A new silvicultural approach to the management of uneven-aged Northern hardwoods: frequent low-intensity harvesting

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We report a new silvicultural approach that is well suited for the management of uneven-aged forests in which timber production is an important objective. The approach recognizes two main components in the stand, i.e. a fiber production component, which provides veneer/sawlog quality products from the high-quality trees (HQT), and an ecological component, which contributes to the overall ecosystem functioning through the lower value stems. The objective of the study was to verify if it is possible to sustainably harvest only HQT in northern hardwood (NH) and thereby produce a viable alternative to high-grading the stands. To do so, a simple stand growth simulator, based on empirical growth rates of HQT in Sugar Maple/Yellow Birch stands in southwestern Quebec, was combined with an optimization tool. The optimization parameters aimed to identify possible tree marking regimes (TMRs) under 10-year rotation partial cutting, which would ensure that the basal area of HQT was maintained for 40 years. Results suggest that sustainability is achievable starting from very different initial stand structures and the application of a wide range of alternative TMRs. We argue that this new approach is one way to apply emerging concepts in forest management, such as ecological integrity, attempts to emulate natural disturbance regimes and provides new possibilities managing for resilience and for adaptation to climate change.

Introduction

In eastern North America, as is the case in many parts of the world, forest stands have been impoverished in terms of their wood quality (stem grade, size and valuable species) through a long period of timber high-grading and diameter-limit cutting during the last century (Robitaille and Boivin, 1987). To replenish timber quality in these stands, forest managers have promoted the use of uneven-aged silviculture, stressing the importance of explicitly addressing the goal of timber improvement through the selective removal of low-quality timber (Erdmann, 1986; Nyland, 1987; Majcen, 1994). Supported by trials that have shown promising results for timber quality improvement (e.g. Strong et al., 1995) and volume production (e.g. Bedard and Majcen, 2003), this silvicultural prescription has subsequently been used extensively in different forest ecosystems throughout the world (Matthews, 1989). Yet, in the sugar maple (Acer saccharum Marshall)–yellow birch (Betula alleghaniensis Britton) forests of the province of Quebec (Canada), its operational application over the past 30 years has led to mixed results, viz., there is no evidence of overall stand quality improvement and yield has been critically lower than that which would be expected from the experimental trials (Bedard and Brassard, 2002). Consequently, several hundred thousand hectares of Northern Hardwoods (NH) remain impoverished today (Coulombe et al., 2004). Obviously, there is a disparity between visions of an ideal stand in which all or most trees can eventually attain veneer/sawlog quality, versus reality, i.e. the low economic value of the stems with which forest managers are frequently confronted when trying to apply selection cuts. In fact, tree values within the same stand can range from negative values (when all costs before transformation are considered) up to several hundred CDN $ m−3. Without government incentives, harvesting crews cannot economically operate within these stands because the costs that are required to harvest negative-value trees exceed the benefits that could be generated from the few high-value trees that are being removed.

Similarly, silviculture in tropical forests is constantly facing this problem, in which contrasting economic values are generated by the inherent high diversity of the tree species that are present. In NH, this situation has yet to be explicitly addressed. Further, silviculture in the NH forests of Quebec is at a dead-end; selection cutting is now being abandoned without a consensus regarding a replacement solution. Hence, there is an urgent need to test other silvicultural approaches that could deal with the problem of stands with contrasting economic values for their constituent species and sizes of trees.

Over the last few decades, views of silviculture have fundamentally switched from the 300-year-long utilitarian tradition that is focussed on optimizing wood production and its outcomes, in order to achieve a range of economic, environmental and social
A frequent and low-intensity uneven-aged silvicultural approach (FLI)

This study reports on a new silvicultural approach that recognizes two main stand components each of which has a different function. First, a fiber production component provides veneer/sawlog quality products from the high-quality trees (HQT) that are present in the stand and, second, an ecological component contributes to overall ecosystem functioning through the presence of lower value stems. In contrast to selection cutting, where the objective is for improving timber quality has overidden other silvicultural objectives, the goal of this new approach is to maintain BA of HQT that represent the fiber function component of the stand. The same BA of HQT is maintained by limiting harvesting levels to the expected in-growth of HQT between two harvests that is carried out at 10-year intervals (a relatively short period for NH). The aim is to more closely mimic the natural disturbance regime and provide greater opportunities for managing for resilience in a context of rapidly changing global environmental conditions, harvests of lower intensities and higher frequencies are implemented instead of traditional selection cuts. Moreover, harvests are mostly limited to the fiber function component of the stand.

Objectives

Many aspects of the FLI approach require scientific validation. These aspects range from economic feasibility, regeneration success, stem quality evolution and confirmation of resilience improvement. However, the most urgent requirement is to demonstrate that the approach does not compromise sustainability. Without such a demonstration, the new approach would have little chance of being implemented in forest management. Therefore, our first objective was to verify whether it was possible to sustainably harvest high-quality trees (HQT) in NH stands. This objective was addressed through the presentation of results from stand growth simulations and optimization. Our second objective, considered mainly in the discussion, was to present possible relationships between the FLI approach and emerging concepts in ecology and forest management, such as ecological integrity, disturbance regime emulation and resilience management.

Methods

Study region

The present study was conducted in forest stands between Lakes Montjoie and Du Sourd, which were located in the Popineau-Labelle Wildlife Reserve (46°13′48″W, 75°09′55″N) of Quebec. The reserve is about 100 km northeast of Canada’s capital, Ottawa, and is situated in the eastern portion of the Lac du Poisson Blanc landscape (Robitaille and Saucier, 1998) of the
western sugar maple—yellow birch bioclimatic region (Saucier et al., 2011). The landscape contains numerous hills with elevations <450 m a.s.l. and averaging 300 m in height. The mean annual temperature is 3.7°C, the mean annual precipitation is about 1100 mm (including 250 mm as snow), and the number of degree-days above 0°C is 2716 (Environment Canada, 2013). Surface geology of the study area is characterized by thin to moderately thin glacial till it is composed of metamorphic rocks, such as gneiss, and which is topped by sandy Dystric Brunisols (GPPC. Le groupe de travail sur les Pédos-paysages du Canada, 2010). The forest canopy is dominated by sugar maple in association with yellow birch, American beech (Fagus grandifolia Ehrh.), American basswood (Tilia americana L.), ironwood or American hop-hornbeam (Ostrya virginiana (Miller) K. Koch), eastern hemlock (Tsuga canadensis (L.) Carrière) and balsam fir (Abies balsamea (L.) Miller).

Sampling protocol

We selected four stands within the Papineau-Labelle Wildlife Reserve that were dominated by sugar maple—yellow birch. In each stand, one 1 ha plot was randomly selected and delimited. Two methods were used to describe each forest stand: one to provide a general description of the stands; and the second, to obtain a precise description of the species composition and diameter distribution of HQT within them. First, the general description of the stand was achieved using nine sub-plots that were systematically spaced 25 m apart on a regular grid, and for which we recorded species and classified trees into broad DBH (diameter at breast height, i.e. 1.3 m above ground level) classes for all trees ≥9.1 cm, as determined using a factor 2 (metric) prism sweep. The four diameter classes were: 9.1–20.0 cm; 20.1–40 cm; 40.1–60.0 cm; and >60.0 cm. The second description consisted of recording each high-quality tree ≥4.1 cm in diameter within the 1 ha plot. To be considered as HQT, stems had to exhibit current sawlog quality (Majcen et al., 1990) for stems ≥23.1 cm. For stems that had diameters <23.1 cm, they had to have the potential to produce sawlog quality timber by the time they reached 23.1 cm. This judgement was based on current tree vigour, stem architecture and defects. Also, species with low or no value such as balsam fir, eastern hemlock or ironwood were not considered as HQT. The same experienced forestry technician sampled the four stands to ensure data quality through consistent sampling and comparison among stands. Finally, to obtain a specific measure of HQT growth for each stand, we cored two sugar maples and two yellow birches by stand and by DBH class. The DBH classes of the cored trees were: 4.1–15 cm; 15.1–25 cm; 25.1–35 cm; and >35 cm. Core ring-widths for the last 10 years were measured (±0.01 mm) under ×40 magnification using a sliding stage (Velmax, Inc., Bloomingfield, NY, USA), which was coupled to a digital meter.

Stand growth simulation

To test whether sustainability may be met through the use of the FLI approach, we chose a method that integrates stand growth simulation and tree marking regime (TMR) optimization. We integrated a genetic algorithm procedure – an optimization technique that uses a biological analogy, e.g. Boston and Bettinger, 2002 – into a simplified stand growth simulator to identify which trees within a stand could be harvested, subject to the constraint of sustained yield in HQT. For each stand, we set a 40-year time simulation horizon during which there were four cutting periods, viz., one every 10 years (t = 0, t = 10, t = 20 and t = 30).

Ideally, we would have used an existing stand growth simulator (e.g. the forest vegetation simulator, Dixon, 2003). However, such a simulator would have required (1) to be readily calibrated for the specific potential growth of our stands; (2) to be flexible in assigning a different growth rate for HQT and non-HQT, since the former was expected to show a more rapid growth; (3) the optimization was able to assess the state of each tree (not only a summary output) at the end of each of the four 10-year cutting period rotations during the 40-year simulation horizon to ensure integration between the growth modelling and the optimization; (4) the use of only deterministic mechanisms, since stochasticity greatly over-complicates the optimization procedure and subsequent interpretation of the results. We were not aware of any model that could have fulfilled these requirements and decided to develop a simple stand growth simulator that was customized for the purposes of this paper.

The stand growth simulator functioned as follows. First, tree DBH increases according to the mean growth increment for the last 10 years that were observed on the sample cores taken from trees of the same species, diameter class and stand origin. The rationale behind this approach was that recent growth is expected to be the most accurate indicator of future growth, since only slight changes in competition that was exerted by competing trees would be expected under low-intensity silviculture. Indeed, the stand BA was not expected to vary more than 3 m² ha⁻¹ between each 10-year period and, consequently, could be considered as almost constant. For this reason, tree growth was considered constant and changed only after a switch in DBH class for a given species in a specific stand. This approach allowed us to account implicitly for the effect of site, stand stocking and tree social position. It should be noted that simulations were applied only to HQT in the stands. Simulating the growth of non-HQT individuals, and how their own growth may affect the growth of HQT growth was not explicitly included. Non-HQT growth was assumed to be low. Moreover, we advocated for the use of tree girdling in cases where competition from non-HQT might be detrimental to HQT. Sugar maple growth was assigned to species for which we did not obtain core samples when estimating site-specific radial growth. In-growth (recruitment of saplings to the tree stage) was generated by the growth of sapling (4.1–9.0 cm DBH) populations that had been surveyed in the stand. Furthermore, no mortality was involved in stand simulation growth for three reasons. First, tree mortality for vigorous trees (HQT are vigorous by definition) in NH forests has been demonstrated to be very low (Fortin et al., 2008). Second, the FLI treatment is designed to first harvest HQT trees with lower vigour (the ones more prone to dying between cutting periods) and rotations in the FLI approach were sufficiently short for removing trees that contributed to mortality among HQT. Third, mortality is usually a stochastic event in models and as previously mentioned, integrating stochasticity and optimization would complicate interpretation of the results.

Tree-marking optimization

The constraints that have been incorporated into the optimization program were developed to identify the timing of the harvesting of HQT > 24 cm in diameter for each stand, so that:

1. the same BA of HQT was harvested at every cutting period;
2. the same mean DBH was harvested at every cutting period; and
3. the same initial and final (t = 40) BA of HQT was present.

We consider that sustainability can be met using the FLI approach when these three conditions are fulfilled. To meet these conditions, we wrote a program (in Python language) that simultaneously simulates stand growth and identifies the timing of harvest for each specific tree (t = 0, t = 10, t = 20 and t = 30, or not harvested at any moment during the simulation horizon) in order to minimize equation (1):

\[
SD_{BA} + SD_{DBH} + |BA_{in} - BA_{init}| \]

where \(SD_{BA}\) is the standard deviation of the BA that was harvested at each cutting period; \(SD_{DBH}\) is the standard deviation of the mean stem DBH that was harvested at each cutting period; \(BA_{in}\) is the BA of the stand remaining at the end of the simulation horizon (t = 40); \(BA_{init}\) is the initial basal residual of the stand (before the first harvest); \(|BA_{in} - BA_{init}|\) is the absolute value of the difference between \(BA_{in}\) and \(BA_{init}\).
In other words, the growth-optimization procedure tried several thousand tree-marking scenarios until the value that had been obtained by equation (1) had stabilized; the closer the value was to 0, the better the optimization. This growth simulation–optimization procedure was repeated 20 times for each stand. For complex problems, random search techniques, like genetic algorithm, may generate different solutions (in our case, the timing of harvest for each specific tree) for equivalent optimization results (the minimized value of equation (1)). Repeating the procedure 20 times allowed us to verify how the solution may differ among optimizations.

Of course, other conditions could have been added to define if a TMR was sustainable. For example, the three aforementioned conditions could also be applied on a by-species basis (sugar maple and yellow birch). Because we did not want to over-complicate the problem and because shifts in species composition in these sugar maple-dominated stands (which regenerate relatively easily under their own shade) were not a primary concern, we preferred to limit the number of conditions defining sustainability.

Results

The four selected stands exhibited different stand features with respect to stocking content, composition and species-specific growth, which allows us to explore how robust the model was across variable stand/site conditions. Initial BA of the four studied stands varied from 18.4 to 27.1 m² ha⁻¹, while BA of HQT ranged from 6.8 to 13.0 m² ha⁻¹ (Figure 1). The HQT diameter distribution in Site 1, being normally distributed, was similar to that in Site 3, although HQT BA was markedly higher in the former than the latter (11.1 m² ha⁻¹ versus 6.8 m² ha⁻¹). The HQT diameter distribution in Sites 2 and 4 was different and mainly negative exponential. The combined proportions of sugar maple and yellow birch exceeded 80% at all sites, with that of sugar maple ranging from 39.5 to 88 per cent and yellow birch from 82 to 49.5 per cent. Further, there were differences in stem diameter growth. For example, mean yellow birch diameter growth was markedly lower (2.2 mm year⁻¹) in Site 1 compared with the other sites (~3.0 mm year⁻¹), while mean sugar maple growth was considerably higher in Site 3 (3.0 mm year⁻¹) compared with the other sites (1.7–2.2 mm year⁻¹).

Optimization was satisfactory achieved in terms of minimizing the value of equation (1) since the minimized values were very close to zero (Figure 2). The initial and final HQT BA were similar for each given site (Figure 2A), as were BA and mean DBH of the HQT that were harvested at each cutting period (Figure 2B,C). Moreover, the variation among optimization runs for a given site in terms of final HQT, and harvested BA and DBH was small, as indicated by the standard deviations, but the solutions varied markedly among sites. Mean harvested DBH ranged from 32 cm for Site 1 to 37 cm for Site 2 (Figure 2C), while harvested HQT BA ranged from 0.88 m² ha⁻¹ for Site 1 to 1.95 m² ha⁻¹ for Site 2 (Figure 2B).

Since pre-harvest HQT BA in Site 2 is about twice as much as in Site 1, we expected higher harvest level of HQT (BA) in Site 2. However, starting with more HQT does not always lead to a higher harvest. For example, BA of HQT in Site 3 was higher than in Site 4 (1.75 m² ha⁻¹ versus 1.50 m² ha⁻¹), but the harvest levels resulting from the optimization were lower in Site 3 (Figure 2B). These examples show that both stem growth and pre-harvest structure influence the level of HQT that may be harvested sustainably.

Tree-marking regimes

For each optimized solution, there was a series of TMRs at each rotation, which were described by the trees that had been selected for harvest. To explore these TMR, we separated the trees that were to be harvested by DBH class (23.1–32 cm; 32.1–40 cm; >40 cm) for each cutting period and site. We then plotted the portion of BA that was harvested in the middle-size category (32.1–40 cm) against the portion that was harvested in the large-size category; the portion harvested in the small-size category could then be easily deduced by difference (Figure 3). For most sites and cutting periods, there was a wide range of tree-marking solutions in terms of large- versus mid-sized trees that could be harvested, and which could lead to very similar optimization solutions (Figure 2). For example, a forest manager could decide to plan his or her first cutting period in Site 1 only for middle-size trees or to harvest 50 per cent of HQT BA as large-size trees and ~10 per cent as mid-size trees (and the remainder as small-size trees). In either case, they would remain on the path of a sustained yield approach for this stand. There are other cases, such as Site 2, for which there was little flexibility with regard to the small-size tree category. A risk of non-sustainability was likely if trees are harvested in the small-size category. Detailed examples of TMR for each site at the first harvest are provided in Table 1. These examples have shown more explicitly how much TMR can differ between optimization solutions. A forest practitioner could then choose among TMRs the one that he or she prefers and apply it easily in the field by simply harvesting the number of trees by DBH classes provided by the optimization tool. Another option would be to translate the TMRs into simplified rules. For example, it would mean to harvest ~1 m² ha⁻¹ concentrated in 29 and 34 DBH classes in Site 1 while in Site 2, it would mean to harvest 2 m² ha⁻¹ mainly in 34 and 39 DBH classes.

Discussion

The results of our modelling optimization suggest that a sustainable silvicultural approach that uses a partial cutting regime to harvest HQT in NH stands without further high-grading is possible. Given the limits of our simplified growth stand model – as well as those limits set by any stand growth model – a real sustainability test would require long-term assessments across many stands, which have been managed using the FLI approach. However, the implementation of this approach requires that the realistic view of permanent stand improvement be abandoned in favour of maintaining only the current quality of stands. While there is a consensus regarding the importance of NH stem quality within the forest industry (Niese et al., 1995), the problem of dealing with poor stem quality has not been adequately considered when defining a viable silvicultural strategy. The usual guidelines, which consist primarily of harvesting low-value trees, frequently have proved to be economically unfeasible. However, it could be argued that harvesting only HQT will decrease stand genetic pool. But, since HQT are still present after almost a century of high-grading, it is reasonable to believe that NH stands are quite robust in terms of maintaining timber quality over successive selective harvesting periods. This robustness could be explained by (1) tree quality being more affected by life history in terms of neighbour- hood competition and random environmental factors than any genetic factor and (2) quality trees having the opportunity to
produce seedlings before being harvested. We thus believe that the approach we have presented is a fair compromise between stand improvement and high-value extraction. Moreover, our approach may apply elsewhere in the world where there are complex stands in terms of species composition, stand structure and stem value differences, such as tropical forests.

Our results have also shown that this approach can be used in stands with quite different structures and compositions. Although only four stands were simulated in this paper, they covered a broad range of stocking (BA ranging from 18.4–27.1 m² ha⁻¹), importance of HQT (6.8–13.4 m² ha⁻¹), DBH structure and HQT diameter growth (sugar maple: 1.7–3.0 mm year⁻¹; yellow birch: 2.2 to 3.3 mm year⁻¹). By succeeding in identifying a theoretically sustainable solution to the harvest schedule in all four stands, which display a diversity of conditions, the results described here indicate that the approach is robust over a 40-year period.

Although a solution was found for each of the four stands, this does not mean that the solution would be economically feasible. For example, in the least productive (Site 1), the optimized yield of harvested HQT was rather low, i.e. 0.88 m² ha⁻¹ every 10 years for culled trees with a mean DBH of 32 cm and a volume yield of 0.6 m³ ha⁻¹ year⁻¹. This low yield, which may appear surprising, was comparable with sawlog/veneer volume yields that are usually harvested under a traditional improvement selection cutting regime in Quebec NH (around 12–20 m³ ha⁻¹ every 25–35 years). Hence, we believe that the costs saved by not harvesting negative-value trees with the FLI approach could at least compensate for the extra costs that would be incurred in having to operate three times more frequently. Therefore, we are confident that our approach is applicable in many economic settings, especially when there is already an existing road network and the sites are close to the mill.

Our results also suggest that, for a given stand, the forest manager has a great deal of flexibility in terms of implementing a tree-marking regime that would tend toward a sustainable yield of HQT. This flexibility is important because it ensures that the implementation of the FLI approach does not need to be so precise it cannot be implemented in practice. The variety of eligible stands to which the approach could be applied, together with the flexibility of its implementation, both rely on the use of quantitative tools, such as combined stand growth modelling and optimization. With this flexibility, the forest manager can be freed from a rigid, predefined stand structure that is inherent to traditional uneven-aged selection cuts, and allowed to design a stand structure that better suits his or her set of objectives (O'Hara, 1998). The idea of coupling stand growth models with optimization engines for assessing TMRs in partial cutting silviculture (uneven-aged and thinning) at cutting period has been frequently suggested in silviculture research (Gove and Fairweather, 1992; Lin et al., 1996), but rarely has it reached the field in the operational planning realm. This approach advocates for a more quantitatively based silviculture. We believe that, with increasing complexity of multiple and often conflicting management objectives that are attached to the forest stands, the balance of the outcomes is much more likely to be achieved with the use of such tools. However, the development of a user-friendly stand growth

![Figure 1](https://academic.oup.com/forestry/article-abstract/87/1/39/599738)
Simulator and tree-marking optimization tool for forest practitioners is necessary for the implementation of the approach. These tools should be used not only once, but prior to each harvest, thereby allowing the simulation–optimization procedure to re-adapt the TMR to the evolving stand state and growth.

In the approach presented here, the forest manager concentrates his or her actions on the fiber production functional component of the stand, while minimizing negative effects on the ecological component. No inherent forest structure is assumed; it only requires managing for a continuous recruitment of HQT. Such basic principles make our approach fundamentally distinct from traditional silvicultural systems that, by definition, are specifically associated with a target structure. Nevertheless, our approach shares some concepts and ideas with uneven-aged silviculture such as achieving sustainability in volume over time (O’Hara and Gersonde, 2004). In addition, our new approach shares the segregation of functions among two different populations of trees in the stand with the coppicing with standards system (Matthews, 1989). When implementing the coppice with standards system, the forest manager recognizes that the overwood provides large sawtimber while the underwood provides the lowest value material such as firewood. However in our new approach, only one part of the stand (the HQT) produces an economic output. It remains unclear to us whether our approach should be considered as an example of the close-to-nature silviculture system (CTNS), which was recommended by Pro Silva (2012). While our approach and CTNS clearly share many goals, it appears less rigid. For example, one of the Pro Silva recommendations requires that the growing stock of a stand be maintained. In our approach, this goal has been specifically associated only with the fiber production component. For the ecological component, there was no such goal since we allowed ecological processes to take place. More fundamentally, those adherents of CTNS seem to believe it should be used everywhere within the landscape. In contrast, we recognize that our approach is one of many options available to forest planners to help them in meeting their management objectives.

Lastly, the use of short cutting periods (e.g. 10 years) is similar in function to the plenter system that has been used in Europe for more than a century (Matthews, 1989). In NH stands, this interval can be considered quite short, since recommendations usually range from 20 to 25 years (Bédard and Majcen, 2003) and, more recently, from 30 to 35 years in Québec in response to the low growth yields that were obtained for stands being managed under selection cutting in the last decades.

The FLI approach in relation to some emerging concepts
Short returns, combined with low-intensity harvests, represent an opportunity to manage stands for forest complexity and for desired

![Figure 2](https://academic.oup.com/forestry/article-abstract/87/1/39/599738)
species in regeneration. Understory light availability in old-growth forests tends to vary more strongly, both horizontally and vertically, than at any other particular stage in the natural succession of a forest, when compared with second-growth forests (Bartemucci et al., 2006) or to managed forest stands (Beaudet and Messier, 2002). For example, in a comparison of old-growth NH forests that had been logged 10–30 years previously (through selection cuts and diameter-limit cuts), Angers et al. (2005) observed the presence of a dense and uniform sub-canopy foliage layer in stands that have been partially logged. They suggested that this layer resulted from the recruitment of pre-established, shade-tolerant regeneration following simultaneous creation of numerous canopy openings during partial harvesting. Similar tree and shrub development following human disturbance has been observed worldwide (Royo and Carson, 2006). Our new treatment, by its low intensity, should reduce this risk of forming uniform sub-canopy foliage layers by creating complex light profiles that more closely resemble those of old-growth forests than those of traditional selection cuts. This complexity of light profiles should also favour a greater diversity of species in regeneration. However, there could be concerns about possible deleterious effects of rapid canopy closure on desired species after a low-intensity treatment. For example, yellow birch is known as a semi-tolerant species in NH stands (Erdmann, 1990). Our new approach offers the possibility for the forest manager to open the canopy through small group-selection cuts to provide sufficient light, which would favour the early development of this species without creating larger openings that would otherwise result in intensive shrub competition (Lorenzetti et al., 2008). Since the cutting periods are frequent, the forest manager can easily readjust the schedule as needed. He or she could enlarge an opening in a subsequent cut if yellow birch regeneration growth is too slow.

Because the population of trees constituting the ecological component is explicitly recognized in the stand and because our silvicultural approach is based on frequent and low-intensity cutting cycles, we believe that our approach is well suited for maintaining ecological integrity and emulating the natural disturbance regime of the NH forests. Letting natural processes occur for trees in the ecological component of the stand is likely to aid in the restoration of desired old-growth attributes, which are critically missing in NH forest landscapes that are being managed under current practices. Indeed, by default, the recruitment of low-value large-size trees would help get closer to the stand structure that characterizes old-growth forests and recruit large deadwood recruitment, as has been promoted by the ‘complex structure enhancement’ approach of Keeton (2006). Moreover, growth of the ecological component of the stand would allow biomass capital to be rebuilt, allowing some forest tracts to attain high BA values (>26 m² ha⁻¹), which are otherwise rare and fragmented within the landscape by low BA (16–22 m² ha⁻¹) stands. Further, the ecological service of carbon sequestration could be recognized, which would generate additional revenues through the carbon-credit

Figure 3
Proportion of BA harvested in middle-size stems versus big-size stems, by site and cutting period. Each point represents a result from one of the 20 optimization runs for each site.
market. Indeed, it has been demonstrated that old-growth NH forests are still accumulating carbon and, therefore, could be considered as carbon sinks (Nunery and Keeton, 2010).

As indicated in the Introduction, a less intensive and more frequent intervention is more likely to foster forest adaptation in the face of increasing biotic and environmental changes. Many recent books (Chapin et al., 2009; Gunderson et al., 2009; Messier et al., 2013) have promoted the idea that forest managers need to show greater flexibility and a readiness to intervene quickly in helping the forest adjust to these new environmental conditions. Resilience management is therefore less concerned with long-term management for timber quality of a few species, since it is less and less certain that these tree species of high quality today will be maintained over the long-term, and more about providing forests with key ecological attributes that are likely to be needed under different future environmental and biotic conditions (Messier et al., 2013). In that regard, resilience management could benefit greatly from a new silvicultural approach that is flexible enough to focus on low intensity and frequent intervention. Such approach would help in recovering declining tree species while promoting other species that are better-adapted to survive and flourish under current and future conditions. It should be remembered that most trees currently left standing following classical selection cutting were established more than 50 years ago, during a period where both biotic and environmental conditions were markedly different from conditions being experienced today or those likely to be experienced in the future. Thus, it may not be prudent for either economic or ecological reasons to leave behind trees that are likely not to be well-adapted to future conditions. One important aspect of this new low intensity and frequent silvicultural approach that will require investigation is the need to intervene not only to capture the currently high-quality timber, but also to maintain the diversity of species and functions necessary to allow this forest to adapt to novel and relatively unknown future conditions. In that respect, this new silvicultural approach will also need to make decisions about the possible future desirable conditions required to reduce the risk of a misbalance in the functioning of the forest ecosystem. Forest managers will need to evaluate each stand in terms of what tree species and attributes are likely for this forest to either resist or adapt to disturbances and environmental conditions most likely to be encountered over the next 50 years. Because we cannot be certain about what these future disturbances and environmental conditions are likely to entail, a highly desirable strategy would maintain as high a diversity of species as possible having both complementary and redundant ecological characteristics.

This new silvicultural approach is likely to fit better into what Messier et al. (2013) have termed ‘managing for complex adaptive systems’. Because it does not focus solely on retaining high-quality timber trees and species, rapid intervention would be encouraged under this approach to help the forest adapt to new current and future conditions. It acknowledges that future conditions are uncertain and that interventions would not be conducted at the stand level, but rather at the scale of the individual tree. As such, the new approach provides a better fit to the view that the forest represents a set of interacting independent elements.

### Conclusions

We have reported on a new silvicultural approach (1) that recognizes two main components in the stand, i.e. a fiber production component and an ecological component, (2) that is closer to the functioning of the natural disturbance regime and (3) that provides greater opportunities for managing forests for resilience in a context of rapidly changing global environmental conditions. By freeing silviculture from its idealized view, i.e. that all trees should be of high timber quality, and simply aiming to maintain the actual quality of the stands, we can then imagine a silvicultural approach in which only high-quality trees are harvested, with lower harvest intensity and higher harvest frequency compared with a traditional selection cut. We believe that this approach can be used worldwide where stands contain trees with highly variable economic value.

In this study, the growth of the fiber component of the stand was modelled independently of the ecological component (which was not modelled at all). In reality, both components are not independent and the development of one is affected by, and in turn, affects the other. Modelling the development of each component using spatially explicit model (e.g. SORTIE, Pacala et al., 1993) would be useful in verifying how these two components interact with one another and in testing some of the assumptions made in our simplified model. First, such an exercise could aid in evaluating how development of the fiber component is influenced by tree mortality (in both components) and by competition among trees. Second, it would enable us to evaluate how the ecological services that are provided by the ecological component develop

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**Table 1** Number of stems to be harvested, by DBH class per hectare (first harvest), for five examples of TMRs that were provided by the optimization tool.

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<th>Site</th>
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<sup>a</sup>Each diameter class is 5 cm wide (except the first one that starts at 23.1 cm), and is represented by the maximum of the class.
through time. Also, the application of this modelling effort to many other stands would be useful in obtaining a more comprehensive description of the stands for which this new approach is appropriate.

A silvicultural approach cannot be considered fully tested until it is incorporated in a broad forest management plan. It would then be interesting to test how the FLI approach contributes, within an optimized forest management model, to achieve specific economic, ecological and social targets at the forest scale. Finally, guidelines have been recently developed for reduced-impact logging (known as RIL), especially in the tropics, to protect soils and advance regeneration (Putz et al., 2008). We believe that our approach could be complemented by the development of RIL techniques that are adapted to NH stands. Since our approach allows for harvesting only HQT for niche markets, we believe that it is possible to use or develop low-cost technologies that will help protect soils and vegetation, instead of using technologies that are adapted to mass markets and which often have undesired effects on the ecosystems.

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Conflict of interest statement
None declared.

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