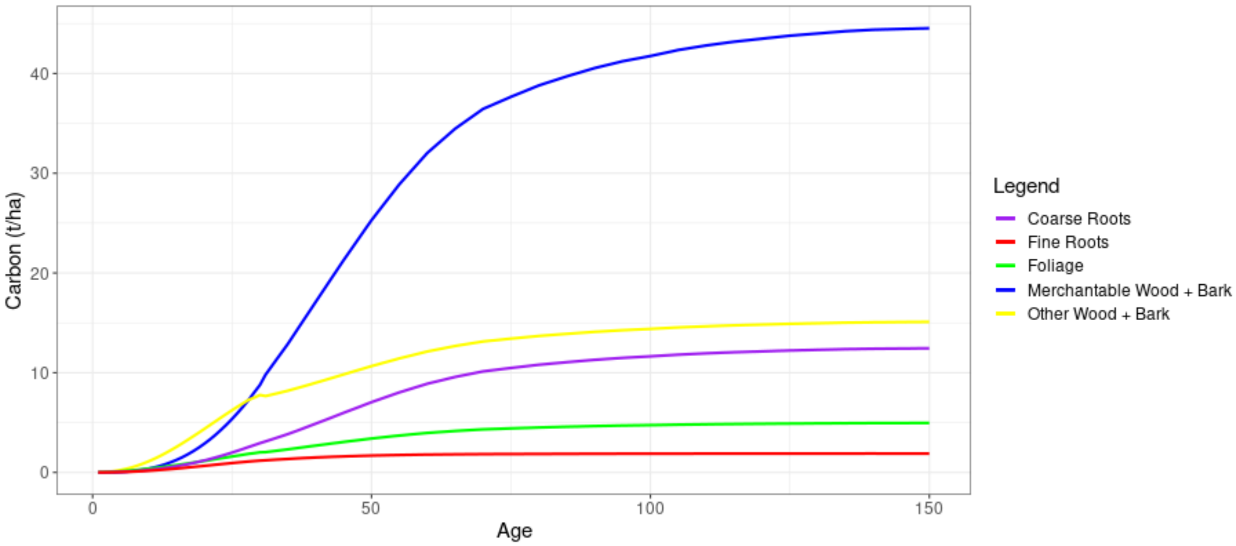

Fig. 14. Example of carbon yield curves for the living forest biomass pools.

Dead organic matter for all pools excluding the two soil pools (Fig. 15) show different temporal dynamics than living forest biomass. Carbon yield curves are initiated by stand-replacing disturbances in CBM-CFS3, which generates a pulse of dead organic matter. These dead organic matter pools then diminish in size through decomposition before accumulating again as sufficient living biomass provides enough annual inputs through turnover and litterfall (Kurz et al., 2009). All carbon yield curves within NSFCC are initiated by harvesting; dead organic matter dynamics would differ in early stages of stand development if initiated by other disturbance types, such as wildfire, wind, or spruce budworm.

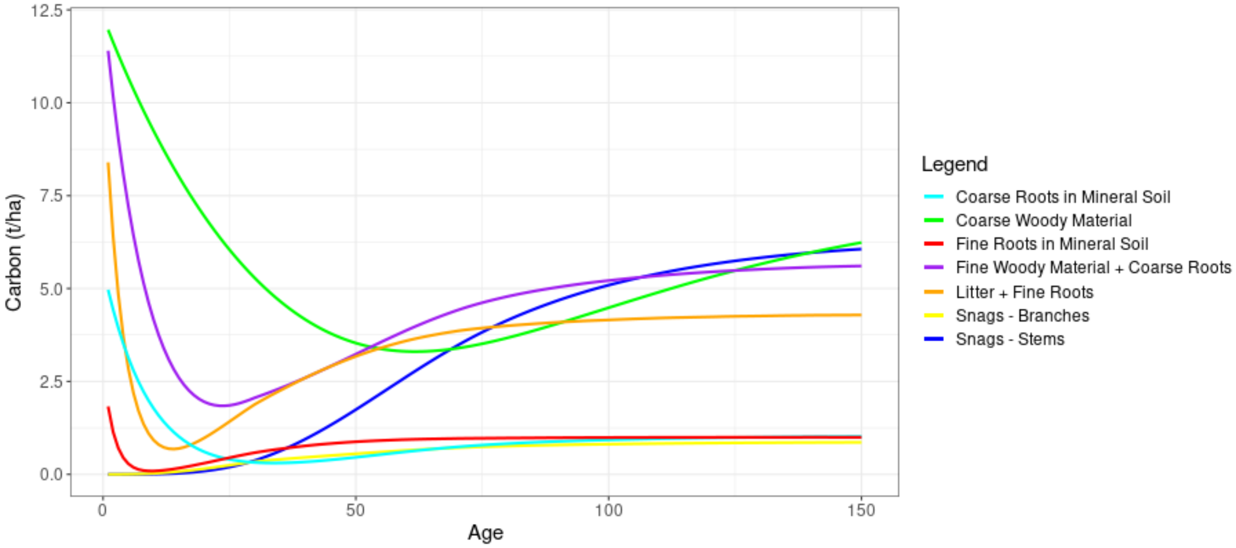

Fig. 15. Example of carbon yield curves for the dead organic matter pools, excluding soils.

Soil carbon yield curves (Fig. 16) are relatively static, though show a slight increase in carbon storage from the increased inputs from decomposing dead organic matter after stand-initiating disturbance, which is more visible in the forest floor (i.e., F, H, and O horizons) than the mineral soil. This slight increase is followed by a slight decrease as carbon pools in other dead organic matter decrease due to decomposition and inputs to soil subsequently decrease, followed by a return to storage values that are near pre-disturbance levels as the stand matures.

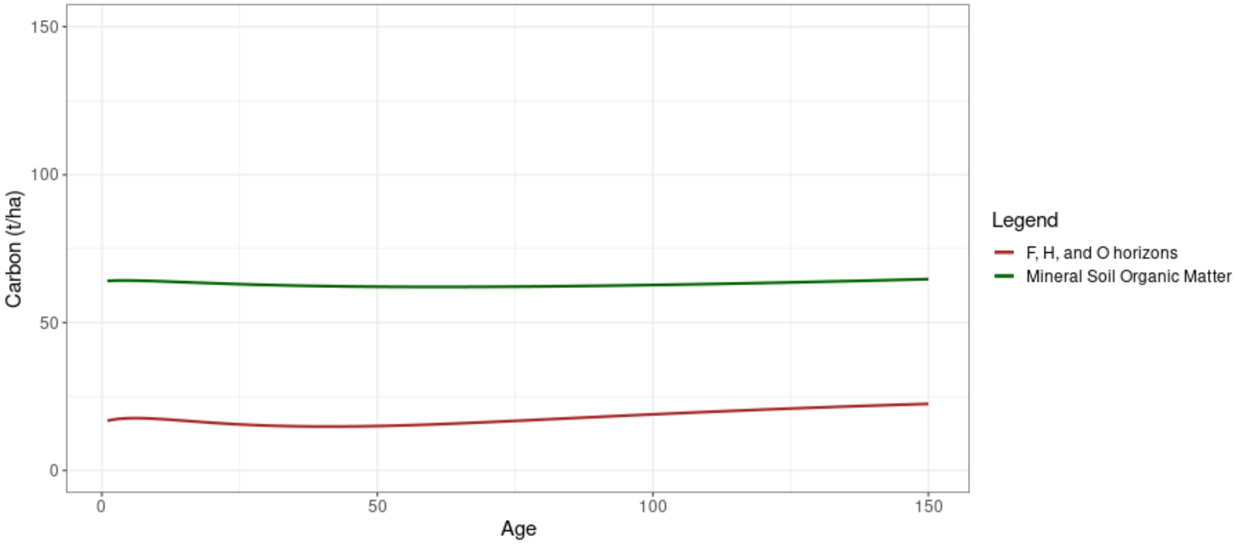

Fig. 16. Example of carbon yield curves for dead organic matter pools within forest soils.

3.3. Nova Scotia Growth and Yield Model

The carbon estimates generated by NSGNY are similar to the carbon yield curves for natural stands (Section 3.2). Carbon yields are calculated for living and dead carbon pools (Fig. 17) though the living pools reported are those used by the Lambert et al. (2005) equations and not CBM-CFS3. Soil carbon pools are not reported in NSGNY because their dynamics require a complex initialization routine based on natural disturbance history (Kurz et al., 2009). Other dead organic matter pools are initialized based on provincial averages. Importantly, the carbon yields generated by NSGNY allow users to adjust productivity (i.e., site index) and stocking to match stand-level conditions. Additionally, users can simulate plantations and silvicultural treatments (i.e., pre-commercial thinning, commercial thinning) and view the effects on forest carbon dynamics. Some dead organic matter estimates for plantations (e.g., snags, CWM) are likely overestimated by CBM-CFS3, which was created from natural stand data across Canada.

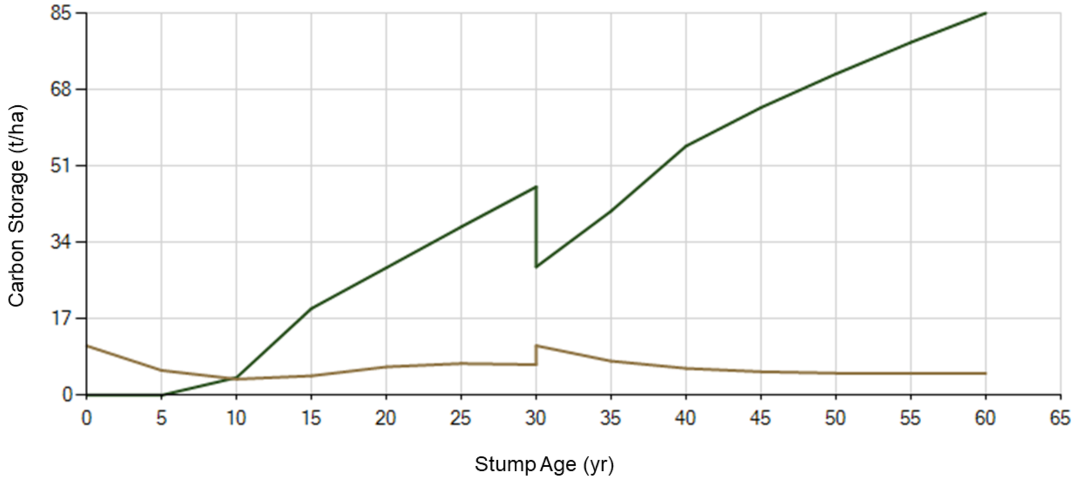

Fig. 17. Example carbon yields generated by NSGNY for a living forest biomass pool and dead organic matter pool for a red spruce plantation with a commercial thinning treatment. Stemwood is shown in dark green and fine woody material is shown in dark brown.

3.4. Spatial Data

The photo-interpreted forest inventory data, along with ecoregion and county data, were used to calculate spatial estimates of forest carbon storage with NSFCC. The tool relies on relating the carbon yield curves generated by CBM-CFS3 to the landbase by estimated stand age and the five stratification themes (Section 2.6). Estimates for all five living forest biomass pools and nine dead organic matter pools, including the two soil pools, are created in the spatial data (i.e., shapefile attribute table). Aggregate pools of living forest carbon (Fig. 18), dead organic matter excluding soil (Fig. 19), and soil (Fig. 20) are also generated for simplified visualizations. Importantly, this tool provides only a snapshot in time of forest carbon storage that is dictated by the year of photo interpretation. There are multiple cycles of photo interpreted inventory available in Nova Scotia that can provide some insight into change, but regardless of input data users should take note to observe the photo year attribute of any given stand polygon.

For the entire province, total carbon storage in dead organic matter excluding soil was 75.0 Mt and total carbon storage in soil was 451.2 Mt. Total carbon storage in living forest biomass was 197.1 Mt, which is notably less than the combined 250.1 Mt in living merchantable trees and 40.6 Mt in saplings. Different methods of carbon estimation are the most likely explanation for this (and many other) discrepancies – in calculated carbon estimates. However, the air photos used in the creation of the inventory data are captured on a 10-year cycle and many stands have a photo year older than 10 years, meaning that there is a time discrepancy that is not present in the PSP data. As mentioned in Section 2.7, stands that may be forested by land use but have no interpreted tree cover (e.g., recent harvests and natural disturbances) and therefore do not have a species classification will not receive any carbon estimates. This means that for the forested landbase estimates provided, dead organic matter will be underestimated because there are no values for land that is forested but without tree cover at the time of interpretation.

Additionally, recall that stand age has known accuracy issues and is an important source of uncertainty in carbon estimates. It is required for NSFCC to link carbon yield curves to the spatial data and provide estimates for both living and dead carbon pools. Photo-interpreted merchantable volume from the inventory data can be used to calculate estimates for living biomass only (Fig. 20) and yields a total storage estimate of 217.8 Mt, predicting on average higher carbon storage values than those based on the carbon yield curves (Fig. 21). Lastly, it is important to note that the carbon yields are based on strata yields for natural stands and thus average forest conditions across a given stratum, which can be tens to hundreds of thousands of hectares. Thus, any given stand in the inventory data will be assigned the strata-level carbon estimate for its age. These yield-based NSFCC carbon estimates are more suitable for landscape level and regional assessment not stand-level assessment.

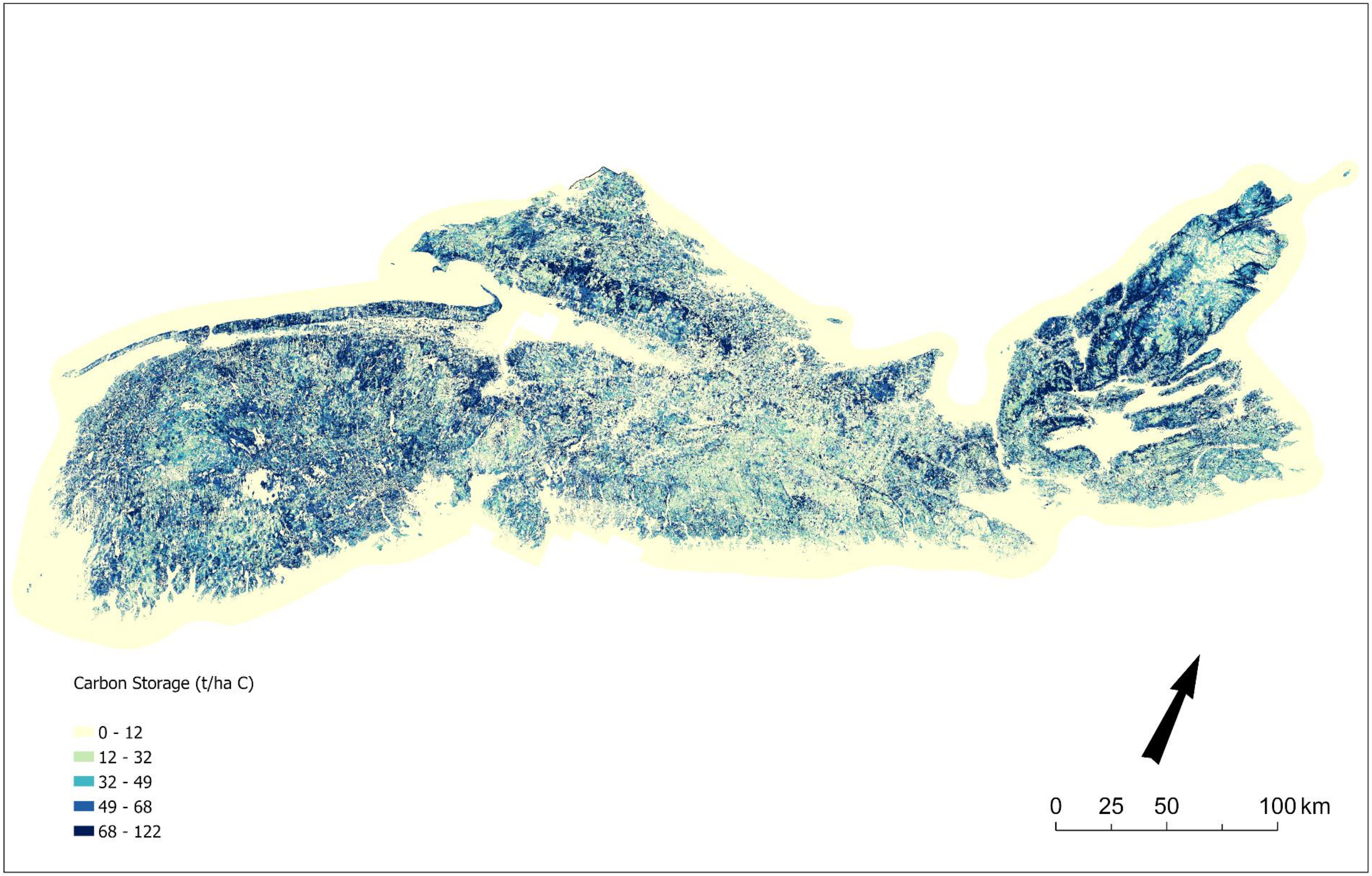

Fig. 18. Forest carbon storage in living forest biomass in Nova Scotia calculated from photo-interpreted forest inventory data.

Fig. 19. Forest carbon storage in dead organic matter excluding soil in Nova Scotia calculated from photo-interpreted forest inventory data.

Fig. 20. Forest carbon storage in soils in Nova Scotia calculated from photo-interpreted forest inventory data.

Carbon estimates from the spatial data enable the comparison of values across administrative regions (e.g., counties) or natural regions (e.g., ecoregions). Across counties in Nova Scotia (Table 3), carbon storage rates varied from 29.5 in St. Mary's to 55.0 in Kings with a provincial average of 46.5 t/ha. Dead organic matter showed relatively similar variability with lower storage values and a provincial average of 16.9 t/ha. Variability in soil carbon storage values is far more influenced by the composition of hardwood forests versus softwood forests in a region than by current growing stock and stand age. The provincial average for soil carbon storage was 102.3 ha with a total storage value of 451.2 Mt, which is more than twice that of living forest biomass.

Table 3. Carbon estimates for living forest biomass, dead organic matter excluding soil (DOM), and soil within forested lands by county or county division with standard deviations provided in brackets, derived from the photo-interpreted forest inventory data and carbon yield curves. In the forest inventory data, Guysborough and Halifax counties are divided due to their size.

County/ Region	Area (10^3 ha)	Biomass (t/ha)	Biomass (Mt)	DOM (t/ha)	DOM (Mt)	Soil (t/ha)	Soil (Mt)
Annapolis	280	53.2 (23.6)	14.9	18.4 (5.1)	5.2	112.2 (37.1)	31.5
Antigonish	119	37.6 (26.7)	4.5	17.5 (7.7)	2.1	107.7 (50.2)	12.8
Cape Breton	191	45.9 (22.9)	8.8	16.8 (5.9)	3.2	105.7 (41.2)	20.2
Colchester	298	36.8 (28.2)	11.0	17.7 (7.6)	5.3	100.5 (46.3)	29.9
Cumberland	356	45.8 (24.7)	16.3	17.5 (5.4)	6.2	109.3 (38.2)	38.9
Digby	222	49.6 (23.7)	11.0	17.3 (5.4)	3.8	104.8 (39.1)	23.2
Guysborough[1]	163	40.9 (24.2)	6.7	15.7 (7.3)	2.6	93.0 (44.8)	15.1
Halifax East	196	35.8 (22.3)	7.0	16.1 (5.8)	3.1	94.5 (36.5)	18.5
Halifax West	240	40.2 (24.9)	9.7	15.0 (7.3)	3.6	87.2 (45.4)	20.9
Hants	251	41.3 (26.9)	10.3	17.2 (6.9)	4.3	100.4 (44.2)	25.2
Inverness	332	52.9 (24.3)	17.6	18.6 (5.9)	6.2	115.4 (40.7)	38.3
Kings	154	55.0 (23.5)	8.5	19.6 (4.5)	3.0	121.5 (31.8)	18.7
Lunenburg	252	52.4 (24.4)	13.2	18.3 (5.3)	4.6	109.6 (37.2)	27.6
Pictou	236	34.7 (27.9)	8.2	17.6 (8.1)	4.2	104.5 (49.3)	24.6
Queens	205	54.3 (21.9)	11.1	17.7 (5.0)	3.6	103.4 (35.4)	21.2
Richmond	100	39.6 (24.0)	4.0	15.8 (7.1)	1.6	94.0 (43.7)	9.4
Shelburne	192	51.0 (20.2)	9.8	16.4 (5.0)	3.2	98.8 (35.0)	18.9
St. Mary's[2]	159	29.5 (24.0)	4.7	15.1 (7.7)	2.4	86.6 (44.9)	13.8
Victoria	231	50.9 (23.2)	11.8	17.7 (5.7)	4.1	110.3 (39.6)	25.5
Yarmouth	162	51.9 (21.6)	8.4	17.1 (5.2)	2.8	105.0 (37.3)	17.0
Nova Scotia	4,336	46.5 (25.3)	197.1	16.9 (6.4)	75.0	102.3 (42.0)	451.2

[1] Eastern half of Guysborough County

[2] Western half of Guysborough County

Ecoregions represent a more ecologically significant delineation of the province and meaningful comparison of forest carbon values (Table 4). Carbon storage is substantially lower in the Northern Plateau (Ecoregion 100) of the Cape Breton Highlands where forests are stunted by climatic exposure and impacted by previous spruce budworm disturbances and moose browsing (Neily et al., 2017). The Fundy Shore (Ecoregion 900) has an abundance of red spruce and tolerant hardwood forests (Neily et al., 2017) and has the highest carbon storage values. In terms of total carbon storage, the Western Ecoregion (700) is both the largest in area of all ecoregions and among the higher carbon storage rates. In sum it contains approximately one third (32.7%) of forest carbon in the province.

Table 4. Carbon estimates for living forest biomass, dead organic matter excluding soil (DOM), and soil within forested lands by ecoregion with standard deviations provided in brackets, derived from the photo-interpreted forest inventory data and carbon yield curves.

Ecoregion	Area (10^3 ha)	Biomass (t/ha)	Biomass (Mt)	DOM (t/ha)	DOM (Mt)	Soil (t/ha)	Soil (Mt)
100 Northern Plateau	16	35.4 (15.6)	0.6	14.4 (5.0)	0.2	80.6 (26.2)	1.3
200 Cape Breton Highlands	159	44.9 (19.6)	7.1	17.2 (4.4)	2.7	103.4 (31.3)	16.4
300 Nova Scotia Uplands	904	49.8 (24.8)	45	20.0 (4.7)	18.0	120.8 (32.6)	109.2
400 Eastern	452	41.5 (22.6)	18.8	17.6 (5.4)	8.0	102.6 (34.9)	46.4
500 Northumberland/Bras d'Or	600	45.4 (22.9)	27.3	18.0 (4.5)	10.8	111.9 (32.6)	67.2
600 Valley and Central Lowlands	227	44.3 (23.6)	10	19.3 (4.6)	4.4	112.5 (31.2)	25.5
700 Western	1,307	53.2 (21.9)	69.4	18.3 (4.6)	23.9	109.6 (33.6)	143.2
800 Atlantic Coastal	282	43.8 (19.4)	12.4	16.3 (4.8)	4.6	96.9 (32.8)	27.3
900 Fundy Shore	119	55.0 (22.2)	6.6	19.5 (3.6)	2.3	123.3 (29.5)	14.7

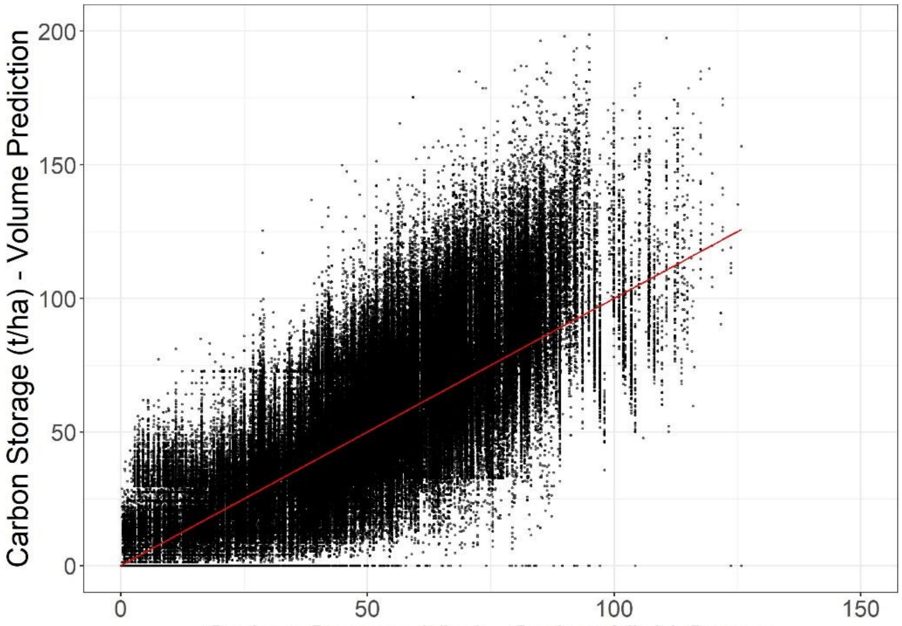

Fig. 21. Carbon storage of photo-interpreted inventory stands calculated using carbon yield curves with age and calculated using merchantable volume.

4. Discussion and Conclusions

NSFCC generates carbon estimates from a variety of data sources and different methodologies. It has advantages for a variety of users but also limitations in design and possible applications. Some of the tool features might be more suited to more simple demonstration and education (e.g., individual trees and plots with drop-down menus within the app) while others are more suited to research and planning (e.g., carbon yields). For example, carbon yields can be used alongside traditional growth and yield data to include carbon objectives in wood supply analysis. It is hoped that the variety of NSFCC features makes it useful to a variety of stakeholders with differing needs. A particular need has been identified among woodland owners to better understand and manage their forest carbon and ideally access carbon markets (Lahey, 2018), with which NSFCC might bring some utility. Note that the carbon estimates provided in this report are preliminary and the purpose of the report is to describe and demonstrate NSFCC not to report on carbon values for the province. Research and monitoring on that subject is underway and will be reported separately.

A critical limitation of carbon estimation in general and the application of NSFCC specifically is the embedded error and uncertainty involved along with the sensitivity of estimation to different methodologies. It is not possible to validate which method has the greatest level of accuracy with PSP data without new destructive sampling and laboratory processing to generate biomass dead organic matter estimates and there are very few such studies/equations available. However, the studies from which the NSFCC derives equations provide valuable insight into uncertainty levels (Li et al., 2003; Lambert et al., 2005; Boudewyn et al., 2007; Kurz et al., 2009; Paré et al., 2013).

Importantly, all NSFCC estimates of carbon storage in dead organic matter (including soils) that are generated by the methods of CBM-CFS3 (Kurz et al., 2009) are not calculated directly from local inventory data as with other methods. These dead organic matter estimates are based on CBM-CFS3 model assumption and architecture for a given stand type. They are highly sensitive to user-defined historical disturbance regimes and leading species, among other factors, and ultimately driven by estimates of carbon storage in living forest biomass. Additional research in Nova Scotia has shown that CBM-CFS3 performs well compared to estimates from empirical PSP data but are scale dependent and have high levels of uncertainty, especially for dead organic matter (Heffner et al., 2021). As such, the CBM-CFS3-based carbon estimates for Nova Scotia (i.e., carbon yield curves and photo-interpreted inventory data) are best applied in a planning context at the landscape level, not stand level.

There is a number of areas of on-going work and future research that will be reflected in future releases of NSFCC. Chief among these is NSDNRR forest modelling of uneven-aged silvicultural systems to better reflect the current shifts in practices occurring in Nova Scotia (McGrath et al., 2021). There is interim modelling occurring with the provincial strategic forest model, and subsequently CBM-CFS3, to create multiple age cohorts from the even-aged estimates in the strata yields and NSGNY. Moreover, the Department is conducting research on individual tree models such as the Open Stand

Model (OSM; Hennigar, 2015) and the Acadian Variant of the USDA Forest Service's Forest Vegetation Simulator (FVS; Crookston & Dixon, 2005; Weiskittel et al., 2017). These models are well-suited to uneven-aged forest modelling and can also generate carbon estimates using the methods already employed by NSFCC.

Forest carbon and climate change mitigation are becoming central values within forest management alongside other core values like biodiversity, timber, and recreation. Moreover, jurisdictions around the world, including both Canada and Nova Scotia, have made legal commitments to reduce their emissions and fight climate change. Forests and forestry represent an opportunity as nature-based solutions to reduce emissions and even act as net sinks of atmospheric carbon (ECCC, 2022). A necessary starting point for mitigation action in forestry is building carbon literacy and quantitative tools like NSFCC to enable a variety of forest stakeholders to estimate and model their forest carbon.

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