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# Developing and Field Testing a Tool Designed to Operationalize a Multitreatment Approach in Hardwood-Dominated Stands in Eastern Canada

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**Abstract:** Variations in species composition, diameter and height distributions, and quality make the management of hardwood-dominated stands difficult, particularly when considering mechanized forest operations. This study aimed to develop and field test a tool designed to improve the feasibility of forest operations in heterogeneous forest stands in Eastern Canada. To address inherent stand variability, a multitreatment approach was selected using conventional forest inventory (one inventory plot per hectare) and a silvicultural treatment decision key as main inputs. The Excel-based spreadsheet in combination with an ArcGIS model, referred to as the Multitreatment Planning Tool (MTPT), allowed to build operational maps identifying the type and spatial extent of silvicultural treatments to be performed. Once uploaded to positioning systems in harvesting machines, the operators were provided guidance on the silvicultural treatment to be performed and the location of the suggested machine trails. Field results obtained from nine harvest blocks (over 300 ha treated in total) showed the potential of using the MTPT until more mature and higher resolution-enhanced inventories become mainstream. Machine operators and operational managers both appreciated the straightforward and flexible method. Additional testing and refinement of the method is necessary, particularly when considering re-entry scheduling.

**Keywords:** stand variability; mechanized harvesting; machine-operating trails; decision support system; multitreatment

## 1. Introduction

In eastern North America, the Acadian Forest region, also known as the New-England/Acadian region, is a prominent ecosystem and encompasses most of the Canadian Maritime provinces, areas of southern Quebec, as well as parts of the northern New England states [1–3]. The hardwood-dominated portion of the Acadian forest is of great importance as it provides not only critical ecosystem services but also traditional and nontraditional consumable products. Much of the hardwood-dominated stands of the Acadian Forest region are considered commercial forests. Whether on public or private lands, they are the subject of silvicultural treatments and harvesting operations to extract goods and products for human consumption. They are complex and highly variable in structure because of natural gap disturbances, past forest-management practices, and forest health issues [4,5].

Silvicultural treatments are not detailed enough to take into account stand variability. Often, there is incoherence between stand characteristics within a harvest block and the intended silvicultural treatment and objectives prescribed for that block [6,7]. There is great variation in species composition, stem density, diameter distribution, quality, composition, and density of regeneration [8–11]. Moreover, harvest blocks are often an amalgamation of already heterogeneous stands into larger operating units designed for reasons other than implementing silviculture. In the commercial forest, this rather coarse stand delineation is challenging for forest managers and many practitioners are advocating the need to design new silviculture regimes that are better suited to current forest conditions or produce inventories at a different scale [12–15].

But recently, the definition of a forest stand is gradually changing from being a discrete entity (polygons in GIS) created by following strict amalgamation rules for general characteristics to being inspired by rapidly evolving remote-sensing technology such as LiDAR, where the stratification of selected features for stand determination is done at a much finer scale than those based on photointerpretation approaches, such as by Alam et al. [16]. Stands are now created based on purpose (selection of harvest system, prediction of products, precise silviculture treatment determination, etc.) and tend to be fractions of hectares in size (called microstands, forels, pixels, cells, etc.).

The implications of this paradigm shift for silviculture are important because from now on, treatments can be applied at a very fine scale rather than through broad prescriptions for large heterogeneous parcels [17,18]. In eastern Canada, applied researchers have been designing processes such as the 1-2-3 method to allow operators of harvesting machines to adapt on-the-fly as they progress through the harvest block [19,20]. The method relies on simple instructions for operators, a controlled trail pattern within the forest stand and mechanisms for the live monitoring of results. Despite these advantages, the 1-2-3 method has a drawback since the entirety of the harvest blocks needs to be tracked by machines because there is no preidentification of areas within a harvest block that could be deemed out-of-bounds (not sufficient standing volume). Because of these advancements, large heterogeneous areas that were previously treated by a single prescription could now become a combination of micro-clearcuts (groups) and single-tree selection in the remaining matrix and all variants in between.

In the Province of New Brunswick, Canada, the adoption of a process to use nonparametric models, leveraging ground-calibration plots, and aerial LiDAR scans to impute inventory variables at the 20 m $\times$ 20 m cell level is changing the way foresters visualize forest stands [21]. Called enhanced forest inventories (EFI), the variables produced include single-tree averages (diameters, heights, volumes, quality, etc.) but also microstand metrics like gross merchantable volume, basal area, product distributions, and vigour. The ability to stratify forested areas into finer units that are customized according to the criteria of the user has great consequences on how we perceive silviculture systems and "irregular" treatments in heterogeneous forests. With the recent ability to focus on microstands as small as 400 m$^2$, it is now possible to simplify and to provide operators with specific instructions that could in theory, change for every 400 m$^2$ cell. Once the forest metrics are derived for each cell, an associated harvesting prioritization (pecking-order) can be developed for each microstand.

This study was meant to design a process for changing silviculture prescriptions on a small spatial scale (potentially every 100 m) for integration with new automated approaches when EFI becomes more mature. Our specific research objectives were as follows:

(i) Develop a Decision Support System (DSS) script to process field forest inventory and suggest silvicultural treatments based on a hardwood-treatment decision key created within the scope of the project.
(ii) Develop an ArcGIS model to spatialize the suggested silvicultural treatments according to harvest block perimeter.
(iii) Field-test the applicability of variable silvicultural treatments in fully-mechanized and semimechanized harvesting operations performed in hardwood-dominated forests.
(iv) Compare performance metrics obtained with the MTPT approach to those gathered from the status quo (SQ) single-tree selection that would normally be applied.

## 2. Materials and Methods

### 2.1. Description of the Multitreatment Planning Tool (MTPT)

The MTPT was developed to assist forest planners in managing and operationalizing harvesting operations performed in complex uneven-aged mixedwood or hardwood stands in the province of New Brunswick, Canada. It is a new tool to address the inherent variability of these complex stands; the aim of the MTPT is to allow the possibility of alternating between different silvicultural treatments on a relatively small spatial scale. The resolution of the silvicultural treatments is dependent on the field inventory sampling scale. In addition to silvicultural treatments (shelterwood first pass, shelterwood second pass, single-tree selection cut, clearcut), wait areas (WA) (no harvest or machine traffic allowed) can also be suggested in areas where desirable species are found but with a low basal area. In the context of this study and the current market conditions, desirable species were considered to be sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britt.). By focusing harvesting operations and associated machine traffic in areas where sufficient wood volume is available and by permitting different treatments (so-called multitreatment) within a harvest block, the MTPT strives to provide a more tailored operation, i.e., performing the required silvicultural treatment where needed while considering stand properties. The MTPT is composed of two separate models: MTPT silvicultural treatment script and a spatial delineator tool.

#### 2.1.1. Silvicultural Treatment Script

The MTPT silvicultural treatment script is an Excel-based spreadsheet designed in Visual Basic Applications. It is composed of 6 distinct sections in addition to an execute command. Key information for each of the main sections is presented in Table 1. Once all relevant information collected during field inventory has been imported in the Excel-based spreadsheet, the user activates the execute command to run the program where the conditions of each inventory plot are processed through the decision key to ultimately provide a suggested silvicultural treatment for that specific inventory plot. The spreadsheet allows the users to modify thresholds of each decision point (eligibility criteria) in the hardwood decision key to better reflect their management and operational goals.

**Table 1.** Key input and output variables within the Multitreatment Planning Tool (MTPT) Excel spreadsheet.

| Level | Group | Key Information Required or Presented |
|---|---|---|
| Input | Inventory information | Size of plots (trees and regeneration), basal area prism factor, tree species code |
| | Stand table | Tree list by plot with species, dbh, form, and risk factors |
| | Regeneration | Number of acceptable regeneration stems by plot [a] |
| Decision key | Silvicultural treatment decision key | Macro-based decision key that considers: basal area, species composition, dbh, quality of merchantable trees, state of regeneration |
| Output | Suggested treatments | Silvicultural treatment suggested per inventory plot along with answers of each decision point used in the decision key |
| | Summary sheet | Key biometrics per silvicultural treatment |

[a] In this context, acceptable species were sugar maple and yellow birch.

#### 2.1.2. Spatial Delineator Tool

Silvicultural treatments suggested by the MTPT script needed to be spatialized into polygons, while respecting the boundaries of the harvest block to provide meaningful operational maps. This procedure was achieved through the development of an ArcMap Model builder tool using the Python programming language [22]. The model requires only 3 inputs: spatial location of inventory plots, output of the Excel MTPT script identifying the silvicultural treatment to be performed for each inventory plot, and the perimeter of the harvest block. The delineation of polygons indicating a respective silvicultural treatment is based on the known nearest neighbors (k-NN) algorithm [23], thereby creating polygons of varying sizes according to pattern recognition. The model automatically agglomerates contiguous polygons with the same silvicultural treatment. Manual override of certain silvicultural treatments is possible if needed. The output of the delineator tool is a map comprised of a mosaic of color-coded polygons indicating the spatial extent and type of silvicultural treatments to be performed.

#### 2.1.3. Design of Machine-Operating Trails

To facilitate the traffic of harvesting machines, a network of machine-operating trails was designed for each harvest block, while considering terrain topography, existing infrastructure (location and condition), as well as the harvesting system to be employed. This was of particular interest because of the presence of WA and since the operations were generally the first entry. It is common practice in New Brunswick, Canada to create new machine-operating trails during re-entry within a harvest block. The proposed network was designed in ArcGIS and incorporated directly into operational maps that could then be uploaded to onboard positioning and navigation systems of harvesting machines. Average trail spacing between proposed adjacent centerlines was 22 m.

### *2.2. Field Testing*

#### 2.2.1. Site Selection and Description

According to the Forest Management Manual for New Brunswick Crown Land [24], eligibility criteria for hardwood management were the following: a stand of more than 5 ha in size with a minimum density of 200 quality stems/ha, and a pretreatment stand basal area greater than 20 $m^2$/ha with a share of quality stems greater than 40% (i.e., 8 $m^2$/ha). In this context, a quality stem is considered to contain or have the potential to contain a log 2.6 m or greater in length and have a dbh greater or equal to 10 cm. All harvest operations occurred in the province of New Brunswick, Canada between August 2013 and March 2014. In total, 9 hardwood-dominated stands (5 blocks on Crown; public land and 4 on private industrial freehold) deemed appropriate for hardwood management were selected for the study (Figure 1). The stands were located between 46°55′ N–47°55′ N and 67°15′ W–68°30′ W.

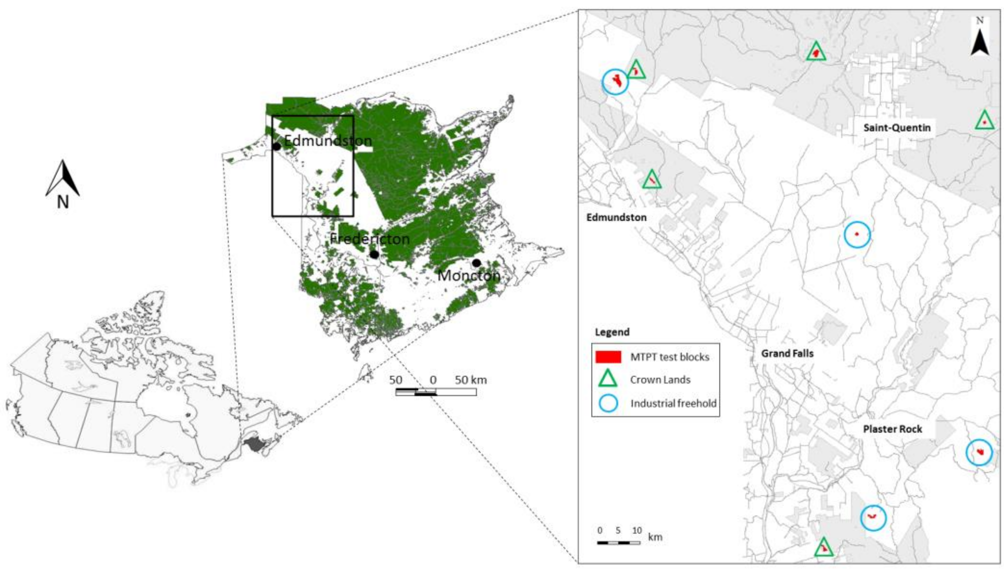


**Figure 1.** Location of the MTPT test sites located in Northwestern New Brunswick, Canada. Green color in the middle map indicates public-forest lands.

2.2.2. Plot Layout and Field Sampling

Pretreatment tree and stand information in each block was obtained using a 100 m by 100 m grid of variable-radius plots using a 2 $m^2$/ha basal area factor angle gauge. All trees selected with the angle gauge were numbered with paint and their diameter at breast height (dbh) tallied in 2 cm classes. A 10 $m^2$/ha basal area factor angle gauge was also used to select trees for height measurements, which was done with a digital height, distance, and inclination instrument. Species, tree form and vigor class [25], and sawlog potential [26] were also tallied. To estimate the quality of the standing trees, the acceptable/unacceptable growing stock (AGS and UGS) method was used with tree species, tree form, and risk of losing vigor employed as evaluation criteria [25]. Density of regeneration by species was evaluated at each plot using a 1.26 m radius subplot (5 $m^2$). Each plot was revisited postharvest to determine which trees had been removed and to ensure that the right prescription had been applied.

2.2.3. Description of Silvicultural Treatments and Eligibility Criteria for MTPT

During the MTPT trials, a total of 5 silvicultural treatments could be performed, including the WA. The silvicultural-treatment decision key along with the eligibility criteria used are presented in Figure 2 and a brief description of the silvicultural treatments along with the target basal area and operator instructions are provided in Table 2. To better address stand variability, the target basal areas were rather soft targets, thus allowing more flexibility for the operators based on actual stand conditions encountered during field operations.

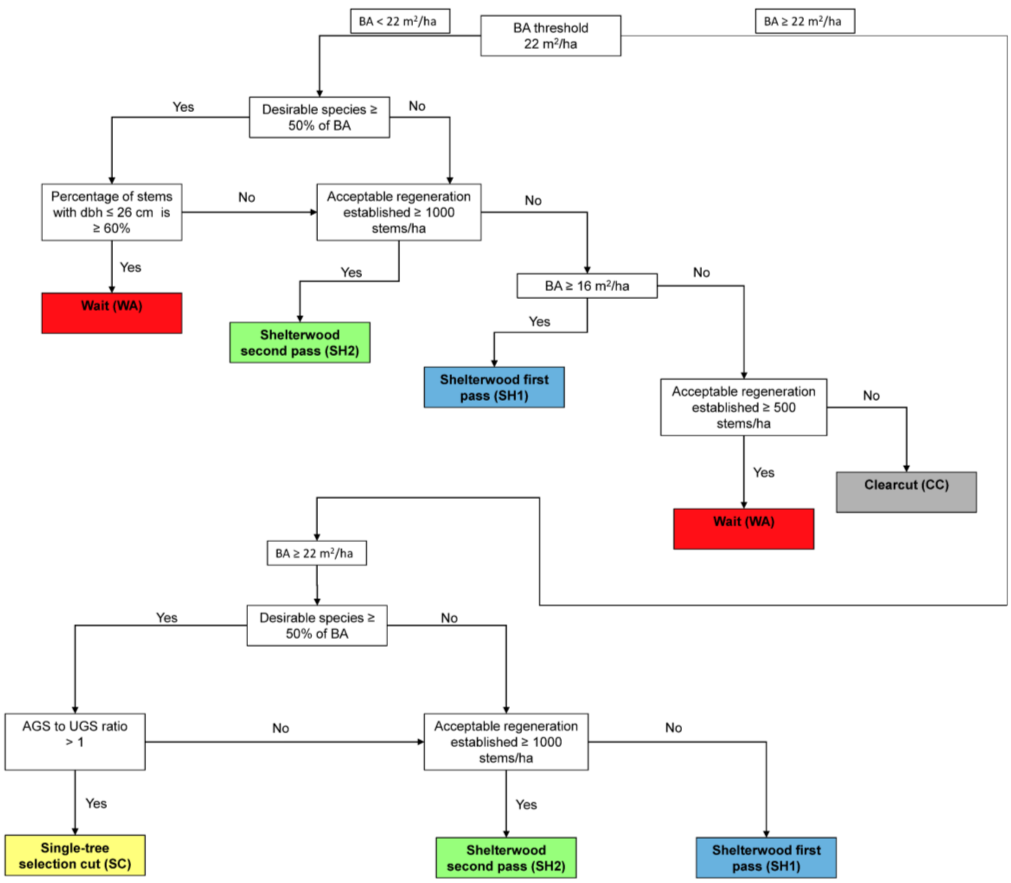


**Figure 2.** Silvicultural treatment decision key with criteria eligibility. The decision key was produced to meet the objectives of the MTPT project and should not be used outside this scope. BA = basal area; desirable species are sugar maple and yellow birch.

**Table 2.** Description of the silvicultural treatments used in the MTPT.

| Treatment (Code) | Brief Description | Target Basal Area | Instructions to Harvester or Chainsaw Operator |
|---|---|---|---|
| Single-tree selection cut (SC) | Improve stand quality by uniformly removing no more than one third of the basal area in all diameter classes | Try to maintain between 16 and 18 $m^2$/ha | Remove:<br>1. Any trees showing signs of dieback which will not be living or lose value in 10 years<br>2. Balsam fir ≥18 cm<br>3. Beech<br>4. Stems with no potential for high grade products<br>5. Intolerant hardwoods<br>6. Other softwood ≥30 cm<br>7. All trees ≥50 cm |
| Shelterwood first pass (SH1) | Rejuvenate stand by establishing a new regeneration cohort in multiple entries | Maximum removal should be 30% of basal area while attempting to leave between 12 and 16 $m^2$/ha | 1. Remove mature trees and leave most pole-size (10–22 cm) trees<br>2. Target unstable and sick trees first |
| Shelterwood second pass (SH2) | Release established regeneration | Not applicable | Remove all merchantable volume while leaving quality pole-size (10–22 cm) trees |
| Clearcut (CC) | Create a new stand | Not applicable | 1. Leave heritage trees †<br>2. Remove all merchantable volume (dbh ≥ 10 cm) |
| Wait (WA) | Good-quality stand but not ready to be harvested | Not applicable | Avoid entering the area |

Note: Information provided is only in reference to the objectives of this research project; † includes uncommon species for the area (pine, oaks, ironwood, black ash, hemlocks, etc.), very old individuals with longevity, historically significant trees (surveyor witness trees), and obvious wildlife trees (large cavities that are occupied and large stick nests).

In addition to the treatments listed above, the area treated with the MTPT method was also subjected to a simulation to estimate the outcomes that would have resulted if the harvest would have been performed as usual (i.e., SQ). Thus, the simulation served as a benchmark to assess the impact of the MTPT approach. The harvest blocks treated had all been previously identified for a single-tree selection cut under their respective management guidelines. The industrial freehold having guidelines that aimed at a more aggressive harvest than on public lands, a different set of assumptions were used for those blocks. The simulations were performed at the individual plot level in a spreadsheet using the following assumptions:

For the four blocks on industrial freehold

- Systematic removal of 30% of the trees, corresponding to 6 m-wide trails with a spacing between trails of 20 m.
- Maximum of 40% of basal area removal.
- Target residual basal area of 14 $m^2$/ha by removing in priority:
    - ○ Softwoods, largest dbh first.
    - ○ Intolerant hardwoods, largest dbh first.
    - ○ Tolerant hardwoods, lowest vigor first.

For the 5 blocks on public land:

- Systematic removal of 25% of the trees, corresponding to 5 m-wide trails with a spacing between trails of 20 m.
- Maximum of 30% of basal area removal.
- Target residual basal area of 16 $m^2$/ha by removing in priority:
    - Low-vigor trees
    - Softwoods, largest dbh first
    - Pulp-grade stems
    - Intolerant hardwoods, largest dbh first
    - Tolerant hardwoods, poor-form classes first according to Pelletier et al. [25]

#### 2.2.4. Harvesting Method and System

Two-thirds of the harvest blocks (6 of 9) were subjected to a full-tree harvesting method using a feller-buncher for felling trees and a grapple skidder for transporting the full trees to a landing near a forest road (Table 3). A single harvest block (4092802) located on public land applied the tree-length method and two blocks (409415A and 4097180) the cut-to-length method. Harvesting activities were mostly performed during fall and winter seasons and all harvesting machines were equipped with a navigation system to allow GPS tracking. Block numbers with a capital F prefix are located on industrial freehold land and the others on public land.

**Table 3.** Harvesting methods and systems per harvest block along with time of harvest.

| Block Number | Harvesting Method | Harvesting System | Time of Harvest |
|---|---|---|---|
| F985052 | Full-tree | Feller-buncher and grapple skidder | August 2013 |
| F985243 | Full-tree | Feller-buncher and grapple skidder | January 2014 |
| F989570 | Full-tree | Feller-buncher and grapple skidder | March 2014 |
| F981966 | Full-tree | Feller-buncher and grapple skidder | August 2013 |
| 4092300 | Full-tree | Feller-buncher and grapple skidder | October 2013 |
| 4092802 | Tree-length | Motor-manual and cable skidder | August 2013 |
| 409415A | Cut-to-length | Harvester and forwarder | September 2013 |
| 1096467 | Full-tree | Feller-buncher and grapple skidder | October 2013 |
| 4097180 | Cut-to-length | Harvester and forwarder | November 2013 |

### *2.3. Performance Metrics*

Beyond conventional operational metrics (basal area removed, harvested volume, etc.), two main indices were used to evaluate the operational performance of the MTPT method. First, the total area classified as WA was tallied per harvest block. Second, monitoring the amount of wood harvested per block (according to pre- and postharvest inventory) and relating the volume to the total length of machine-operating trails for a respective block allowed the calculation of a metric expressed as cubic meter harvested per linear meter of trail. Additionally, to estimate the quality of the standing trees, the AGS and UGS method was used with tree species, tree form, and risk of losing vigor employed as evaluation criteria [24].

## 3. Results

### *3.1. Preharvest Inventory*

A total of 320.7 ha was planned to be treated with the MTPT method with blocks ranging in size from 9.3 to 105.9 ha (Table 4). All analyses from this point forward will focus on inventory plots (278) that were deemed representative during the preinventory field work. A total of 2637 trees were inventoried and the average dbh varied between 25.3 cm in block F989570 to 35.8 cm in block 4097180, with an average of 31.7 cm for all blocks combined. Average tree heights were lowest for block 4097180

(15.7 m) and highest in block 4092300 (20.5 m). The ratio of AGS to UGS was lowest in block 4092802 (0.46:1) and highest in block F989570 (1.81:1). Overall, the proportions of AGS and UGS (1.08:1) were similar, thus indicating about a 50/50 split between AGS and UGS.

**Table 4.** Preharvest tree inventory. Average dbh and height are presented for each harvest block along with the ratio of acceptable to unacceptable growing stock (AGS/UGS).

| Block Number | Planned Area (ha) | Number of Inventory Plots † | Number of Trees Inventoried | Avg. Dbh (cm) (Standard Deviation) | Avg. Height (m) (Standard Deviation) | AGS to UGS Ratio |
|---|---|---|---|---|---|---|
| F985052 | 34.4 | 34 | 357 | 32.1 (14.1) | 18.4 (4.4) | 1.19:1 |
| F985243 | 18.0 | 17 | 143 | 35.3 (15.2) | 19.4 (3.4) | 1.51:1 |
| F989570 | 25.1 | 23 | 219 | 25.3 (9.0) | 16.7 (3.0) | 1.81:1 |
| F981966 | 105.9 | 104 | 993 | 32.5 (13.3) | 18.7 (3.4) | 1.19:1 |
| 4092300 | 26.8 | 16 | 140 | 34.3 (15.7) | 20.5 (4.5) | 1.12:1 |
| 4092802 | 9.3 | 10 | 101 | 26.7 (9.2) | 18.8 (3.6) | 0.46:1 |
| 409415A | 15.7 | 15 | 149 | 30.5 (13.1) | 18.3 (2.8) | 1.16:1 |
| 1096467 | 66.9 | 57 | 480 | 31.3 (13.5) | 19.5 (4.5) | 0.79:1 |
| 4097180 | 18.6 | 12 | 121 | 35.8 (16.8) | 15.7 (3.0) | 0.64:1 |
| Combined | 320.7 | 278 | 2703 | 31.7 (13.6) | 18.7 (3.9) | 1.08:1 |

† Reflects the number of plots deemed representative of the area based on visual observations made in the field by experienced foresters.

### 3.2. Silvicultural Treatments Performed

Most harvest blocks had a minimum of four silvicultural treatments applied (Table 5); treatments SH1 and SH2 combined for approximately 60% of all treated area, whereas SC contributed to about 20%. The remaining 20% was shared almost equally between the CC and WA treatments. WA areas were suggested in seven out of nine harvest blocks and ranged in size from 0.1 to 6.1 ha (total area within a harvest block). Average preharvest basal areas fluctuated between 15.6 $m^2$/ha in block F985243 and 21.2 $m^2$/ha in block 409415A. Following harvesting operations, basal areas with the MTPT method ranged from a low of 4.5 $m^2$/ha in block F9850582 to a high of 12.8 $m^2$/ha in block F989570 with an overall average of 9.4 $m^2$/ha for all blocks. Postharvest basal area of the simulated SQ showed less variation than with the MTPT method and was generally higher, with an overall average of 13.5 $m^2$/ha.

**Table 5.** Distribution of silvicultural treatments performed with the MTPT method and average pre- and postharvest basal area for both MTPT and status quo (SQ).

| Block Number | Treated Area (ha) | Distribution of Silvicultural Treatment (ha) (% of Treated Area) | | | | | Average Basal Area ($m^2$/ha) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SH1 | SH2 | SC | CC | WA | Pre Harvest | Post Harvest MTPT | Post Harvest SQ † |
| F985052 | 34.3 | 10.3 (30) | 8.6 (25) | 7.1 (21) | 8.4 (24) | 0 (0) | 20.1 | 4.5 | 13.3 |
| F985243 | 17.2 | 8.4 (47) | 3.6 (21) | 2.4 (14) | 3.6 (18) | 0.1 (<1) | 15.6 | 9.3 | 12.1 |
| F989570 | 21.9 | 4.9 (22) | 4.2 (19) | 6.8 (31) | 0 (0) | 6.1 (28) | 18.4 | 12.8 | 12.7 |
| F981966 | 104.5 | 37.6 (36) | 29.6 (28) | 24.2 (23) | 3.5 (4) | 9.7 (9) | 16.7 | 7.3 | 12.7 |
| 4092300 | 21.8 | 6.3 (29) | 7.4 (34) | 2.5 (11) | 2.0 (9) | 3.7 (17) | 17.8 | 10.7 | 13.1 |
| 4092802 | 9.3 | 5.6 (60) | 0 (0) | 0 (0) | 3.7 (40) | 0 (0) | 19.1 | 8.2 | 14.5 |
| 409415A | 13.2 | 7.1 (54) | 1.7 (13) | 2.6 (20) | 0.1 (1) | 1.6 (12) | 21.2 | 10.6 | 15.5 |
| 1096467 ‡ | 66.9 | 23.5 (35) | 16.2 (24) | 8.5 (13) | 12.6 (19) | 6.2 (9) | 16.5 | 11.9 | 12.6 |
| 4097180 | 18.6 | 6.8 (37) | 5.8 (31) | 3.4 (18) | 1.5 (8) | 1.1 (6) | 18.0 | 8.1 | 15 |
| **Sum** | 307.7 | 110.2 (36) | 77.0 (25) | 57.5 (19) | 34.8 (11) | 28.4 (9) | N/A | N/A | N/A |
| **Average** | 34.2 | 12.3 | 8.6 | 6.4 | 3.9 | 3.2 | 18.0 | 9.4 | 13.5 |

† Based on simulated single-tree selection cut silvicultural treatment for the entire treated area, ‡ planned and treated areas were assumed to be of equal size.

### 3.3. Harvested Volumes

According to field inventory, standing preharvest merchantable volumes ranged from 89.4 $m^3$/ha to 126.6 $m^3$/ha for blocks F985243 and F985052, respectively (Table 6). Removal rates, expressed in percent of preharvest merchantable volumes were again highly variable in the MTPT method and ranged from 28% to 81%, with a combined average of 50% for all blocks. Results from the SQ simulation varied between 26% and 36% removal rates for blocks 1096467 and F985052, respectively. Total volume harvested with the MTPT method varied between 552 to 6869 $m^3$ for blocks 409415A (13.2 ha) and F981966 (104.5 ha), respectively. The same trend could be observed with the simulated SQ results but with lower total harvested volume per block.

**Table 6.** Description of volumes (standing preharvest, postharvest, harvested) for the MTPT and SQ treatments.

| Block Number | Average Volume ($m^3$/ha) (% of Preharvest Volume) | | | | | Total Volume Harvested ($m^3$) | |
|---|---|---|---|---|---|---|---|
| | Preharvest | Postharvest MTPT | Harvested MTPT | Postharvest SQ | Harvested SQ | MTPT | SQ |
| F985052 | 126.6 | 24.1 | 102.5 (81) | 79.9 | 45.8 (36) | 3558 | 1571 |
| F985243 | 89.4 | 53.5 | 35.9 (40) | 70.7 | 33.4 (32) | 873 | 576 |
| F989570 | 105.2 | 68.9 | 36.3 (35) | 71.2 | 39.0 (35) | 764 | 856 |
| F981966 | 96.6 | 41.3 | 55.3 (57) | 72.6 | 39.1 (34) | 6869 | 4089 |
| 4092300 | 106.8 | 64.3 | 42.5 (40) | 78.3 | 28.2 (26) | 1045 | 616 |
| 4092802 | 108.5 | 42.6 | 65.9 (61) | 82.1 | 32.4 (28) | 586 | 301 |
| 409415A | 103.4 | 58.9 | 44.5 (43) | 88.3 | 34.3 (28) | 552 | 448 |
| 1096467 † | 94.3 | 67.5 | 26.8 (28) | 72.4 | 26.4 (26) | 2053 | 1767 |
| 4097180 | 94.0 | 39.2 | 57.8 (61) | 83.1 | 31.6 (27) | 1302 | 588 |
| **Average** | 102.8 | 49.5 | 51.9 (50) | 75.1 | 34.5 (30) | 1956 | 1201 |

### 3.4. Machine-Operating Trails

The density of machine-operating trails inside the harvest blocks with the MTPT ranged from a low of 291 m/ha in block F989570 to 474 m/ha in block F985052, with an overall weighted average (based on size of treated area) of 362 m/ha for all blocks combined (Table 7). Every harvest block that was assigned portions in WA area had lower trail density in the MTPT method than with the simulated SQ since the latter would theoretically require the entire harvest block to be travelled by machines, despite the conditions of the stand. When considering the volume harvested and reporting it in relation to the length of trails, MTPT results ranged from a low of 0.09 $m^3$/m of trail to 0.22 $m^3$/m of trail for blocks 1096467 and F985052, respectively. With the absence of WA areas and the possibility of performing small-scale clearcuts, the ensuing volume harvested per linear meter of trail decreased to a low of 0.07 $m^3$/m with the simulated SQ approach. Overall blocks, MTPT had an average of 0.16 $m^3$/m of trail and the simulated SQ has an average of 0.09 $m^3$/m of trail, thus equaling a 77% difference between treatments when considering the simulated SQ results as the benchmark.

The location of all machine-operating trails determined by machine GPS tracking is illustrated in Figure 3 along with the mosaic of the MTPT silvicultural treatments performed in the nine harvest blocks. The only harvest block that was not provided with a preharvest digitized trail network was 4092802 since these were conventional harvesting operations with the use of chainsaws and a cable skidder and were the first entry into the harvest area. Areas identified in red are the innovative WA areas where machine entry and harvesting activities were not permitted due to low standing volume.


**Figure 3.** Operational maps for all harvest blocks showing the type and spatial distribution of MTPT silvicultural treatments, and GPS positioning of the harvesting machines.

**Table 7.** Specifics on machine-operating trails and associated removal rates for the MTPT and SQ treatments.

| Block Number | MTPT | | | SQ | | |
|---|---|---|---|---|---|---|
| | Trail Length (m) | Trail Density (m/ha) | Volume Harvested Per Linear Meter of Trail ($m^3$/m of Trail) | Trail Length (m) | Trail Density (m/ha) | Volume Harvested Per Linear Meter of Trail ($m^3$/m of Trail) |
| F985052 | 16,267 | 474 | 0.22 | 16,267 | 474 | 0.10 |
| F985243 | 7320 | 425 | 0.12 | 7363 | 428 | 0.08 |
| F989570 | 6390 | 291 | 0.12 | 8165 | 373 | 0.10 |
| F981966 | 34,869 | 334 | 0.20 | 38,109 | 365 | 0.11 |
| 4092300 | 7393 | 339 | 0.14 | 8647 | 397 | 0.07 |
| 4092802 | 3057 | 329 | 0.19 | 3057 | 329 | 0.10 |
| 409415A | 5227 | 397 | 0.11 | 5862 | 444 | 0.08 |
| 1096467 † | 22,607 | 338 | 0.09 | 24,703 | 369 | 0.07 |
| 4097180 | 8080 | 435 | 0.16 | 8559 | 460 | 0.07 |
| Sum | 111,210 | N/A | N/A | 120,731 | N/A | N/A |
| **Average** | 12,357 | 362 ‡ | 0.16 ‡ | 13,415 | 392 ‡ | 0.09 ‡ |

† Trail length was extrapolated from GPS data obtained on approx. 30% of the treated area; ‡ weighted average according to size of treated area.

## 4. Discussion

### *4.1. Applicability of the MTPT*

The tool we developed is one of the first of its kind to spatially delineate silvicultural treatments on a small spatial scale, which are then fully integrated into the harvester's onboard computer. It allows real-time navigation using GIS shapefiles or derived outputs for equipment without GIS software (navigation GPS). The color-coded maps enable the operators to quickly identify the suggested silvicultural treatment to be performed. The scale of resolution is limited only with regards to the forest practitioner's choice of sampling intensity, which determines the cell size (in our case, one point per hectare).

Even where remote-sensing-based EFI are available, we find that the prediction of stand and tree variables in mixed and hardwood stands lag far behind that of managed pure forests. Until many improvements are made with EFI, the approach studied under this project can be very useful if field surveys are used to capture key inventory variables that will trigger prescription and/or appropriate harvesting systems.

Forest management professionals considering adopting a process such as the MTPT will not obtain full benefits unless considerable time is spent to redesign the logic behind determination keys for treatments as they were usually developed at a scale that was not as sensitive to forest operations as is now required.

### *4.2. Addressing Stand Variability Through Multitreatments*

Our analysis has not focused on the ability per se of the approach to capture variety in stand structure and species composition, but we are of the professional opinion that it represents a considerable improvement over the SQ, where a single treatment is assigned to an entire stand polygon (between 5 ha and 120 ha in size) derived from photointerpretation using broad classes and categories for key grouping parameters. We also believe the approach is widely applicable in heterogeneous northern hardwood and mixedwood stands, where tree marking is not employed and variable post-treatment conditions are allowed.

The selection of a minimum cell size is not a trivial exercise and is imbedded in the rationale for determining cell boundaries, defining criteria for stands/microstands, etc. Results indicate that postharvest basal area thresholds were not always maintained, both in the MTPT method and with the simulated SQ scenario. Allowing flexibility for adapting removal rates based on visual assessment during forest operations is necessary for two reasons: (1) the silvicultural treatments suggested by MTPT were based on field inventory performed at a scale of one plot per hectare and extrapolated the results from the individual variable-radius inventory plots to an area surrounding each plot; and (2) until EFI becomes more common, well-trained machine operators remain the best-suited individuals to make modifications to a harvest prescription since they have a close view of the entire harvest block. Nevertheless, certain harvest blocks in the study seemed to have been overharvested and a close supervision of live forest operations is warranted when using a variable treatment approach such as the MTPT. The considerable difference in cubic meters harvested per linear meter of trail between MTPT and the SQ is caused by the higher harvest rates in certain areas of the harvest blocks, via the permission to use a clearcut treatment, in combination with the preidentification of WA areas that did not permit machine traffic and associated harvesting activities. By concentrating machine traffic in areas deemed to have sufficient standing volume to warrant entry, more wood was harvested per linear meter of trail. This, in turn, can increase revenues of the operation by reducing unnecessary machine-tracking time, where both fuel and time are being consumed without any harvesting activities performed [27].

Feedback from planning foresters and machine operators were to the effect that the MTPT was much more agile at recognizing changes in stand conditions (sometime criticized as being too detailed). This observation was often additive to the realization that the variable sampling method and the low sampling intensity used in this project were rendering extrapolation of stand attributes between points difficult. Poor representation of the real stand conditions between sampling points might only be addressed with future advances in the production of enhanced forest inventories at the microstand level.

Such improvements could easily be made to the MTPT and should improve the sensitivity of the suggested treatments according to stand conditions. In some instances, suggested WA areas were not respected and machine movement occurred within the areas. For the most part, this happened out of necessity to access an area beyond the originally planned boundary of the harvest block and was not linked to comprehension issues. Nevertheless, daily monitoring of live forest operations is suggested.

### 4.3. Limitations and Possibilities for Improvement

The MTPT is not meant to optimize or produce a heuristic solution based on financial returns, value, or other operational criteria. Future versions of this tool should be developed with those considerations in mind and, at the minimum, perform cell amalgamation based on practical factors such as timing of re-entry for subsequent treatments. In some of the experimental blocks used in this study, we may have created situations where the required future treatments can be out of synchronization, thus further complicating re-entry scheduling. One technique that could be utilized is by combining larger areas and only assigning either even-aged or uneven-aged types of silvicultural treatments, but not alternate these regimes on a small spatial scale. For example, harvest treatments could be classified into groups (families) based on the timing of the next entry. In addition, identifying stands that can be assigned a second-best treatment alternative and/or a 'wait' designation might enable the development of a logic to better amalgamate cells into larger polygons that have similar future-treatment schedules without compromising the intent of the prescriptions.

The recent and rapid development of EFIs hold great promise. Cross-platform technology (point clouds and spectral imagery) may be the key to fully operationalize the concepts behind the MTPT [28–30]. It was designed at the outset with hopes that some day, remote sensing would be the engine behind the process.

Finally, much energy should be focused on the refinement of silviculture treatment determination logic, keys, and algorithms. We envision that a change of paradigm is needed so that we cease to deal with silviculture planning separate from operations planning as well as producing forest and stand inventory.

## 5. Conclusions

Against the background of significant variation in species composition, stem density, diameter distribution, quality, composition, and density of regeneration, a tool was designed and field-tested to facilitate the operational implementation of silvicultural treatments in hardwood-dominated stands in Eastern Canada. Due to these variations, frequent incoherencies are observed between tree and stand characteristics within a harvest block and the intended silvicultural treatment and associated objectives for that block. The developed MTPT attempted to address stand variability on a plot-by-plot (one plot per hectare) basis for altering silvicultural treatments. Results suggest that alternating between silvicultural treatments with the use of operational maps identifying the spatial boundary of each treatment and the location of machine-operating trails is promising, particularly when these maps are uploaded directly in the navigation system of harvesting machines. At the very least, the ability to map microstands to avoid nonoperable sections or areas where protection is needed is already a considerable improvement over the SQ. Until higher-accuracy enhanced forest inventories become less expensive, the low-cost MTPT method is one option to address stand variability within an operational context.

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