2023 Forest Carbon Inventory

New Brunswick

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Department of Natural Resources and Energy Development

Report NB-FPSB-2024-1
New Brunswick's 2023
Forest Carbon Inventory

This report provides inventory estimates of carbon storage in living woody tree biomass on all forestland in New Brunswick in 2023, as partial fulfillment of the department's commitment, Action 16a in *Our Pathway Towards Decarbonization and Climate Resilience New Brunswick's Climate Change Action Plan 2022-2027*.

Prepared by: Chris Hennigar, PhD, RPF and
Beth Brooks, BSc.ENR, MF

Forest Strategy Section,
Forest Planning and Stewardship Branch,
Forestry Division,
Department of Natural Resource and Energy Development

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This work would not have been possible without the coordination and field sampling efforts of over 100 provincial foresters and forest technicians, including both full-time staff and many seasonal staff. This report is but one small outcome of their efforts to collect these data, which will live on and be used for generations to come.

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Executive Summary

WHY WE DID THIS

New Brunswick (NB) is a forested province, with approximately 84% of its area considered forestland (6.12 million hectares). As such, forests play an important role in NB industry and culture. Each year, the need for better information about the role forests can play toward reducing net greenhouse gas emissions (GHG) seems to double; for example, the recent development of a Federal Private Land Improved Forest Management Carbon (C) Offset Program in 2023 or recent announcements regarding 2050 net-zero GHG emissions targets by both New Brunswick and Canada. Forest management and forest policy are known to have potential impacts on net GHG emissions, but good management and good policy can only be informed by good data. Thus, it is vitally important to develop a high-quality quantitative inventory of the state of C in NB forests.

OBJECTIVE

The objective of the 2023 Forest Carbon Inventory Report was to partially fulfil the commitment, **Action 16a,** in NB's 2022-2027 Climate Change Action Plan (CCAP) by calculating a statistically robust forest carbon inventory estimate for alive trees on Crown$_{TL}$, Freehold, and Private lands. Forest ownership in NB is comprised of three main types: Crown$_{TL}$ ($_{TL}$ = Timber Licensed; 49%), Freehold (17%), and Private (28%) lands, with remaining forestlands owned by the Federal (e.g., national parks, Canadian Forces Base Gagetown) or Provincial (e.g., parks, other leased, department of transportation) governments.

HOW WE DID IT

Forest C projections were developed using plot data from 8,990 forestland plots that were surveyed from 2016-2022 as a part of the NB Continuous Land Inventory (CLI) survey program. Inventoried C pools at this time were restricted to above- and below-ground live biomass for trees ≥ 1 cm in diameter at breast height (DBH, 1.3 m). Forestland included recently harvested and areas of low productivity with some trees (barren, wet), but excluded land classified as wetland, agriculture, gravel pits, roads, and other non-forest features.

WHAT WAS EXCLUDED

This Year 1 report does not include carbon estimates in forest deadwood or soils and does not quantify the balance of CO_2 emissions and removals; however, this will be the focus in subsequent project years under **Action 16a** of the NB CCAP. Wetlands are valuable C sinks and are currently being assessed in a parallel project by the NB Department of Environment and Local Government (DELG) under **Action 16b** of the NB CCAP.

KEY OUTCOMES

For 2023, there was an estimated 377 (± 3.9) million tonnes of C stored above and below ground in living trees on NB forestlands; averaging 61.6 tonnes of C per hectare with an uncertainty of 1.03%. This equates to 1.382 billion tonnes of equivalent CO_2, or 100 times the total provincial greenhouse gas emissions in NB in 2020.

Carbon stocks from 2016-2023 were generally stable on Industrial Freehold, Private Woodlot, and $Crown_{TL}$ lands, and possibly increasing slightly on 'Other' lands for this survey period. Crown and Freehold forestlands had about the same amount of C per hectare in 2023 at about 60 tC/ha, and slightly higher for Private lands at about 64 tC/ha. 'Other' lands had significantly more C than the other three land ownership groups at about 74 tC/ha, which was expected because of much higher proportions of land conserved in federal and provincial parks.

INTENDED AUDIENCE

This report is intended for forest practitioners and researchers to help advance the state of knowledge regarding recent inventory methods to quantify and estimate forest live tree C in New Brunswick.

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1 Background

1.1 NEW BRUNSWICK'S FORESTS

New Brunswick (NB) is the largest province in the Maritimes (≈ 7.3 M ha total) with 6.1 M ha of forestland. New Brunswick lies primarily in the Acadian forest region, with some northern and highland areas of the province in the boreal forest region. The Acadian forest is representative of the transition zone between the hardwood dominant forest to the south and softwood dominant forest to the north. Key species in the region include balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), white pine (*Pinus strobus*), red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), white birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*).

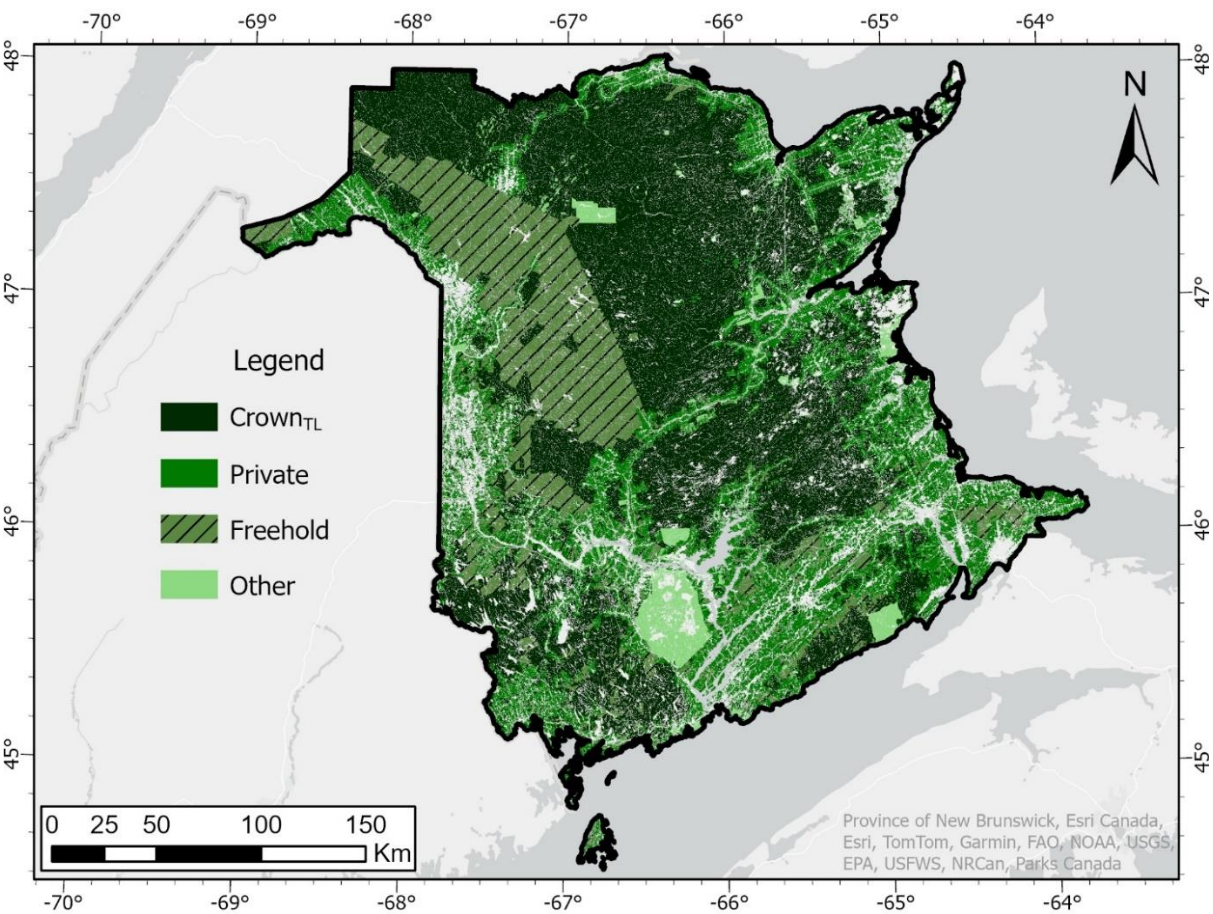

Figure 1.1 Spatial distribution of forested land in 2023 by landowner type in NB.

Forest ownership in NB is comprised of three main types: $Crown_{TL}$ Licensed ($_{TL}$ = Timber Licensed; 49%), Freehold (17%), and Private (28%) lands, with remaining forestlands owned by the Federal (e.g., national parks, Base Gagetown) or Provincial (e.g., parks, other leased) governments (Fig. 1.1). There are approximately 3.0 M ha of forest on $Crown_{TL}$ lands, which are divided into ten Crown timber licenses. Freehold lands are large land tracks (≥ 100,000 ha) which are privately owned by large industrial companies that operate wood processing facilities; Freehold lands include roughly 1.1 M ha of forest. Freehold land is a distinct ownership type from what is considered Private woodlot land in NB, where Private woodlots are divided among thousands of individuals, families, and companies and amount to 1.7 M ha of forest. The collection of Private woodlot owners is represented within the NB forestry sector by seven regional forest product Marketing Boards.

New Brunswick forests are managed for a wide range of values, including, lumber and paper manufacturing, maple syrup production, recreation, wildlife habitat, and carbon sequestration. The forestry sector in NB is important both socially and economically, supporting more than 24,000 fulltime jobs and contributing more than $1.5 billion annually to the provincial economy (NB DNRED, 2023a). On a per capita basis, NB has the highest forest products GDP in Canada. Approximately 1.5% of forestland is harvested annually (NB DNRED, 2023a).

Given the rich composition of tree species and long history of forest management in NB, forests comprise a very diverse range of forest conditions from even-aged spruce plantations to multi-aged shade-tolerant hardwood and mixedwoods to shelterwood white pine, with various states of maturity, such as recently clearcut to old forest habitats and old forest communities in conservation forest.

1.2 CONTEXT

This report was initiated as a part of the New Brunswick Department of Natural Resources and Energy Development's (DNRED) commitment to fulfil **part *a*** of **Action *16*** under the 2022-2027 Climate Change Action Plan (CCAP). **Part *a*** of **Action *16*** necessitates publishing an assessment of the carbon (C) stock of New Brunswick's forests.

The objective of this report was to partially fulfil **Action *16a*** by calculating a statistically robust forest C inventory estimate for $Crown_{TL}$, Freehold, and Private lands in 2023. Inventoried C pools at this time were restricted to above- and below-ground live tree biomass for trees ≥ 1 cm in diameter at breast height (DBH, 1.3 m).

A rigorous estimate of NB's forest C stock provides useful information for federal and provincial governments and other organizations to validate C models and track forest C stock changes over time. Future reports under ***Action 16a*** may include assessments of deadwood and soil organic C pools, projections of forest C stocks into the future, and may help to quantify the benefits of alternative forest management on net GHG emissions.

2 Methods

New Brunswick's Continuous Land Inventory (CLI) ground plot sample network was used to develop estimates of forest C storage in live tree biomass on all forestland in NB. Forestland included recently harvested and areas of low productivity with some trees (barren, wet), but excluded land classified as wetland, agriculture, gravel pits, roads, and other non-forest features. Current forestland was determined through the NB DNRED's provincial photo-interpreted geographic information system (GIS) landbase layer (NB DNRED, 2023b; herein 'NB GIS'). Projected biological tree growth and mortality and removal of live trees though harvesting between time of survey and 2023 was considered. Details on survey methods and modelling assumptions are provided in the following sections.

2.1 CONTINUOUS LAND INVENTORY PLOT NETWORK

The Continuous Land Inventory (CLI) vegetation sampling program began in 2016 with the purpose of developing a statistically representative and unbiased provincial forest inventory. Samples (ground plots) were arranged along a 2 km grid with a total of 18,334 plots located throughout the province, with 10% scheduled to be measured annually. Plot locations were fixed on the 2 km grid and are not permitted to be moved by field crews during establishment for roads, wet areas, houses, or other features, even if the sample plot location straddles two different features (e.g., forest and road). A small percentage of plots have been moved to different randomly selected locations due to safety concerns (e.g., extreme slope) or major access issues.

Plots were clustered by map sheet (4.2 ha, 12 plots) and each cluster was assigned a measurement year at random. A quarter of total plots were randomly designated as individual tree growth and survival monitoring plots (Fig. 2.1) and are currently visited every five years after establishment on Crown_{TL} land; every 10 years after establishment on other ownerships. This network of ground plots represents New Brunswick's best unbiased sample of its forest inventory.

2.2 PLOT ELIGIBILITY FOR C INVENTORY ESTIMATION

Only plots with central points on forestland were considered (15,320 or 84% of total plots). Between 2016 and 2022, 9,242 forestland plot surveys were conducted, including some locations that had being re-measured within that period. If a plot had been surveyed multiple times only the most recent plot measurement was used for inventory estimation here, reducing eligible sample plots to 8,990.

Some minor data cleaning was required on plots with obvious data entry errors (e.g., decimal place location incorrect). There were 131 cases where the plot existed in the CLI database, but no survey visit occurred, or the tree records were confirmed lost. All 131 of these referenced plots were omitted.

2.2.1 Plot Design

Each CLI plot includes a 50 m^2 fixed area circular plot for small trees (≥1 cm and ≤7 cm DBH), a 400 m^2 plot for large trees (>7 cm DBH), and a variable radius (metric basal area factor of 2; BAF) plot to subsample large trees for more detailed measurements of such as tree height, crown dimensions, health risk, and stem form. Each plot had a 360-degree image captured from its central point using a Theta Camera and survey grade global positioning system (GPS) coordinates established.

2.2.2 Calculation of Plot Tree Biomass and Carbon

Total live tree above-ground biomass was calculated using the Lambert et al. (2005) species-specific allometric biomass equations for all trees with DBH ≥ 1 cm. Coarse root and fine root below-ground biomass was calculated using equations from Li et al. (2003). 50% of oven-dry biomass weight was assumed to be C. These tree-level C estimates were summed in each plot and scaled to per hectare estimates using plot area expansion factors. Each plot represented one sample unit of C.

2.3 EDGE PLOTS

Of the 8,990 eligible forestland sample plots, 569 (6%) had some plot area that intersected with land types other than forest; herein referred to as ‘edge plots’. All eligible forestland edge plots had their central point in forestland according to the NB GIS layer, but had some overlap between the large-tree fixed-area sample plot (11.28 m radius) and other land types; e.g., a lake or road. As we are estimating only C on forestland, the area of the plot was reduced in proportion to area of non-forestland that overlapped the original plot boundaries. For example, if only 75% of a plot area was forestland (e.g., 25% of the plot area classed as wetland) then the area of the plot was reduced by 25%, which in turn increased the per hectare C estimates for the plot sample point by 25%. Each edge plot sample contributed the same weight as non-edge (100% forestland) plot samples when averaging per hectare C stocks across all forest land in this report.

2.4 ACCOUNTING FOR BIOLOGICAL TREE GROWTH AND NATURAL MORTALITY

Growth, survival, and regeneration of individual trees from year of survey to 2023 was predicted for each plot using an empirical tree-list simulation model known as Open Stand Model: Acadian Variant (OSM-ACD; OSM 2022, Version 2.0.0.0). OSM-ACD has been calibrated for NB using millions of tree growth and mortality observations between 1980-2010 and is used widely in NB for forest growth and treatment response forecasting. OSM-ACD is used by NB DNRED for development of forest management planning models and wood supply calculations. This model varies growth rates by jurisdiction, Biomass Growth Index (BGI; Hennigar *et al.* 2016), management type (planted, pre-commercially thinned, partial-cut, unmanaged), tree species, tree size, tree social position, and stand-level basal area and density. Growth and stocking on very poor productivity sites (e.g., very wet, organic soils, barren) was constrained by OSM-ACD to ≤ 1 m^3/ha/year. Growth in planted and thinned stands was accelerated by OSM-ACD. No changes to the current OSM-ACD growth calibration were applied to adjust for climate change.

OSM-ACD was used in three capacities:

1) To estimate heights for trees without height measurements in plots; all plots have some trees without height measurements by design. Where enough tree height samples are available for a given species, OSM-ACD will localize its tree height predictions for the plot or stand.

2) To annually grow all plots from year of survey (earliest 2016) to exactly 2023 in annual timesteps; e.g., plots that were surveyed in 2016 were grown forward seven years.

3) To simulate effects of harvest (e.g., commercial thin, continuous cover irregular shelterwood, clearcut, pre-commercial thinning) on tree C removals and growth response of remaining trees, if treated after survey, which included 349 plots.

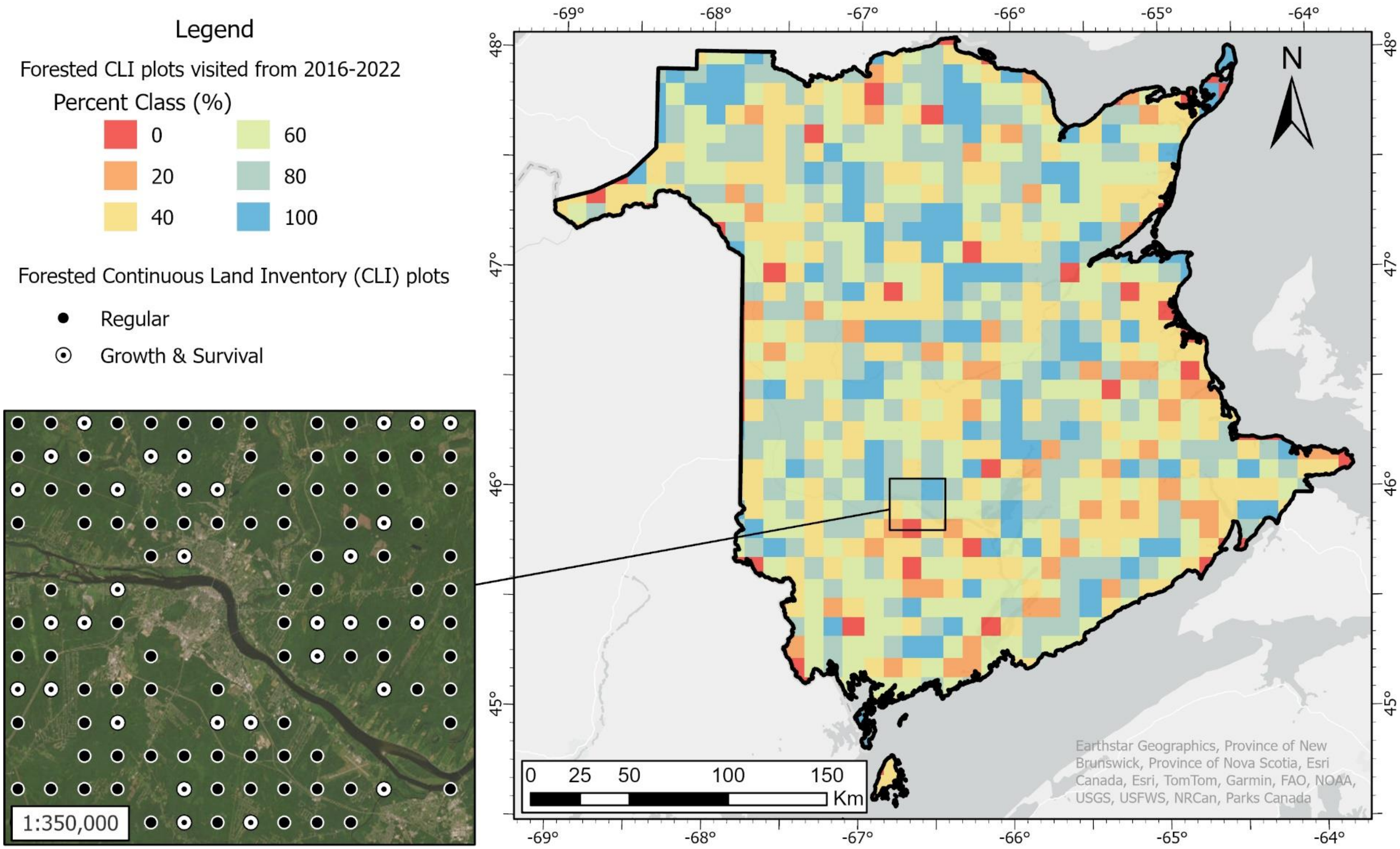

Figure 2.1 Percent of CLI plots on forestland visited between 2016 and 2022 by 10 square kilometre grid cells across the Province of Brunswick. Inset zoomed rectangle displays CLI plots (points) falling on forestland, where thick border points identify plots that individual trees are monitored for growth and survival.

2.5 ACCOUNTING FOR FOREST MANAGEMENT TREATMENTS

Tree removals from clearcut (CC) and partial harvest (PC), commercial thinning (CT), pre-commercial thinning (PCT), and plantation cleaning (CL), as well as tree additions though plantation (PLT) establishment, between time of survey and end of 2022 had to be considered to calculate accurate estimate of 2023 live C stocks in the forest. If a treatment was observed at a plot post survey, then that treatment was simulated in OSM-ACD to remove harvested trees or introduce new ones, in the case of planting. High value and climate resistant species, such as spruce, white pine, and maple, were prioritized for crop retention during thinning compared to species such as balsam fir, poplar, white birch, and non-commercial hardwoods. Partial cut treatments were assumed to remove 50% of stand basal area (m^2); clearcuts assumed 100% removal. There was no recruitment of stems ≥ 1 cm assumed between treatment and 2023 in the case of clearcut simulations. Plantation vegetation cleaning treatments were assumed to retain 1,800 trees, preferably large spruce crop trees. CTs practiced a 'thin-from-below' approach and retained at least 60% of stand volume. Plantations assumed 1,800 spruce seedlings were planted per hectare, along with 200 balsam fir trees per hectare naturally regenerating.

Harvest, reforestation and stand improvement treatments are submitted annually by Crown timber licensees to NB DNRED and updated in the NB GIS dataset. At the time of this work, $Crown_{TL}$ treatment updates for 2022 were not complete. Reforestation and stand improvement treatment updates on Private lands are submitted annually by the forest product marketing boards; however, harvest treatments are not. In some years and locations, treatment updates for Private and Other lands were missing. Locations and years without harvest treatment history had harvest depletion year and percent removed (partial, full) manually assigned by visually cross-referencing several satellite imagery sources at each plot location. This was done for all eligible forestland plots. The Global Forest Watch (GFW) '*Year of Tree Loss*' raster (30 m resolution; Hansen *et al*., 2013) predicted areas of tree loss between 2001 and 2022. Sentinel satellite imagery (10 m resolution) depicted conditions at a higher resolution in 2018. For 2019 – 2022, SPOT (Satellite Pour l'Observation de la Terre) satellite imagery at 1.5 m resolution was examined (Airbus Intelligence, 2019-2022). If a recorded treatment occurred near the year of survey, or if the treatment visually appeared to have been conducted before time of survey, the 360-degree plot images were assessed to confirm whether the treatment occurred before or after survey.

If a plot was treated post survey either from NB GIS records or through satellite observation, then the observed treatment type in the observed treatment year was simulated in OSM-ACD before reporting C stocks for 2023. There were 349 treatments applied to 349 respective plots.

2.6 ACCOUNTING FOR NATURAL DISTURBANCE

There were no recorded or observed stand-replacing natural disturbances (e.g., major wind blowdown, wildfire) in any of the eligible forestland plots between time of survey and the end of 2022.

2.7 PLOT CLASSIFICATION AND AGING

Plots were classified and examined by Ecodistrict (Zelazny et al., 2007), landowner class (i.e., $Crown_{TL}$, Private, Freehold, and Other), survey year, height class, stand age and origin.

Stand management origin was classified for even-aged stands with historical records of stand-replacing disturbances as:

- **CC-None** - Naturally regenerating post clearcut,
- **CC-PLT** – Planted post clearcut, or
- **CC-PCT** - Pre-commercially thinned post clearcut or overstory removal.

Plantations and PCTs that were later commercially thinned were still considered plantations or PCTs.

Stand age was assigned based on the timing of CC, PLT, CL, PCT, or CT treatments. CL, PCT, and CT was assumed to occur at age 10, 13, and 35, respectively. Where possible, if CC or PLT year was available, it was used over CL, PCT, and CT year to calculate stand age. Stands with no treatment history or that were partially cut, were classified as age ‘unknown’ and excluded. Age classes were limited to a maximum of 40 years due to potential unreliability of old treatment records.

Plots with extreme heights for a given age class (i.e., average tree height weighted by basal area exceeding the 90^{th} percentile per age class) were considered outliers and excluded during the summary of carbon stocks by age class and origin. In many cases these tall plots included residual mature trees post clearcut (e.g., seed trees, small residual patches in cut block) and are not reflective of C stocks sequestered since disturbance. These young, tall plots were included in all other estimates.

2.8 UNCERTAINTY

Uncertainty, or sampling error conveyed as a percent of the mean forest carbon estimate, was calculated at a 90% confidence level (Equation 1), which currently aligns with the Federal Private Land Improved Forest Management C Offset Program (ECCC, 2023).

Equation 1.

$$Uncertainty = \left(\frac{z \times SE}{\overline{X}\ tC\ year^{-1}}\right) \times 100$$

Where,

Uncertainty	=	Sampling error as a percentage of the mean forest carbon above and below ground, in living trees ≥ 1 cm DBH, rounded to the nearest $1/10^{\text{th}}$ of a percent.
z	=	Critical value at a 90% confidence interval
SE	=	Standard error of forest carbon estimate
$\overline{X}$ tC $year^{-1}$	=	Mean of estimated forest carbon (tonnes) per year (2023)

3 Results

In 2023, there was an estimated 377 M tC stored above-and below-ground in living stems ≥ 1 cm DBH on NB forestlands (6.1 M ha); averaging 61.6 tC/ha with a standard error of 0.38 tC/ha and an uncertainty of 1.03%.

The highest mean carbon value of 75.5 tC/ha was identified in the Cranberry Ecodistrict (130,000 ha), located in the Southwest of the province along the border with Maine (Fig. 3.1). In contrast, the Caraquet Ecodistrict (210,000 ha), part of the Acadian Peninsula in the Northeast, expressed the lowest mean carbon estimate at 53.5 tC/ha. Generally, the mean carbon was observed to be higher in the Southwest of the province and lower along the coast. Across Ecodistricts, mean C was negatively associated (Pearson correlation; r= -0.44) with the proportion of low merchantable volume stands (<35 m^3/ha).

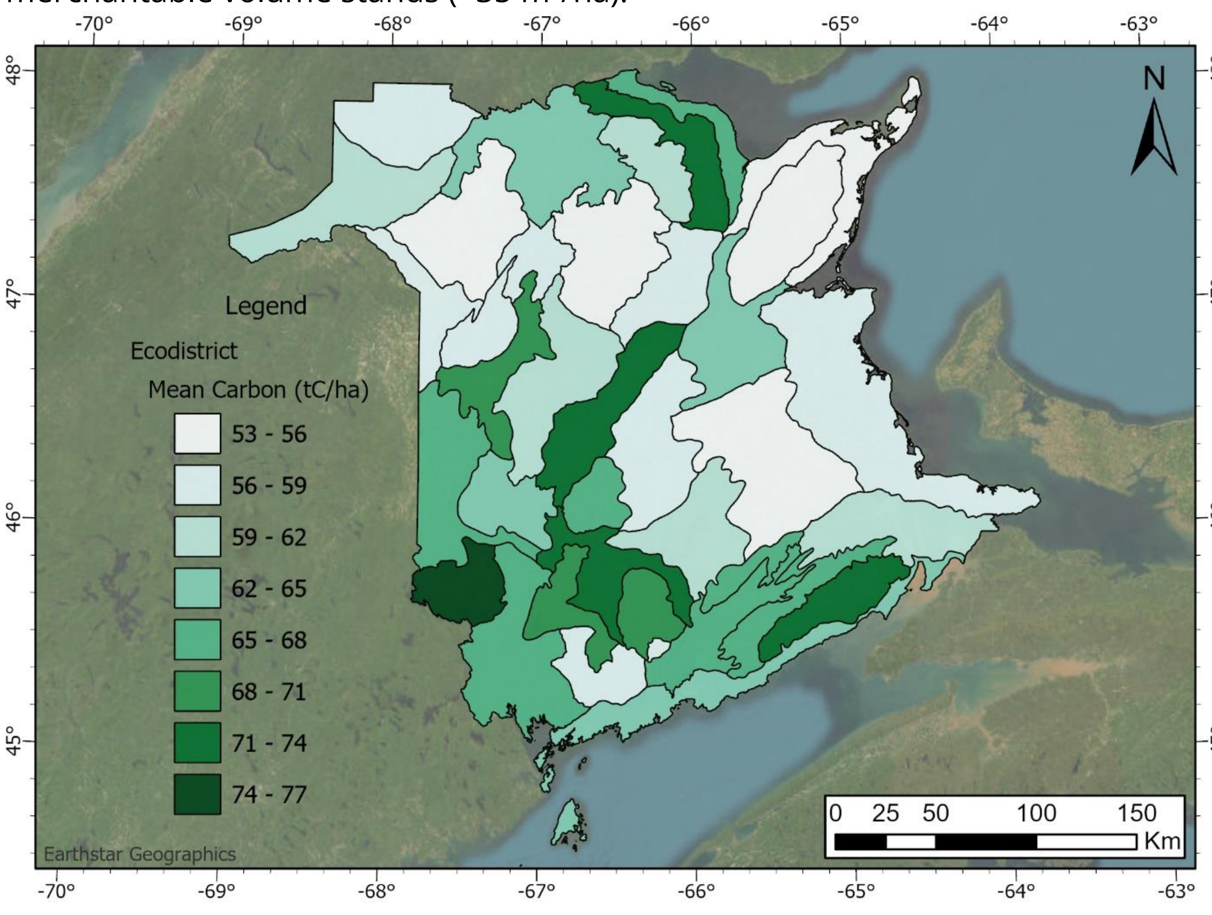

Figure 3.1 Mean tC/ha in forested plots across the 35 New Brunswick Ecodistricts described by Zelazny et al. (2007).

3.1 CARBON ESTIMATES BY LAND OWNERSHIP

The 2023 mean forest C inventory estimate for $Crown_{TL}$ land was 60.2 tC/ha or a total of 181 M tC with an uncertainty of 1.5% (Table 3.1). The standard error, and uncertainty estimates for $Crown_{TL}$ land were the lowest of any land ownership group, due mostly to sample size. Private and Freehold lands had similar C per hectare as $Crown_{TL}$ forestlands, the amounts being within 2-3 tC/ha (Table 3.1). The 'Other' landowner group includes lands that are part of provincial or federal agencies and include wildlife reserves, lands held by the Department of National Defence, unassigned lands, and areas of active commitments such as leases and easements on Crown land. Carbon estimates for the 'Other' land ownership group had the highest C inventory values per unit area (74.3 tC/ha) as well as the highest standard error (2.00 tC/ha) and uncertainty (4.4%).

CLI plots located on $Crown_{TL}$ land made up 52.2% of the dataset used to generate the 2023 forest C inventory results. Private land had the second highest number of CLI sampling plots per land ownership class (24.9%), followed by Freehold (18.6%), and 'Other' (4.3%). This sampling ratio was within 1-4% of forestland area proportions of each ownership group in Table 3.1, confirming that this sample is very representative of ownership types across NB.

Table 3.1 Descriptive statistics for the projection of 2023 carbon (tC/ha) stores in aboveground, living stems ≥ 1 cm DBH broken down by land ownership group.

Land Ownership Group	No. Plots	Area (M ha)	Mean	Median	Max	Standard Error	Confidence Interval (90%)* [LL, UL]
$Crown_{TL}$	4,696	3.01	60.2	62.4	191.4	0.54	[59.3, 61.1]
Private	2,235	1.73	63.7	65.7	172.5	0.73	[62.6, 64.9]
Freehold	1,670	1.06	59.6	59.0	184.6	0.90	[58.1, 61.1]
Other	389	0.32	74.3	76.1	191.0	2.00	[71.0, 77.5]
Total	8,990	6.12	61.6	63.2	191.4	0.38	[61.0, 62.2]

* 90% confidence interval calculated from a two-tailed probability distribution, showing lower (LL) and upper (UL) bound mean estimates.

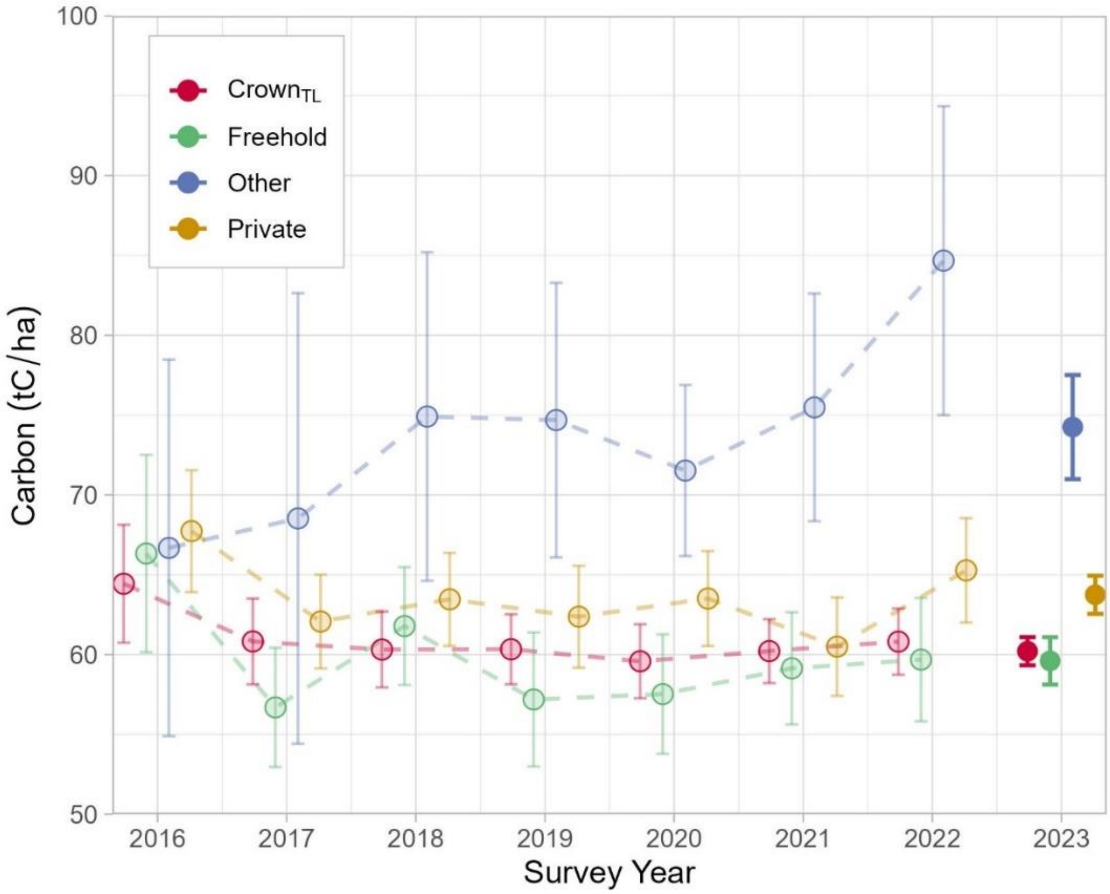

Figure 3.2. Mean C (tC/ha) and 90% confidence interval estimates by survey year (hollow points, at time of survey; *n*=8,990) broken out by landowner group, and the 2023 projected mean C estimate from all forestland plots with tree growth and disturbance simulated (bold, *n*=8,990).

Overall, the projected 2023 C values by landowner group align with the trends defined by the mean C at the time of survey (Fig. 3.2). The Crown$_{TL}$ plots demonstrate the least variability in mean C from 2016-2022. Private land plots had consistently higher C than the Freehold and Crown$_{TL}$ plots, with a minimum difference of 0.2 tC/ha and 1.35 tC/ha between Crown$_{TL}$ and Private and Private and Freehold land respectively in 2021. The mean tC/ha derived from the 'Other' plots across survey years was higher than the estimates from the working forest, however, there was an average sample size of only 56 (±33) plots from 2016-2022. The increasing C trend was slightly positive (slope = 2.2 tC/ha/year from 2016-2022) but not statistically significant with 95% confidence with only 56 plot samples. It is possible that 2021-2022 plots resulted in higher estimates of C at random, as projected 2023 estimates across all plots showed no significant increase from previous years.

A two sample Kolmogorov–Smirnov (KS) test was used to determine which land ownership groups had different frequency distributions of CLI plots across C classes (Fig. 3.3) with 95% confidence. Private and Freehold were the only two land ownership groups to have no significant difference in the distribution of plots among C classes (*p*=0.3). When comparing the distribution of plots on $Crown_{TL}$ or Freehold or Private to 'Other' lands, 'Other' was always significantly different ($p \leq 0.001$) with a higher ratio of plots in higher C classes (Fig. 3.3). There was also significant difference between C class distributions on Crown vs. Freehold (*p*=0.001) and Crown vs. Private (*p*=0.005); however, these differences were visually less dramatic than to 'Other' lands (Fig. 3.3). Higher C/ha content for 'Other' land ownership types was expected due to a higher proportion of area conserved from harvest than other ownership types.

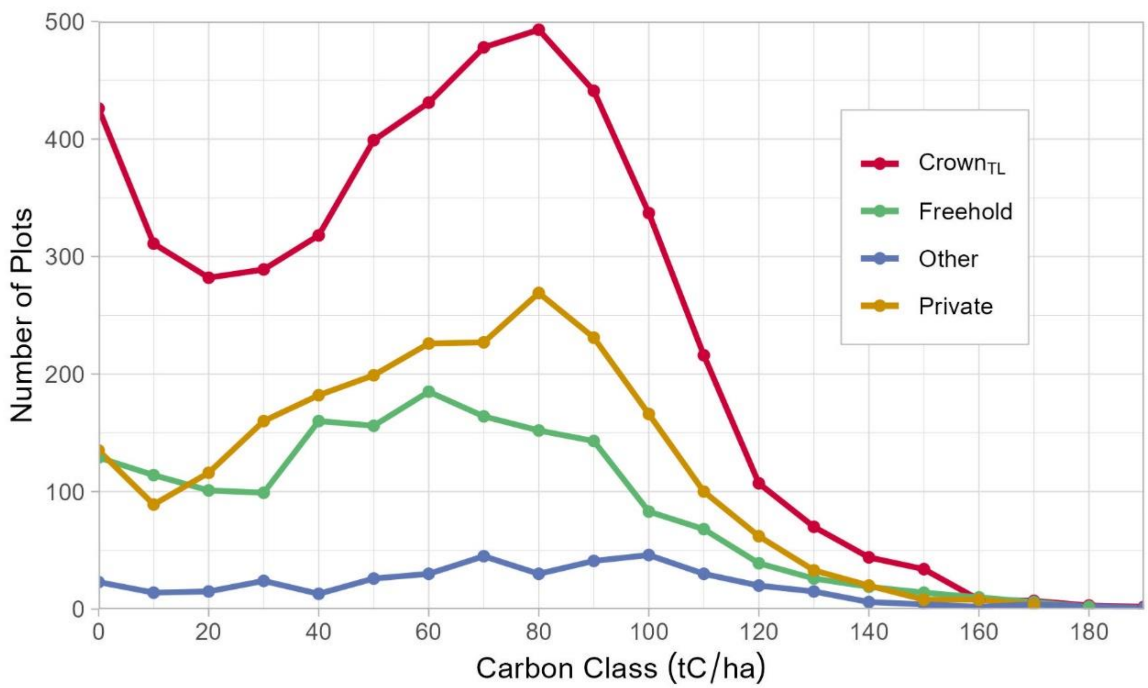

Figure 3.3 Number of plots by carbon class (tC/ha) according to land ownership group based on CLI plots from 2016-2022 (*n*=8,990). Land ownership group was determined using NB GIS.

3.2 CARBON ESTIMATES BY SURVEY YEAR

Carbon estimates across survey years, at time of survey (no growth projection), were relatively similar, within a range of 5.4 tC/ha (60.0 – 65.4 tC/ha; Fig. 3.4), and generally stable over time. The average mean forest C inventory estimate with no growth or disturbance projection (i.e., at the time of survey) was 61.6 tC/ha. In comparison, the 2023 projected C inventory with growth simulated and disturbances accounted for was also 61.6 tC/ha (Fig. 3.4).

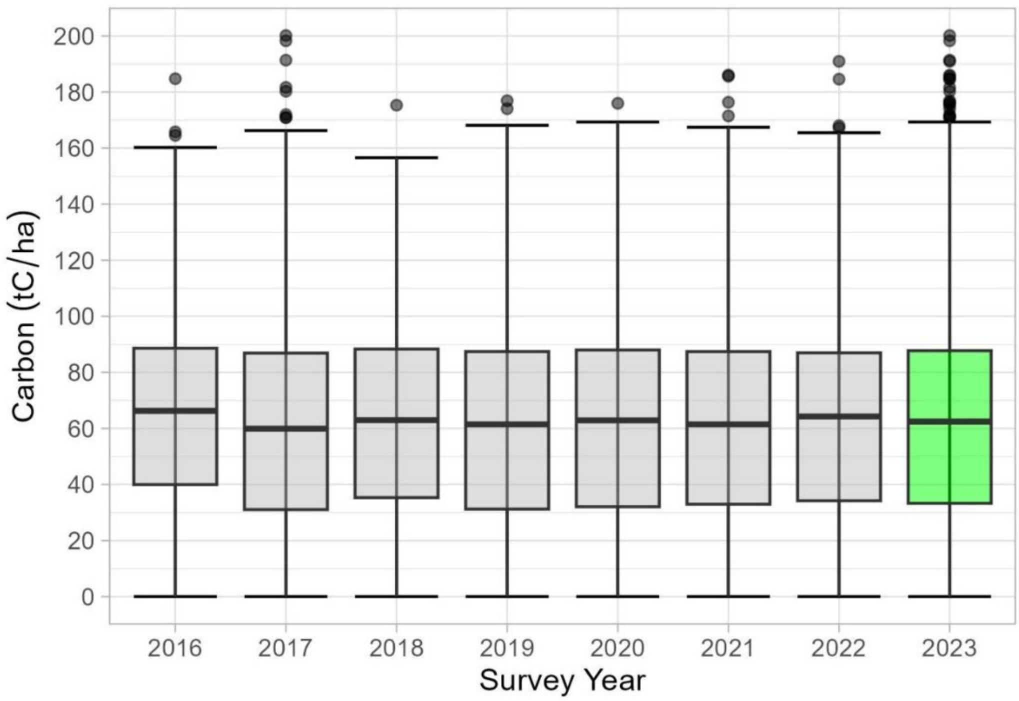

Figure 3.4 Mean C (tC/ha) estimate by survey year (at time of survey; *n*=8,990), and the 2023 projected mean C estimate with projected tree growth and observed disturbances considered (green, *n*=8,990).

Table 3.2 Descriptive statistics for the projected estimates of 2023 carbon (tC/ha) stores aboveground in living stems ≥ 1 cm DBH by survey year.

Survey Year	No. Plots	Mean	Median	Maximum	Standard Error	Confidence Interval (90%) [LL, UL]*	Uncertainty (%)
2016	617	65.4	68.0	161.4	1.47	[63.0, 67.8]	3.7
2017	1283	60.0	59.6	191.4	1.06	[58.2, 61.7]	2.9
2018	1323	61.6	63.1	167.7	0.99	[60.0, 63.3]	2.6
2019	1361	60.5	61.7	172.5	1.00	[58.9, 62.2]	2.7
2020	1438	61.4	63.9	169.0	0.96	[59.8, 63.0]	2.6
2021	1585	61.5	63.1	184.8	0.89	[60.0, 63.0]	2.4
2022	1383	62.7	65.3	191.0	0.97	[61.1, 64.3]	2.6
Total	8990	61.6	63.2	191.4	0.38	[61.0, 62.2]	1.0

* 90% confidence interval calculated from a two-tailed probability distribution, showing lower (LL) and upper (UL) bound mean estimates.

The 2023 projected forest C estimates had a maximum range of 6.4 tC/ha, from 60.0 tC/ha projected from 2017 plots to 65.4 tC/ha projected from 2016 plots (Table 3.2). When comparing the C inventory at the time of survey to the projected 2023 C values, the difference of the greatest magnitude was observed in the 2021 plots, where the mean carbon from 2021 plots was 0.8 tC/ha higher than 2023 projected. Across all plots, there was an average increase of 0.01 tC/ha (±14.3) in C at the time of survey and the projected 2023 C inventory values.

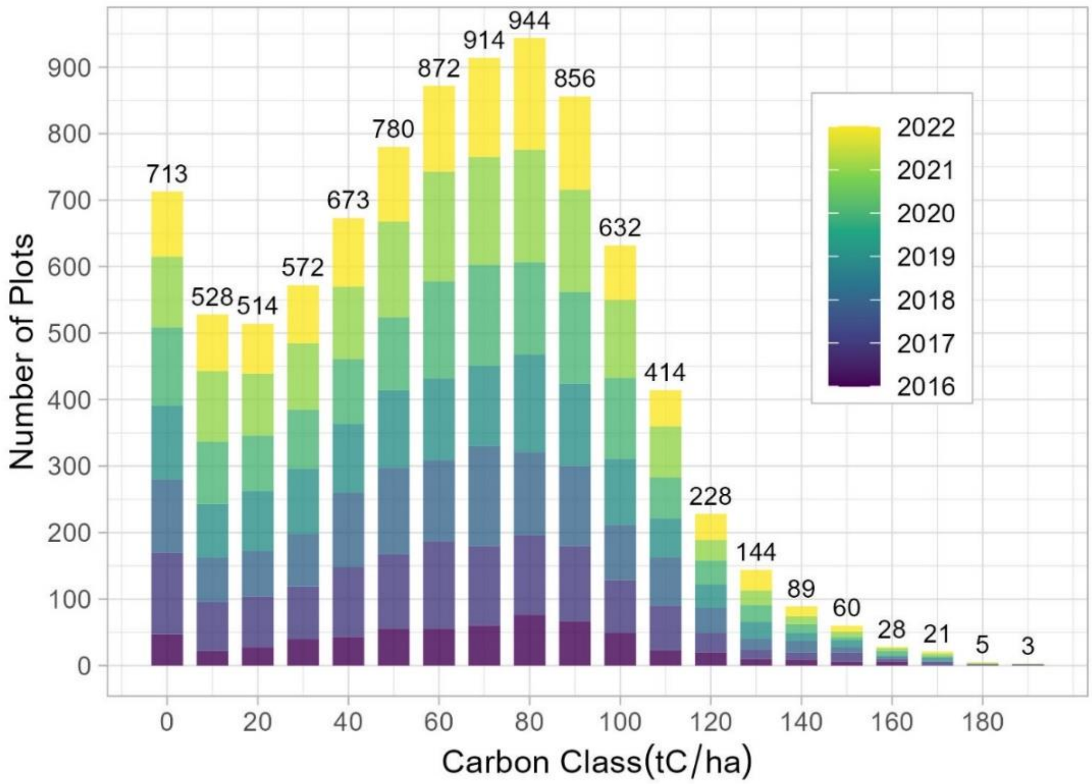

Figure 3.. Number of plots by carbon class (tC/ha) according to CLI plot survey year (*n*=8990).

The number of eligible plots surveyed increased by 108% between 2016 and 2017, caused by the initial 'ramp up' of the CLI program in 2016; however, the sample size remained consistent around or above 1,300 plots in years following 2016. There was an even distribution of plots per survey year across carbon classes (Fig. 3.5), which was expected based on the systematic sample design with random clusters of plots sampled by inventory map sheet in each year.

3.3 CARBON ESTIMATES BY HEIGHT CLASS

As expected, the C inventory for NB forestland in 2023 was positively and strongly correlated (r = 0.831) with 'Lorey's height', which is calculated by averaging tree heights weighted by tree size (basal area), for all trees ≥ 1 cm DBH within each plot. Lorey's height classes 9 – 18 m contained 78% of eligible plots (Fig. 3.6). The two outlying plots in the 27 m and 30 m height classes in Figure 3.6 had tree lists that were predominantly made up of smaller trees with a few large, veteran white pine trees. Similar forest conditions, having a single or a few large trees, explain low C/ha outliers in most height classes in Figure 3.6.

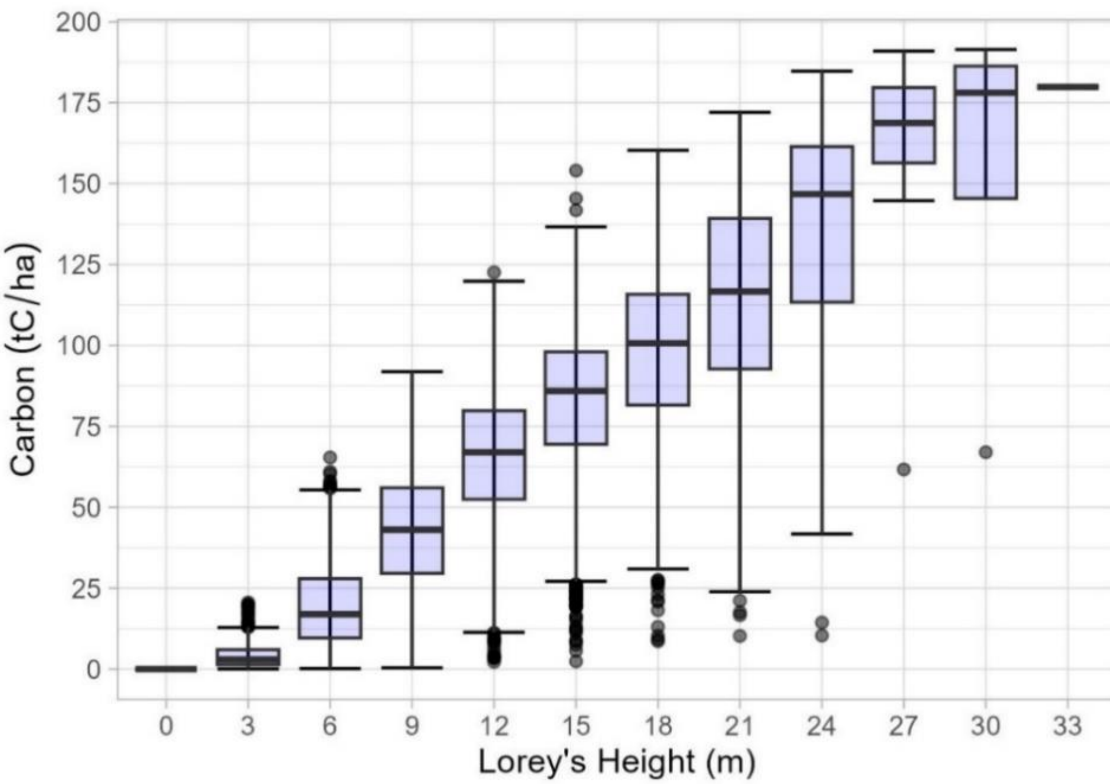

Figure 3.5 Mean forest C (tC/ha) estimates for 2023 by Lorey's height class (m) (*n*=8,990). Boxes represent the height range between the first and third quartile, horizontal bars represent the minimum, median, and maximum heights per Lorey's height class in ascending vertical order.

Lorey's height is a common forest inventory metric predicted across NB's forests from LiDAR scans (Light Detection and Ranging) that could be used in combination with other LiDAR-derived inventory variables or satellite imagery to develop estimates of forest C on smaller tracts of land that lack ground surveys, or for mapping forest C across all lands and over time.

3.4 CARBON ESTIMATES BY AGE CLASS AND STAND ORIGIN

Carbon stores and the rate of carbon sequestration are known to be a function of stand age and origin (Neilson et al., 2007). Stand origin types discussed here were limited to regeneration silviculture following clearcut (None, PCT, and Planted), where stand age can be confidently calculated from time of clearcut harvest and annual silviculture records on $Crown_{TL}$ lands.

The projected forest C in 2023 on $Crown_{TL}$ land increased as age increased, as expected, while rate of sequestration, or rate of C stock change, peaked between age 20 and 30 (Table 3.3). This was true across all origin types. Forest C by age class 40 in CC-PLT, CC-PCT, and CC-None plots averaged 68.4, 70.5, and 58.4 tC/ha respectively.

The 30-year age class is the only point at which planted stands had the greatest C estimate (56.1 tC/ha) compared to the other origin types; however, 30-year and older plantations in NB are made up of mostly slow growing black spruce (*Picea mariana*) with no genetic tree improvement. Black spruce was planted frequently in NB in the 1980s and 1990s due to its resistance to spruce budworm. Today, faster growing white spruce (*Picea glauca*) is planted most often and planted stock has been genetically improved for faster growth through tree breeding over two generations of seed orchards.

Table 3.3 Number of CLI plots and mean forest carbon per hectare (tC/ha) in 2023 by origin type and age class on Crown Timber Licensed land, excluding poor-quality sites and height outliers.

	Clearcut Regeneration Origin*							
	CC-PLT		CC-PCT		CC-None		All	
Age Class†	No. Plots	Mean	No. Plots	Mean	No. Plots	Mean	No. Plots	Mean
0	54	0.8	0	0	95	4	150	2.9
10	174	6.8	0	0	220	12.9	394	10.2
20	173	25.7	136	29.7	175	30.7	484	28.6
30	105	57.1	224	52.5	80	53.9	409	54
40	140	68.4	264	70.5	50	58.4	454	68.5
Total	646	32.9	624	55.2	620	25.5	1891	37.8

* CC-PLT – Clearcut and planted, CC-PCT – clearcut and pre-commercially thinned, CC-None – Clearcut with no additional silviculture, All – all clearcut areas with an age.

† Age class was defined based on recorded treatment history from New Brunswick's inventory records.

For age classes 0 - 20, CC-None stands possessed the greatest C estimates, compared to CC-PCT and CC-PLT. CC-PCT treatments generally occur at about age

12-14 in NB, so no CC-PCT area was present in the 0 and 10 age classes. On $Crown_{TL}$ land, CC-PLT and CC-PCT experience tree density reduction treatments shortly-after stand establishment. For CC-PLT, one or two applications of herbicide occur at around ages 2-4 and about 50% of plantations require manual vegetation cleaning at age 10. For CC-PCT, natural regeneration thinning to 1800-2200 crop trees/ha occurs at age 12-14. Given these vegetation management interventions, it is not unreasonable to see reduced levels of C at age 20 among managed regenerating types.

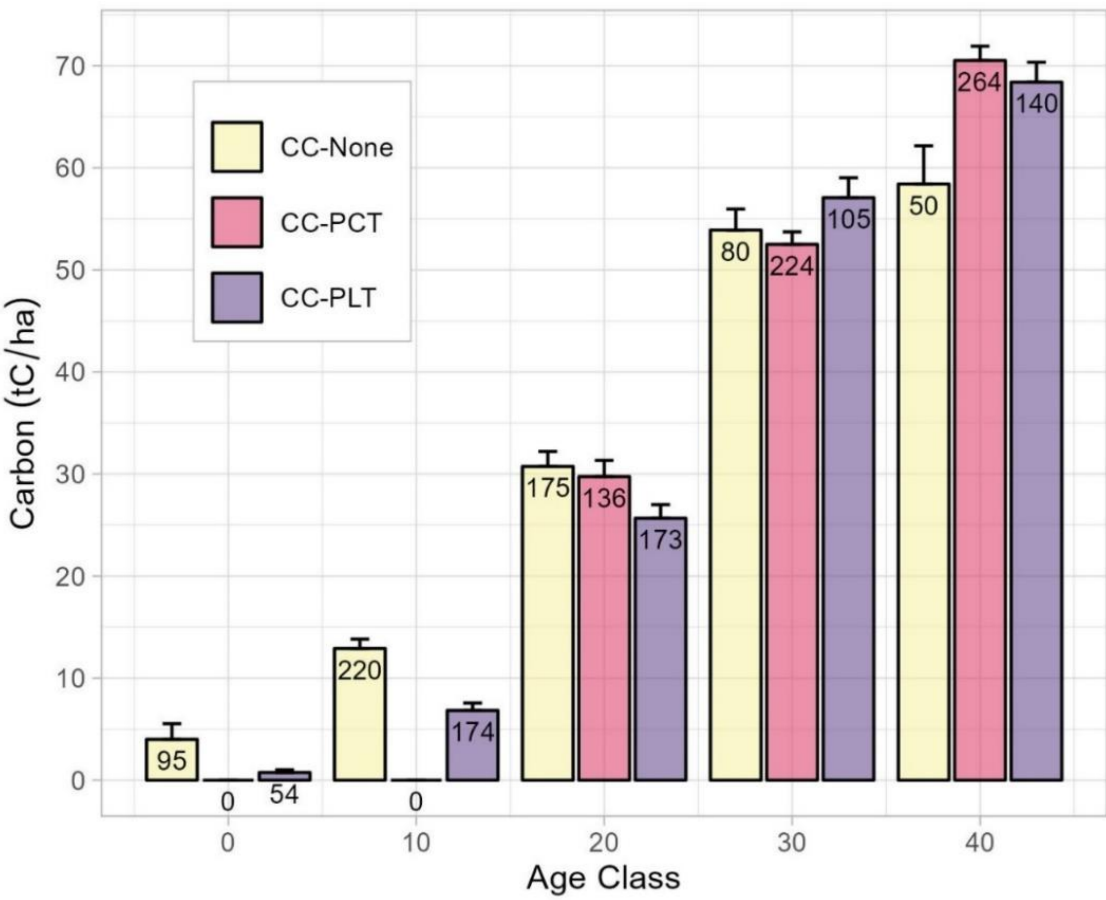

Figure 3.6 Mean carbon (tC/ha) by stand age class and origin type for plots on $Crown_{TL}$ land, excluding poor-quality sites and plots where Lorey's height is greater than or equal to the 90th percentile (*n*=1,891). Data labels correspond to sample size.

Commercial thinning of softwood CC-PCT and CC-PLT types typically occurs at ages 20-30. Commercial thinning of hardwood is rare but does occur occasionally at about 25-35 years old. Approximately 5% of CC-PLT and 1% of CC-PCT plots older than age 19 had been commercially thinned by the end of 2022. Rates of commercial thinning are expected to increase in the future, especially for faster growing white spruce and Norway spruce (*Picea abies*) plantations that have become more frequently planted over slower growing black spruce and jack pine (*Pinus banksiana*). As age increases to 40-years-old, planted and thinned plot average C per hectare surpassed naturally regenerating (Fig. 3.7).

Some NB historical context regarding silviculture program changes from the 1980s to present is important to know to interpret these results relative to today's expected silviculture outcomes. Of note is that these 30 and 40-year-old CC-PCT stands in 2023 may be up to 10 years older than stated in Figure 3.7, as actual age of clearcut is often unknown for these older CC-PCTs, which were likely conducted closer to age 15 to 25 in the large 1990s PCT programs. Post-harvest residual live trees (10-20 cm) were common in these PCTs. Today, PCT is typically performed at age 12-14 in more even-aged conditions and the growth response from thinning at earlier ages has improved significantly compared to older CC-PCTs that are on the landbase today. Major changes to plantation management have also occurred from the 1990s to present, including, tree improvement through breeding faster growing trees, better site selection, better management of herbaceous competition, and use of faster growing white and Norway spruce over black spruce. It is likely that these plantation management improvements will result in a larger C stock in plantations by age 40. On the other hand, natural regeneration in recent harvested cutovers tend to be more delayed compared to cutovers in the 1990s, due to large brush mats, less soil disturbance resulting from single-grip harvesters, and higher proportions of non-commercial hardwood species making up the species growing on the site.

4 Conclusions

This report provides the most statistically accurate estimates of live tree forestland C inventory for the province of NB to date, due largely to the wealth of ground survey information recently collected through the CLI program administered by the NB DNRED. Provincially, the mean C estimate for forestland was 61.8 tC/ha in 2023 with only 1% sampling error. This translates to 377 (± 3.9) million tonnes of C stored across all 6.12 million ha of NB forestland in only the live tree component of forests; i.e., excluding deadwood and soil organic matter C. In terms, of carbon dioxide equivalent gas weight, this equates to 1.382 billion tonnes of CO_2, or 100 times the total provincial greenhouse gas emissions in NB in 2020.

Carbon stocks from 2016-2023 were generally stable (error in annual estimates greater than year over year change) on Freehold, Private, and Crown_{TL} lands, and probably increasing on 'Other' lands for this survey period. Crown and Freehold forestlands had about the same amount of C per hectare in 2023 at about 60 tC/ha, and slightly higher for Private lands at about 64 tC/ha. 'Other' lands had significantly more C than the other three land ownership groups at about 74 tC/ha, which was expected because of much higher proportions of land conserved from industrial harvesting.

The 2023 Forest Carbon Inventory Report offers many benefits to parallel agencies and private citizens of NB. The level of statistical robustness that is central to this report means that it could be used in the calibration or validation of forest carbon models developed by the federal government for national greenhouse gas reporting and other public or private organizations that want to better understand C stocks and recent forestland C changes. This report could serve as an example for small, private woodlot owners who wish to learn more about the state of forest carbon in NB or begin to investigate carbon on their own property, and how to go about calculating it. Considering the prevalence of family woodlots in NB, providing a 'template' that managers of small woodlots could adhere to begin their own carbon inventory could provide significant benefits at the individual and community levels.

The NB Forest Carbon Reporting project is not anticipated to end with this publication. Work under this Climate Change Action Plan project is expected to continue in 2024 to additionally account for the carbon in coarse woody debris, standing deadwood, soil organic matter, and harvested wood products. In 2025-2026, forest C estimates will be projected backwards to gain a better picture of the historical forest C trends and then C estimates are to be projected forwards under alternative forest management scenarios to identify important GHG trade-offs associated with not only forest management but also alternative forest product end-uses and the energy sector.

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Glossary and Acronyms

BAF	Basal area factor
C	Carbon
CC	Clearcut harvest treatment
CCAP	Climate change action plan
CLI	Continuous land inventory
CO_2	Carbon dioxide
CT	Commercial thinning silvicultural treatment
DBH	Diameter at breast height (1.3 m)
DELG	Department of Environment and Local Government
DNRED	Department of Natural Resources and Energy Development
ECCC	Environment and Climate Change Canada (department)
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic information system
GPS	Global positioning system
ha	Hectare
k	Thousand
LiDAR	Light detection and ranging
M	Million
NB	New Brunswick
OSM-ACD	Open Stand Model: Acadian Variant software
PC	Partial cut harvest treatment
PCT	Pre-commercial thinning silvicultural treatment
PLT	Planting silvicultural treatment
SE	Standard error
tC	Tonnes of carbon
tC/ha	Tonnes of carbon per hectare