Land sparing and sharing patterns in forestry: exploring even-aged and uneven-aged management at the landscape scale

Clément Hardy[1*], Christian Messier[1,5], Yan Boulanger[2], Dominic Cyr[3], Élise Filotas[4]

[1]Department of Biological Sciences, Centre d'Étude de la Forêt (CEF), Université du Québec à Montréal, Canada (UQAM)
[2]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Québec, QC, Canada
[3]Sciences et Technology Branch, Environment and Climate Change Canada, Gatineau, QC, Canada
[4]Department of Science and Technology, Université du Québec (TELUQ), Canada
[5]Department of Natural Sciences, Institut des Sciences de la forêt tempérée (ISFORT), Université du Québec en Outaouais (UQO)

***Correspondence:** Clément Hardy
clem.hardy@pm.me
514-600-4478

ORCIDs:

Clément Hardy: 0000-0003-4969-1298

Abstract

Context

Uneven-aged forest management is sometimes seen as offering interesting compromises between timber production and other important ecosystem services, compared to even-aged approaches. However, uncertainties remain concerning its impacts over longer time periods and broader spatial scales, as larger areas and further roads are required to harvest the same amount of wood.

Objectives

We compared the large-scale and long-term impacts of uneven-aged and even-aged managements on the composition, road density and fragmentation of a landscape composed of northern temperate and boreal forests, and presenting frequent forest fires.

Methods

We simulated an 800 000 ha forested landscape in the Mauricie region (Quebec, Canada) over a 150-year planning horizon with the LANDIS-II model and an extension that simulates forest road construction. We compared 30 different management scenarios that varied the proportion of even- and uneven-aged managements, the level of aggregation of the harvested areas, and the presence of pre-existing forest roads.

Results

Compared with even-aged management, uneven-aged management increased (i) the density of forest roads and their operational costs, (ii) the amount of old forests, and (iii) their fragmentation. Aggregating harvested areas did not noticeably reduce road density , and the presence of an initial road network had no long-term effects. Differences in landscape fragmentation between scenarios were reduced in the northern region of the landscape due to the fire regime.

Conclusions

Choosing uneven-aged over even-aged management represents a trade-off between the amount of old forests in the landscape and three variables related to roads : their density, their related cost, and the fragmentation *per se* that they generate, This trade-off seems to disappear in the presence of stand-replacing disturbances in the landscape and is unlikely to be improved by aggregating the harvested areas.

Keywords: uneven-aged management, forest roads, LANDIS-II, forest fragmentation, forest landscape modelling, aggregated harvest

1. Introduction

Forests provide essential ecosystem services for societies across the globe and harbour most of the Earth's terrestrial biodiversity (FAO and UNEP 2020). Yet, the increasing demand for land and forest products as well as climate-induced changes to forest structure and functions are threatening forest health (Trumbore et al. 2015). In fact, about 30% of the area covered by forest biomes in the world is managed, under varying intensities, to produce timber and non-timber forest products (FAO 2020). In the temperate and boreal forests, forestry represents the most important form of anthropogenic disturbance on forests (Curtis et al. 2018). Thus, designing sustainable forest management strategies that can balance the trade-offs between timber demand and conservation objectives is a pressing challenge (D'Amato et al. 2011; Lindenmayer et al. 2012; Brang et al. 2014).

In North America, even-aged forest management is still widely used, especially in boreal and mixed forests. Indeed, clearcutting accounts for more than 80% of all forest harvesting in Canada, whereas it is around 40% in the USA (Oswalt and Smith 2014; Statistics Canada 2018). However, clearcutting has been increasingly perceived as having negative environmental impacts. Multiple scientific studies have shown that even-aged management can alter the structure of forest ecosystems and reduce biodiversity when applied across wide forest landscapes (Cyr et al. 2009; Martin et al. 2020) or in forests that are not adapted to stand-replacing disturbances (Burton and Canada 2003; Park et al. 2005; Nolet et al. 2018). For example, Paillet et al. (2010) observed that clearcutting in European forests was associated with a decline in species richness of several taxa, and Cyr et al. (2009) showed that even-aged management shifted the age-class distribution of boreal forests towards younger stands, to the detriment of old-growth ones. Moreover, the unaesthetic scenery created by clearcutting has led to widespread public dislike of this method (Ribe 2005).

Consequently, forest scientists and policy makers have recently shown renewed interest in uneven-aged forest management (O'Hara 2002; Diaci et al. 2011; Schütz et al. 2012) where three or more age classes within harvested stands are preserved through selection cutting of individual trees or groups of trees (Hawley and Smith 1962; Matthews 1991; Puettmann et al. 2009). Because uneven-aged management can maintain a constant forest cover and many important attributes associated with older stands, it is considered a relevant alternative to even-aged management whose widespread use tends to create open habitats and younger forest landscapes. This is particularly true in forest regions that are known to mostly experience rather fine scale, partial natural disturbances (e.g., windthrows, insect outbreaks) which are appropriately emulated by uneven-aged management (Kuuluvainen et al. 2021).

Indeed, uneven-aged forest management has been associated with improved protection of biodiversity and sustainability of ecological services (Fedrowitz et al. 2014; Pukkala 2016). For example, some studies have shown that forests managed with uneven-aged compared to even-aged management captured more carbon (Strukelj et al. 2015), had a greater abundance and diversity of birds (Tittler et al. 2001), mammals (Ruel et al. 2013), plants

(Götmark et al. 2005), bryophytes (Stone et al. 2008; Boudreault et al. 2013), and insects (Graham-Sauvé et al. 2013; Joelsson et al. 2017) several years following harvesting, and showed an increased resilience in landscapes associated with high fire frequency (Cyr et al. 2022). Other studies have also shown that uneven-aged forest management conserved several important characteristics of old-growth forests, such as tree species diversity, species abundance, and a broader tree diameter distribution (Gronewold et al. 2010; Adamic et al. 2017).

However, evidence of the ecological advantages of uneven-aged management over even-aged management remains equivocal or disputed (Nolet et al. 2018). In addition, most studies to date reporting on the benefits of uneven-aged management have been carried out at the stand scale and over a short period of time (e.g., 1-35 ha and 2-9 years in previously cited studies), while focusing on specific groups of species (1-3 taxa in previously cited studies). It is also currently unclear how disturbances created by uneven-aged management interact with the cross-scale spatiotemporal dynamics of natural disturbances, such as forest fire (Kalabokidis and Wakimoto 1992; Kuuluvainen et al. 2012; Nolet et al. 2018). Hence, a comprehensive understanding of the impact of uneven-aged management on forest structure and function at spatial and temporal scales at which forest management is performed is currently lacking (Nolet et al. 2018).

Uneven-aged management may have several shortcomings when it comes to conserving forest structure and diversity, especially at the landscape scale. During a planning horizon, uneven-aged management requires that silvicultural operations extend over larger forest areas than even-aged management to harvest the same volume of wood (Betts et al. 2021). Consequently, uneven-aged management may require the development of a larger and more permanent forest road network to reach distant stands over shorter rotation periods especially in countries or regions with vast expanses of remote forest like Canada (Alexander and Edminster 1977; United States Department of Agriculture 1997; Nolet et al. 2018). As such, uneven-aged management likely increases landscape fragmentation, with potential negative effects on habitat connectivity for several species and ultimately on biodiversity (Haddad et al. 2015). Forest roads have also been linked to other negative effects such as contributing to the decline in the macroinvertebrate soil fauna (Haskell 2000), beetles (Koivula 2005) and salamanders (Marsh and Beckman 2004); facilitating the spread of invasive plants (Mortensen et al. 2009); reducing habitat quality for some species of birds (Ortega and Capen 1999); changing movement patterns of large mammals such as the elk (Witmer and deCalesta 1985); increasing wolf predation on the caribou (James and Stuart-Smith 2000; Whittington et al. 2011; Vanlandeghem et al. 2021); and influencing the spatial boundaries of forest fires (Narayanaraj and Wimberly 2011). In addition, the shorter rotation periods of uneven-aged management would mean more frequent disturbances within stands, possibly reducing the potential benefits of uneven-aged management described above in the long-term.

From these considerations, even-aged management can be seen as a land-sparing approach where intensive harvesting is carried out on a smaller portion of the landscape while uneven-aged management can be seen as a land-sharing approach (Lindenmayer et al. 2012). As such, even-aged management would "spare" the remaining forests of the landscape by reaching a harvest target over a reduced area; whereas uneven-aged management would "share" the entire forest landscape for different purposes through less damaging harvesting. This debate between the efficacy of land-sparing and land-sharing strategies for conservation has been long ongoing in conservation sciences, especially in the context of agriculture (Balmford 2021). Consequently, this raises questions regarding the potential trade-offs between even-aged and uneven-aged approaches: How do these trade-offs evolve over time? How many more forest roads does uneven-aged management require? How do the effects of roads on forest fragmentation and composition differ between even- and uneven-aged management? Can some of these effects be altered by the aggregation of harvested zones in the landscape? In the present study, we compare the effects of even- and uneven-aged forest management on the amount and fragmentation of old forests over a 150-year planning horizon and across an extensive management unit located in the northern temperate and boreal forests in Quebec, Canada. This management unit is almost entirely composed of forests and lakes with very few rural communities (covering only 0.1% of the unit area). As such, it is an interesting area to study the land sparing – land sharing question in forestry. Indeed, the large surface of forests in the area allows the implementation of both strategies on a large scale. In addition, its fragmentation will be sensitive to the presence of forests roads, which are the majority of roads found in the area (more than 90%).

We focus on old forests since they present characteristics that are essential for multiple species (Thomson 1994; MacKinnon 1998; Terry et al. 2000) and provide key ecosystem services (Luyssaert et al. 2008; Clark 2011; Frey et al. 2016), but have severely declined in managed landscapes (Cyr et al. 2009; Shorohova et al. 2011; Martin et al. 2020). Therefore, conservation of old forests has become an important management objective in both governmental regulations and international certification programs (Strittholt et al. 2006; Knorn et al. 2013; Merschel et al. 2019). Here, we used the term "old forests" to describe forests with old trees, to distinguish it from the term "old-growth forests" which can refer to a set of structural characteristics, processes, functions or legacies (Wirth et al. 2009).

We use LANDIS-II, a forest landscape model (Scheller et al. 2007), in combination with the Forest Roads Simulation module (FRS), a new extension that simulates the construction of forest roads needed to reach harvesting sites (Hardy et al. 2023). We simulated 30 different management scenarios where three factors modulating the impact of uneven-aged management on the fragmentation of old forests were varied: (i) the proportion of aboveground tree biomass harvested with uneven- vs. even-aged silviculture, (ii) the presence/absence of an initial forest road network, and (iii) the level of spatial aggregation of logging sites. Our study area was composed of mixed and boreal forest, with frequent forest fires in its northern half, but not in its southern part. We compared these scenarios based on the temporal dynamics of the following response variables: the density of forest roads, their cost of construction and repair, and the amount and fragmentation of old forests. Our goal was not to attempt to find an optimal location for even- or uneven-aged cuts (i.e. Tittler et al. 2015), but to explore two broad management strategies and their interactions with forest roads and natural disturbances. Furthermore, we did not include climate change as a varying factor, in order to better isolate and interpret differences resulting from the different management strategies and reduce the computational load of the simulations.

We hypothesized that a land-sharing strategy, represented by a higher proportion of the landscape harvested under uneven-aged management, protects a larger amount of old forests compared to a land-sparing strategy characterized by more even-aged management. On the other hand, we also hypothesized that uneven-aged management increases road density and usage of roads, along with the fragmentation of the landscape. As such, simulations with a higher level of uneven-aged management would lead to higher road density, greater costs in road construction and maintenance, and higher fragmentation of old forests. Additionally, we hypothesized that aggregating harvesting areas requires less forest roads and thereby reduces their negative impacts on cost and fragmentation. Finally, we hypothesized that the presence of natural disturbances interacts with harvest prescriptions by lightening or exaggerating their effects on the composition of the landscape.

2. Methodology

2.1. Simulated area and study area

Our study area corresponds to a forest management unit in Mauricie, Quebec (Figure 1) where both even-aged and uneven-aged management are currently being used (Messier et al. 2009). The total area covers around 800 000 hectares and is typical of the temperate mixed wood and southern boreal coniferous forest. It extends mostly from the balsam fir and yellow birch region in the south to the balsam fir and white birch region in the north (Robitaille and Saucier 1998). The dominant species in the southern part of the landscape are balsam fir (*Abies balsamea*), yellow birch (*Betula alleghaniensis*) and trembling aspen (*Populus tremuloides*). Further north, the main species are balsam fir, white birch *(Betula papyrifera),* trembling aspen, black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*). While fire is an important natural disturbance in the region with a return interval of around 300 years in the north and 5300 years in the south (Boulanger et al. 2014; Couillard et al. 2022), recurrent spruce budworm outbreaks are also significant in balsam fir stands particularly in the south (Bergeron and Fenton 2012). Because of the prevalence of severe forest fires, even-aged forests occur naturally in this landscape (MFFP 2018). The study area is characterized by few rural communities (covering only 0.1% of the unit area) connected by a sparse network of paved roads. Large-scale logging began in the south of the area during the late 1920s, progressively spreading to the north during the following decades (Messier et al. 2009). Forest management until today consisted largely of clearcutting followed by planting or natural regeneration, mixed with different forms of partial cutting. Being almost entirely composed of public forests, forest management in the area is currently regulated by the Ministère des Ressources naturelles et des Forêts du Québec (MRNF, formerly MFFP). As of this 2018, most of the forest surface in the area was classified as being less than 70 years old, with only 11% being 90 years old or more; whereas 12% of the surface is considered as having an uneven-aged structure (3 age classes or more) (MFFP, 2018).

2.2. The LANDIS-II forest landscape model

LANDIS-II is a spatially-explicit forest landscape model (FLM) that simulates forest dynamics through both stand-level processes (e.g., succession through intra- and interspecific interactions) and landscape-scale processes, such as seed dispersal (Scheller et al. 2007) as well as natural (e.g., fire, wind, and defoliating insects) and human disturbances (e.g., harvesting and land-use change) based on the life-history traits of tree species. Trees are modelled as cohorts, i.e., as a group of trees of a given age class and species.

In LANDIS-II, the simulated landscape is composed of square cells that are either forested or non-forested (e.g., water, urban area, etc.). Each forested cell is categorized into an ecoregion, representing the effect of climate and/or soil on tree growth, and is assigned to a management area for harvesting purposes. The model is composed of multiple extensions, each simulating one of the main processes driving forest dynamics. During one iteration, each extension operates sequentially. Parameters for the extensions used in the present study are summarized in Appendix A.

Our simulations were executed with LANDIS-II v. 7.0 on a landscape of around 4 million forested cells encompassing our study area surrounded by a 50 km buffer zone (Figure 1). We chose a cell size of 1 hectare, which is typical of LANDIS-II studies as it represents a good compromise between computational load and simulation of fine-scale processes (Shinneman et al. 2010; Sturtevant et al. 2012).

2.3. Parameterization of LANDIS-II

General parameterization

The parameter values for our study were derived from the protocol described in Boulanger et al. (2017) and subsequently used in several studies using LANDIS-II to simulate forest landscapes in Quebec and elsewhere in Canada (Boulanger et al. 2017, 2019; Tremblay et al. 2018). Simulation duration was set to 150 years (from the year 2000 to 2150) to reflect the strategic planning horizon of forest management in Quebec (Bureau du forestier en chef du Quebec 2013). All modules operated on a time step of 10 years, a compromise between simulating processes occurring over short and long terms (Shinneman et al. 2010; Sturtevant et al. 2012; Boulanger et al. 2017).

The initial composition and age structure of the forest community within each cell were determined using data from the Canadian National Forest Inventory (Beaudoin et al. 2014) and Quebec’s permanent and temporary sample plots (Alain et al. 2016a, b). Each cell was assigned a sample plot using a nearest neighbour analysis based on age and species-specific biomass (Boulanger et al. 2017; Tremblay et al. 2018). In total, 17 different tree species were modelled (see Appendix B). In addition, the ecoregions of our landscape were defined by assigning cells to homogeneous units of soil (Mansuy et al. 2014) and climate (Boulanger et al. 2017). Each of the nine management areas in our landscape corresponded to those currently used by the MRNF. Finally, the forest stands (which are groups of cells within management areas) were defined spatially using the stands identified during Quebec's provincial inventory (MFFP, 2018a).

Biomass succession

Succession was modelled using the "Biomass succession" extension (v. 5.2) of LANDIS-II, which computes the biomass and biomass increment of tree cohorts. This module relies on a collection of parameters that determine the competitive ability of each species and its establishment and growth potential under specific environmental conditions. The latter parameters were derived using the model PICUS (Lexer and Hönninger 2001), an individual-based spatially-explicit model of stand dynamics, as in Boulanger et al. (2017) and Tremblay et al. (2018) (see Appendix C for further information).

Life-history traits and shade tolerance parameters for the 17 tree species modelled were estimated from the literature (Appendix A). The values of the other parameters (e.g., growth curves and shade impact on productivity) were determined from calibration runs with the goal of minimizing differences with initial estimates of biomass made by LANDIS-II and biomass estimates from the National Forest Inventory for the simulated area (Appendix C).

Natural disturbances (Fire)

Two main natural disturbances are present in our landscape: forest fire, and epidemics of spruce budworm (*Choristoneura fumiferana*). We simulated forest fire, which consists of the dominant natural disturbance in our study area (see section 2.1) using the Base Fire extension of LANDIS-II, but for simplicity we decided not to simulate spruce budworm outbreaks. This choice facilitates the interpretation of the results since the simulated forest dynamics emerges from fewer interactions between forest management and natural disturbances. .The Base Fire (v. 4.0) extension of LANDIS-II follows a simple dynamic (He and Mladenoff 1999) where a fire is initiated within a cell according to a probability dependent on the age of the oldest cohort. The fire then spreads successively to neighbouring cells based on probabilities modulated by a randomly determined wind direction. Finally, local fire damage depends on fire severity and species composition. The minimal, average, and maximal sizes of fire, and its return interval can be specific to "fire regions" determined by the user.

Following the method employed in Boulanger et al. (2017), two fire regions were defined in our landscape from the delimitation of the homogeneous fire zones of Boulanger et al. (2014). The parameters of LANDIS-II for each fire region were estimated in order to reproduce the historical maximal and minimal fire sizes in each region as well as the percentage of area burned each year on the simulated landscape during the initial 30 years of simulation (see Appendix D).

Harvesting

Timber harvesting in LANDIS-II is modelled as a set of prescriptions (e.g., clearcutting, selective cutting, etc.) that are applied within user-defined management areas. Each management area can thus have a different set of prescriptions that are applied on a certain percentage of its surface. For each management area, prescriptions are realized one by one in a random order and are applied to selected stands based on a set of conditions and/or ranking algorithm (random, economic value, age structure, etc.). Cohort harvesting using a given prescription stops once the surface to be harvested in the management area has been reached.

The current LANDIS-II harvest module can only define prescriptions based on a targeted percentage of the total surface of the management area to be harvested. However, our research question required that we harvest the same amount of biomass, not surface, with different prescriptions in order to properly compare the impacts of even-aged and uneven-aged management on the same landscape. Hence, we used the Magic Harvest extension for LANDIS-II to better control the biomass that was harvested by the Biomass Harvest extension via a custom Python script (Hardy 2022) (see Appendix E).

The biomass target in each of the nine management areas was based on the annual allowable cuts (AAC) determined by Quebec Chief Forester's Office and the MRNF for the 2018-2023 period (MFFP, 2018b). The targets were also adjusted to the temporal resolution employed in our simulations (10 years instead of 5 years for the AAC; see Appendix E). The computation of the AAC in Quebec is a multi-constraint optimization exercise realized for each management unit. This optimization includes a constraint on the amount of older forests that must be preserved in the landscape, which was integrated in the harvest targets that we employed. Harvesting prescriptions and the criterion used to prioritize the stands to be harvested were defined to simulate typical harvesting operations conducted in Quebec today, which may differ from prescriptions in other countries.

The main prescriptions used in our study area include clearcutting, shelterwood cutting, and continuous-cover forestry (sometimes referred to as irregular shelterwood) (Table 1). The first two prescriptions correspond to even-aged management, while the third corresponds to uneven-aged management. All prescriptions were applied only to stands 30 years or older, meaning stands that had at least one age cohort of more than 30 years. This age constraint implied rotations of at least 30 years. However, these stands could contain age cohorts younger than 30 years that could be harvested by the clearcutting and shelterwood prescriptions. Clearcutting harvested all age cohorts older than 10 years in a cell (to mimic clearcutting with protection of regeneration as is currently done in Quebec). Shelterwood cutting harvested 90% of the biomass of all age cohorts older than 10 years in the cell in a first cut, and then harvested every remaining cohort older than 20 years in a second cut 20 years later. Finally, the irregular shelterwood was initially modelled to harvest 30% of the biomass of all age cohorts 30 years and older in the cell every 30 years. We fixed the proportions of clearcutting and shelterwood cutting (our two even-aged management prescriptions) to the proportions currently used in our study area. Hence, shelterwood cutting harvested 10% of the biomass target calculated for even-aged management, while clearcutting removed the remaining 90% (Table 1). Finally, we allowed the 30-year return cycle of the irregular shelterwood prescription to be overridden in the case where the biomass target couldn't be reached by respecting this delay. This could happen in management areas with a large biomass target, in scenarios where a high proportion of uneven-aged management was used.

We varied the size of harvested patches among the different aggregation scenarios that we tested (see section 2.5 below). The maximal area that could be harvested in a single cut was defined according to historical records of cut size in our study area (MFFP du Québec 2018b). Harvesting was simulated by "propagating" the harvested area from forest stand to forest stand until the maximum cut size was reached or until no adjacent stands satisfying the age constraint (30 years or older) were available.

2.4. The Forest Roads Simulation Module

To model the dynamics of forest roads, we used the LANDIS-II "Forest Roads Simulation" (FRS) extension (Hardy et al. in press). The FRS extension generates or updates the forest roads needed to carry the harvested wood in the landscape in a realistic yet computationally efficient way. To do this, the FRS extension generates a path of road segments that connects cells from a harvested area to an exit point (either the location of a sawmill or a point on the existing main road network) with minimum construction costs based on landscape topography and existing roads.

The running of the FRS extension is described in Figure 2. The extension uses a raster layer, the "road landscape", to track the location of forest roads. Roads belong to a size category (tertiary road, secondary road, primary road, etc.) that accommodates an increasing flux of trucks needed to carry the harvested timber (Karlsson et al. 2006). The FRS extension is activated during the initiation phase of a LANDIS-II simulation and at each iteration following the harvesting procedure.

During the initiation phase, the FRS extension computes the cost of constructing a potential forest road within each cell. This cost map considers the cost associated with several landscape features, including the "coarse" elevation (mean slope of the cell), the "fine" elevation (presence of breaks or cliffs requiring a detour), water bodies (such as lakes and rivers that would require a bridge), streams (requiring a culvert), and soils (Figure 3A, B).

Following the initialization phase, and at each time step where the FRS extension is activated, an attempt is made to create a road toward every cell harvested since the last module activation (Figure 2). There are no interactions between the harvest and the FRS extensions. The harvest extension determines the position of cells to harvest, whereas the FRS extension simply creates roads towards these cells. Timber transportation through the network is then simulated, and the size category of roads is updated to accommodate an increasing traffic of logging trucks. Road aging was also considered by removing forest roads that reached their persistence limit (a road type parameter), if they were not repaired (see Appendix F). Finally, when a cell is harvested under uneven-aged management, the algorithm considers the necessity of future returns to the cell by selecting the least expensive option between creating a low-cost, nondurable road that may need to be reconstructed or repaired when returning to the cell and creating a higher grade, more durable road that will persist for future access.

In the present study, the FRS module was parameterized using several MRNF datasets reporting on the construction costs of forest roads (e.g., mean costs of construction of road segments by slope, soil type and road category), along with key characteristics of forest roads (e.g., real mean skidding distance, persistence by road type) (see Appendix F). Our exit points for the wood were simply the cells containing the main paved roads of the landscape. The transport of wood was oriented toward these cells, and no new main paved roads were created during the simulation. Calibration of the FRS module over our study area was performed in Hardy et al. (2023).

2.5.Scenarios

To compare the long-term and landscape-scale impacts of even- and uneven-aged management strategies, we defined harvesting scenarios varying three different factors (Table 2). First, we considered the presence or absence of an initial road network in the simulated area. When present, the initial road network corresponded to the existing roads reported in the governmental database "AQReseau+" containing all terrestrial transport routes in Quebec, including forest roads (Gouvernement du Québec 2015). When absent, the initial network consisted of the main existing paved roads only. To improve the realism of the simulated roads, we calibrated the harvest module such that in the absence of an initial road network, harvested areas and new forest roads would progressively spread in the landscape during the first five iterations (50 years) of the simulation (see Appendix E).

Second, we compared the use of uneven-aged (i.e., irregular shelterwood) to even-aged management (clearcutting and shelterwood) by progressively varying the fraction of the total biomass target to be harvested under uneven-aged management (0%, 25%, 50%, 75% and 100%). The remaining fraction of the biomass target was harvested using even-aged management.

Finally, we considered the level of aggregation of harvest cuts given its potential influence on the extent of the resulting road network and on landscape fragmentation (Tittler et al. 2015). The aggregation levels were defined in relation to the maximum size for all the areas harvested in our study area since the year 2000 (209 ha, 359 ha, 117 ha for clearcuts, shelterwood cuts, and uneven-aged cuts, respectively; MFFP du Québec 2018a). As such, we set the maximum size of harvest events in LANDIS-II to the historical average for the intermediate aggregation level. Alternatively, we set the maximum size of harvest events to half and twice that of the intermediate aggregation level for the low and high levels of aggregation, respectively.

We developed one management scenario for each combination of levels for the three factors investigated, resulting in a total of 30 distinct scenarios. We simulated five replicates for each scenario to account for the stochasticity of LANDIS-II using the infrastructure of Compute Canada.

2.6. Data analysis

Three classes of metrics were calculated at each time step during our simulations: succession and disturbance dynamics, forest road network and landscape fragmentation. We compared the management scenarios through their effect on the size of each metric during the simulation period (0 – 150 years) (White et al. 2014). Replicates for each scenario captured within-scenario variability due to stochastic processes such as forest fire and succession.

Succession and disturbance dynamics

As a validation exercise, we evaluated the impact of the different management scenarios on forest succession and disturbance dynamics. Succession was measured by the aboveground biomass annual net primary productivity (P; measured in $g \cdot m^{-2-ye}$), corresponding to the total change in aboveground biomass averaged across all forested cells, and by the average age of all age cohorts in the landscape (A, in *yr*). In addition, we assessed the landscape-scale impact of the simulated disturbances by measuring the total surface harvested (S_h, in hectares), the total biomass harvested (B_h, in Mg) and the total surface burned (S_b, in hectares). These measurements are presented in the appendices of the article (Appendices H and J), as they are not of direct relevance to our research question.

Forest road network

We determined the size and monetary cost of the forest road network in our simulated landscape. Network size was measured by road density (D_r), which is the proportion of cells that contained a road. The cost (C_r), in 2020 Canadian dollars (CAD), for road construction and repair (i.e., size category upgrade and restoration of old roads) was estimated based on the cost parameters cited in section 2.4 (Appendix G).

Landscape fragmentation

Finally, we estimated the landscape-scale impact of forest management on the amount and fragmentation of old forests. We defined old forests as forest stands containing at least one age cohort older than 91 years based on the definition employed by the MRNF (MFFP du Québec 2016). The amount of old forest in the landscape was measured as a percentage of the total forested area (S_o). Fragmentation was measured using the clumpiness index (*Clumpy*) which estimates the aggregation of pixels of a given type (e.g., pixels containing old forests) (equation in Appendix L; see McGarigal et al. 2012). More precisely, the index measures the deviation in the proportion of adjacencies between pixels of this type in the simulated landscape from the proportion that is expected under a random distribution of the pixels of that type. It varies from -1 (minimum aggregation possible) to 1 (maximum aggregation possible). *Clumpy* also presents a low correlation with habitat amount, making it ideal for measuring fragmentation *per se* (Wang et al. 2014). We used the R package *landscapemetric* (Hesselbarth et al. 2019) to compute the index.

3. Results

We present the temporal dynamics of each metric investigated over the planning horizon (150 years). Results are presented for simulations that varied one factor (initial road network, ratio of use of uneven-aged management, or aggregation of cuts) while keeping the other factors at an intermediate value (i.e., no initial road network, 50% of the biomass harvested using uneven-aged management, and intermediate aggregation level). Additionally, results concerning the fragmentation of the landscape are illustrated for the northern and southern regions of the landscape separately (results for the entire landscape are available in Appendix K). In so doing, as fire regimes differ in both regions, we are better able to distinguish the potential contribution of fire to landscape fragmentation.

Road density and cost

We observe a much higher road density (Figure 4a) and cost of construction and repairs (Figure 4b) throughout the simulations with an increased use of uneven-aged management across the landscape. Indeed, the scenarios where more than 50% of the biomass target was harvested with uneven-aged management (green to yellow curves) presented more than twice the density of forest roads in the landscape and up to three times the cost of road construction and repairs than scenarios where only even-aged management was used (purple curve). As the proportion of uneven-aged management increases above 50%, differences between management scenarios become marginal for both the road density and road costs (Figure 4a, b). This suggests a saturating effect in the increased use of uneven-aged management for these two variables. The level of aggregation of the cuts, on the other hand, only had a minor effect on the forest road network where higher aggregation slightly reduced road density (Figure 4c) and had almost no effect on road construction and repair costs (Figure 4d). However, the effect of aggregation on road density was more visible for scenarios with only even-aged management (not shown in Figure 4; see Appendix J). Lastly, the presence or absence of an initial road network only had noticeable effects on the road density and the cost of roads in the first 20 years of simulations, after which no significant differences were observed (Figure 4g, h).

Amount of old forests and fragmentation level

Following the first 70 years of the simulations, the quantity of old forest increased with an increase in uneven-aged management (Figure 5a, c). In contrast, *Clumpy* was lower in scenarios with more uneven-aged management, indicating that the fragmentation *per se* of the landscape increased (Figure 5b, d). We observed no strong effect of the aggregation level of cuts on the amount of old forests (Figure 5e, g). Moreover, an increase in aggregation level was associated with slightly higher values of *Clumpy*, indicating lower fragmentation in the southern region (Figure 5g), but the effect of increased aggregation was almost non-existent in the northern region (Figure 5f). Note that the northern and southern regions of our study area were both subjected to a similar intensity of management, as the areas harvested in each of these forests in our different scenarios were almost identical (Appendix F).

Irrespective of the proportion of uneven-aged management and aggregation level, the amount of old forest increased rapidly after a 50-year time step period of stability. Then, it slightly decreases with time during the second half of the simulations, except for the 0% uneven-aged level in the north which showed a marked increase in the quantity of old forests, and the 50% uneven-aged level in the south which showed a steep decline (Figure 5a, c, e, g). *Clumpy*, on the other hand, showed a weaker contrast between scenarios. In the north, *Clumpy* decreased at the beginning of the simulation but increased afterwards with small differences between management scenarios (Figure 5b, f). In the south, from 50 years of simulation and onwards, *Clumpy* exhibits a marked decrease for scenarios with more uneven-aged management, indicating an increase in fragmentation. However, no such difference in the value of *Clumpy* is seen for aggregation scenarios (Figure 5f).

4. Discussion

The goal of this study was to compare the long-term and large-scale effects of even- and uneven-aged forest management on the amount and fragmentation of old forests. We wanted to determine whether forest roads, necessary to access harvested areas, played an important role in differentiating the effects of these management approaches on forest landscapes. Our results provide important insights into the impact of different types of forest management, and their interaction with existing natural disturbances.

4.1. The forest road network

Results from our simulations clearly indicate that uneven-aged management as defined in our study (irregular shelterwood with a rotation of 30 years) increases the density of forest roads in the landscape (Figure 4a). This outcome was expected since uneven-aged management scenarios extend over a larger surface to harvest the same amount of wood biomass as even-aged management scenarios (Nolet et al. 2018) (see Appendix H). Consequently, more roads are needed to access vaster harvested areas. This tendency would have been even stronger had the FRS module been required to build forest roads lasting up to the next cycle of uneven-aged management cuts.

In addition, smaller differences in road density and costs between scenarios with increasing uneven-aged management suggest a saturation effect where a larger ratio of uneven-aged management does not increase the density of roads anymore. We believe that this saturation effect occurs when the additional areas to be harvested under uneven-aged management become accessible through existing roads. In our study, this saturation threshold corresponds to a proportion of about 50% in the use of uneven-aged forest management. This threshold value probably varies according to the biomass target for the landscape, and the amount of available harvestable wood (not simulated).

The increased costs of road construction and repair present a possible limitation for the use of uneven-aged management. In Quebec, where our study area is located, forest roads currently represent 10 to 18% of the operational costs for the forest industries and the government (Groupe DDM and MFFP 2020). If these costs were to increase (i.e., by promoting the use of uneven-aged management), it is difficult to determine the economic consequences for the forest industry. The denser forest road network that results from using uneven-aged management increases the access to remote forest areas, which could be desirable for some stakeholders (e.g., hunters, trappers, residents, tourists, etc.) but not necessarily so for others (First Nations, conservation organizations, etc.) (Adam et al. 2012). The increased human presence might lead to negative impacts on the ecosystems surrounding the roads (e.g., increased fire risk, spread of invasive plants, disturbance of wildlife, etc.) (Kneeshaw and Gauthier 2006; Hunt et al. 2009; Adam et al. 2012). These potential landscape impacts of an increased road density reveal an important aspect of the land-sharing approach in forestry – represented by a prevalent use of uneven-aged methods – and should be taken into account when comparing the sparing and sharing approaches. However, increasing road density in the context of Reduced Impact Logging (RIL) in the Amazon was shown to increase species richness (Carvalho Jr et al. 2021). Hence, social and ecological context is essential to understanding the impact of forest roads.

The aggregation of harvested areas decreased the density of roads in the landscape far less than what was expected and did not reduce the cost of road construction and repair (Figure 4c, d). In fact, the effect was undetectable at 50% uneven-aged management and remained minor even when harvesting was entirely done through even-aged management (see Appendix J). The limited effect of aggregation, especially under higher levels of uneven-aged management, can be explained by constraints on the available surface to be harvested. Indeed, when the surface to harvest is large compared to stand availability, cut zones become concentrated in the landscape regardless of the imposed aggregation level. As such, the density of roads in the landscape remains similar even under increased aggregation. Furthermore, aggregating the harvested areas concentrates the quantity of transported timber onto a smaller number of roads, which in turn requires that these roads be updated to a higher size category. The costs to update a few larger roads can be equivalent to those required to construct a higher number of smaller and less expensive roads, which could explain why aggregation does not reduce road costs. Our results might have been different if we had considered other factors such as the more frequent road repairs required with increased traffic of logging trucks, for example.

These results suggest that it would be difficult to compensate for the increase in road density associated with uneven-aged management by simply increasing the aggregation of cuts. In addition, aggregation may not always be operationally possible. Indeed, extending the area of harvest over surrounding stands may be constrained by the lack of trees of the appropriate age or composition or the absence of forest. Local legislation may also limit the size of cuts, which is the case in Quebec since 2018 (Gouvernement du Québec 2018). As such, it seems unlikely that a high enough level of aggregation could be reached to offset the effects of a switch to more uneven-aged management. Still, aggregation might compensate for a smaller increase in uneven-aged management use if coupled with a strategic spatial distribution of cuts (Tittler et al. 2015).

Our results also indicate that the presence of an initial forest road network did not have a long-term influence on road density and cost (Figure 4e, f). Differences in these measures were eliminated over the first 50 years of simulations (a period which also corresponds to the life expectancy of the largest roads in our study). Without the process of road aging and deterioration, we expect that the initial road network would have had a more persistent impact on the landscape. Nevertheless, including forest road aging in our FRS module is a more realistic scenario reproducing the inevitable decay of roads due to erosion, forest regrowth or wear, after which roads are ultimately either repaired or abandoned (Gucinski 2001).

Additionally, the timing at which the scenarios with and without an initial road network converge (around 30 years) is determined by our calibration of the harvest module: new forest roads progressively spread in the landscape during the first five iterations of the simulation. Had we chosen a shorter or longer period for the expansion of new roads, the convergence of both networks would have occurred earlier or later during the planning horizon.

4.2. Amount of old forests

Our study shows that uneven-aged management, in the form of irregular shelterwood, can increase the quantity of older tree cohorts across the landscape. This can be an advantage over even-aged management in terms of conservation of old-growth attributes harbouring rare species (MacKinnon 1998; Mosseler et al. 2003), even though a much greater area needs to be harvested to achieve the same harvesting biomass. Indeed, the area harvested at each time step was about five times superior in scenarios using only uneven-aged management when compared with scenarios using only even-aged management (see Appendix H). Hence, certain uneven-aged management practices could be seen as promoting forest stands with more desirable attributes, from both an ecological and aesthetic perspective. However, these potential benefits of uneven-aged management may be limited by two factors.

First, forests with old-growth attributes are reduced when a stand-replacing disturbance such as fire occurs in the landscape, as evidenced by the stark difference in the amounts of old forests in the north and the south regions due to the different fire regimes between these two ecoregions. In the northern region, the total area of burned forest at the end of a simulation was about ten times larger than in the southern region (Appendix H), reducing the accumulation of old forests over time in that region. This suggests that stand-replacing disturbances constrain the capacity of uneven-aged management to preserve more mature forests. Critically, in future climates where natural disturbances such as forest fires are expected to be more frequent and severe, the ability of uneven-aged management to maintain old forests may be weakened (Dale et al. 2001; Régnière et al. 2012; Seidl et al. 2017).

Second, while uneven-aged management can be perceived as less impactful than even-aged management at the local scale, it remains a disturbance to forests. Indeed, through the periodic returns to harvested stands, impacts on soil, understory, and local fauna may accumulate over time (Nolet et al. 2018). Even if those impacts are reduced locally when compared to even-aged management (such as clearcutting), they extend across a larger surface in the landscape. This echoes some elements of the debate regarding land-sparing and land-sharing strategies (Edwards et al. 2014).Hence, our study reveals some of the limits of using such an extensive land-sharing approach in a landscape to protect important ecosystem services. Yet, other arguments are present in the existing literature, advocating for the utility of both approaches (Edwards et al. 2014; Mori and Kitagawa 2014). Our results further reveal some interactions between even- and uneven-aged management. For instance, we observed a steep decline in the amount of old forest in the south of our study area, at the end of the simulation when the proportion of uneven-aged management reached 50% (Figure 5c). This decline results from the even-aged harvesting of old forests that had been preserved by prior uneven-aged cuts. In scenarios with less uneven-aged management (i.e., 0% and 25%), this decline is compensated by the higher quantity of younger forests that are in the process of transitioning to old forests. These trends suggest that the effects of both even-aged and uneven-aged management on forest age could become more similar over time, had we simulated these interactions beyond 150 years.

Our results also present artifacts resulting from both our definition of old forests and from our modelling choices. The first is represented by the sudden increase in the amount of old forests between 40 and 70 years of simulation especially in the south of our study area (Figure 5a, c) but also at 100 years of simulation in the north in scenarios with no uneven-aged management (Figure 5a). These increases are the result of many age cohorts of the landscape reaching the critical age of 91 years old from their initiation at the beginning of the simulation, or from earlier even-aged cuts and burned forests. Had we chosen a different definition of old forest and modelled all the disturbances that historically affected the landscape (see section “Limitations” below), this increase might have happened at a different time, or not at all. Still, we do not expect that this departure from the initial conditions of the landscape had any effect on our results or our conclusions since our analysis compared relative differences between scenarios.

4.3.Fragmentation of old forests

Our results point to a complex trade-off between the amount and fragmentation of old forests in uneven-aged management. Indeed, in the south of our study area, the consistent decrease of *Clumpy* with time in scenarios using uneven-aged management seems to indicate that while the number of old pixels increases, their contiguity is generally not preserved because of the higher road density required in these scenarios (Figure 5b, d, f, h). However, it should be noted that even-aged management did fragment old forests across the landscape through roads, and also by creating patches of younger forest.Intermediate scenarios also reveal changing trends in the values of Clumpy in the south of the area until the end of the simulation. This suggests that interactions between even-aged and uneven-aged cuts might have changed the results if the simulations had gone on for several decades. The potential effects of this trade-off are difficult to evaluate from an ecological perspective and will be highly dependent on how roads and younger forests actually impact species on the landscape. However, the presence of a stand-replacing disturbance seems to heavily influence this trade-off as this pattern almost disappears in the north of our study area characterized by much more frequent forest fires compared to the south. Therefore, the occurrence of stand-replacing disturbances should also be considered when comparing the effect of even- and uneven-aged management on old forests (see section 4.4).

Furthermore, the effect of fragmentation *per se* (i.e., differentiated from habitat loss) on biodiversity is currently a highly debated subject in the scientific literature, allowing for different interpretations of our results. Indeed, some authors argue that fragmentation has a generally neutral or even positive effect on biodiversity in the landscape (Fahrig 2017) while others defend the opposing view (Fletcher et al. 2018). Therefore, questioning the long-term, large-scale effects of uneven-aged management on biodiversity through its impact on habitat connectivity might provide different conclusions. For example, species such as the Pacific marten (*Marten caurina*) tend to select forest stands with a higher structural complexity to ease their movement in the landscape, avoiding “simpler” stands with characteristics resembling even-aged stands (Moriarty et al. 2015). Although uneven-aged management creates more numerous and dispersed smaller roads, even-aged management generates fewer but bigger roads, and may have less impact on the terrestrial fauna that tends to avoid these larger pathways (Tittler et al. 2012). As our study focused on structural connectivity at the landscape scale, we expect that pertinent information will come from future research exploring different management scenarios similar to this study but taking into account the effect on the functional connectivity of different species. Thus, differentiating the effect of even and uneven-aged management on biodiversity will require comprehensive functional connectivity analyses.

Surprisingly, changing the aggregation levels of the cuts had little to no effect on the fragmentation of old forests as measured by *Clumpy* (Figure 5f, h). This result could be explained by the fact that aggregation only slightly reduces the density of forest roads in the landscape (Figure 4c), which is an important element of fragmentation captured by *Clumpy*. Moreover, *Clumpy* is sensitive to the presence of patches of young forests that are generated by even-aged management and the occurrence of fire, but these patches are absent under uneven-aged management. Therefore, *Clumpy* was relatively unaffected when areas harvested with uneven-aged management were aggregated, and when the aggregation of young forest patches created by even-aged management was weakened by forest fires, which vary in their location and extent. The effect of forest fires is discussed in more detail in the following section.

4.4. Interactions with stand-replacing disturbances

Two types of fragmentation of old forests were operating in our simulated landscape: fragmentation due to forest roads and due to patches of younger forests resulting from stand replacing disturbances. In our simulations, the former is increased using uneven-aged management which increases road density (Figure 6a) while the latter is increased using even-aged management which creates patches of regenerating forests after clearcutting (Figure 6b). Indeed, the fragmentation of old forests was stronger than anticipated under even-aged management because it compounded the two types of fragmentation: one as a result of harvesting and the other due to construction of forest roads. However, the fact that uneven-aged management was associated with higher levels of fragmentation in the south of our study area indicates that roads had a bigger effect on *Clumpy* than the patches of young forest in this landscape.

With these two fragmentation types present throughout the study area, the factor responsible for the difference observed in the values of *Clumpy* between the north and the south of our study area becomes clearly apparent (Figure5b, d), namely forest fires. In our simulations, the harvested surface was similar in both regions of our study area, but the total burned surface was almost 10 times superior in the north than in the south, increasing the area of young forests (see Appendix H). Consequently, our results suggest that fragmentation in the northern region is mainly driven by forest fires, as varying the proportions of uneven-aged management only slightly affected *Clumpy* (Figure 5b). On the other hand, the southern region, which is almost unaffected by forest fires, displays clear differences among uneven-aged management scenarios (Figure 5d).

Therefore, our simulation results suggest that stand-replacing disturbances, such as forest fires, can reduce the differences observed between even- and uneven-aged management in terms of fragmentation and amount of old forests. This could be crucial in areas such as the boreal forest, where frequent forest fires would reduce the capacity of uneven-aged management to preserve more mature forests (see section 4.2). Nonetheless, this lower quantity of old forests in the north is expected no matter the type of harvesting used as the fire regime naturally leads to a lower proportion of old forests. Indeed, using the equations from Wagner (1978) and the fire zone characteristics of Boulanger et al. (2014), it is expected that the northern region of the area would contain 20% fewer forests older than 90 years than the southern region at a theoretical equilibrium induced by the fire regime of both regions. This 20% difference is approximately what we observed in our results, when comparing the amount of old forests in the north and the south of the study area after about 60 years of simulation, for similar management scenarios (Figure 5a, c). Consequently, the differences in the effect of land-sharing and land-sparing management approaches on the amount and fragmentation of old forests will heavily depend on the occurrence, extent and severity of natural disturbances.

Our results also suggest that uneven-aged management in the boreal forest increases the fragmentation by forest roads in a landscape already fragmented by patches of younger forest (due to forest fires). In contrast, even-aged management could be seen as emulating a type of fragmentation already present in boreal forests (patches of younger forests), while reducing a second type of fragmentation not naturally present (forest roads). Nevertheless, forest roads created for uneven-aged management could facilitate access to recently burned forests for salvage logging and reforestation purposes (Cyr et al. 2022). In addition, even-aged management could bring an additional fragmentation to that already caused by forest roads in regions where stand-replacing disturbances are less present (Guldin 1996). This distinction of where best to use even-aged or uneven-aged management touches on one of the key concepts of ecosystem-based management: sustainability of forests can be achieved under management methods able to reproduce their natural disturbance regime (Bergeron et al. 2002; Harvey et al. 2002; Gauthier and

Vaillancourt 2008). Furthermore, the large surfaces of forest and the dense road network needed for uneven-aged management could also present an advantage in the context of global changes. Indeed, the uneven-aged harvested forests could be managed in a way that helps them transition more rapidly to a different state of structure and composition that would make forests more resistant and resilient to the new conditions created by global changes (Messier et al. 2019).

While both the fragmentation due to roads and to patches of younger forest are operating simultaneously, their effects are not equivalent. Indeed, forest roads are associated with diverse management and ecological issues, such as the spread of invasive species (Mortensen et al. 2009; Meunier and Lavoie 2012), collisions with fauna (Lugo and Gucinski 2000), increased presence of humans (Gucinski 2001), and corridors or barriers to animal movement that can disturb their population dynamics (Marsh et al. 2005; Whittington et al. 2011). It has also been suggested that roads create up to twice the amount of habitat edges than clearcutting does (Reed et al. 1996). Moreover, forest road usage is increased under uneven-aged management since it requires periodic re-entry into stands and a larger surface to harvest (Nolet et al. 2018), causing an increase in the transit of forestry vehicles which in turn intensifies disturbances on fauna and flora, and emits additional greenhouse gases. Forest roads also represent a constant loss of productive forest surface over time, contrary to young forests, as shown by Figure 4a where up to 12% of the cells of our landscape are continuously occupied by forest roads after the first 50 years of simulation. Although individual forest roads deteriorate over time, if forest management is maintained, other roads will be reconstructed elsewhere. For their part, young forests generated by even-aged management will eventually grow into mature forests. However, if stand-replacing harvesting is maintained across the landscape, old forests will be reduced. Moreover, forest regeneration must be ensured following even-aged cuts by the proximity of mature trees and seed banks, the planting of saplings, or the protection of the youngest cohorts during harvesting. If these three elements are missing, which might be the case in some contexts, then forest regeneration will be compromised, leading to long-lasting habitat loss (Timoney and Peterson 1996).

4.5. Limitations

Our modelling approach presents some limitations worth mentioning. First, our results are highly dependent on the way we define old forests. We followed the definition of old forest used by the MRNF: a forest containing at least one age cohort older than 91 years (MFFP du Québec 2016). Yet this definition does not fully capture the concept of old-growth forest often used when discussing the conservation value of older forests, which is both complex and context-dependent (Hilbert and Wiensczyk 2007; Wirth et al. 2009). An “old-growth forest” (McMullin and Wiersma 2019) can refer to a certain forest structure (e.g., old and large trees, logs and snags or a wide distribution of tree size), specific successional processes (e.g., climax forest or steady-state condition), or even certain biogeochemical processes (e.g., decay of snags and logs or nutrient retention) (Wirth et al. 2009). Moreover, an old-growth forest in a boreal biome can be much younger than what would be considered an old forest in other biomes, e.g., a tropical biome. In addition, the definition of old forest that we used does not distinguish between an "untouched" old forest that has not been harvested or disturbed for a long time (i.e., an old-growth forest) and a forest harvested by uneven-aged management, but that still presents some relatively old cohorts (i.e., a forest with old trees). Therefore, we expect that uneven-aged management would have fared worse regarding the fragmentation of "untouched" old forests. This could be important for species that are sensitive to the quality rather than the quantity of available old forests (e.g., Regolin et al. 2021). Lastly, while we did not measure the diversity in forest age classes across the landscape, it can be argued that the quantity of old forests can capture this structural heterogeneity. Indeed, old forests tend to contain more age classes even if originally disturbed by a stand replacing disturbance such as a severe forest fire or even-aged cut (Bergeron 2004; Martin et al. 2022).

A second limitation comes from the geographical context of our study area. The Mauricie region is characterized by vast expanses of mixed and boreal forests located far away from the main road network or any community. In more densely populated regions where the permanent road network is closer to harvested areas, we expect that increasing the use of uneven-aged management would not necessarily lead to an increase in forest road density. In addition, had we simulated epidemics of spruce budworm, we would likely have observed a less important difference in the proportion of old forests between the southern and northern regions. This significant agent of disturbance affects mature fir-spruce stands in the south of our study region but does so less frequently in the north where the growing season is too short for completing their life cycle (Régnière et al. 2012). Tree mortality due to repeated years of spruce-budworm defoliation contributes to the rejuvenation of old stands.

A third limitation is that our results may be sensitive to the particularities of the forestry methods that we simulated, which are based on the common harvesting prescriptions in Quebec. As such, our results may not be generalized to different combinations of harvesting methods used in other countries. In addition, the harvesting stand prescriptions that we simulated with LANDIS-II are quite simple and broad in their application. This is because LANDIS-II currently does not allow prescriptions based on a complex assignment of stands including, for example, species, age structure, or soil conditions. As such, further studies might be needed to explore the nuances that might result from more complex prescriptions assignments.

Fourthly, we did not include the effect of a changing climate in our simulations, even if their effects on forest regeneration, precipitation, and fire regimes are expected to take place on a 150 year horizon. Indeed, in Quebec, climate change is predicted to increase the frequency of forest fires and affect the growth of many tree species (Boulanger et al. 2023). To better distinguish and interpret differences resulting from different management strategies, and to reduce the computational load of the simulations, we opted not to consider the impact of climate change. But as highlighted previously, more frequent fires might reduce the differences in fragmentation and quantity of old forest observed in our study between even-aged and uneven-aged management scenarios.

Additionally, changes in species growth might require different harvesting prescriptions to facilitate the regeneration of species more impacted by climate change in the future.

Finally, it is important to recall that the density of forest roads (D_r) reported here corresponds to the proportion of cells in the landscape that contain a road. Because the actual surface occupied by a road is smaller than the spatial resolution of the model (1 ha), the road density variable certainly overestimates the density of forest area transformed into roads. Thus, while forest roads were present in up to 12% of the cells of our simulated landscape (Figure 4a), they did not occupy 12% of the surface of the landscape.

5. Conclusion

Our simulation study demonstrates that a land-sharing strategy in forestry, characterized by a prevalence of uneven-aged management methods,can increase the density of roads, the level of fragmentation, the cost of road construction and repair, and the amount of forests with old-growth attributes in the landscape. It also suggests that fragmentation could be slightly lowered by aggregating harvested areas. The presence of an initial road network did not alter fragmentation in the long term. Thus, our study shows that despite the potential benefits of uneven-aged management for conservation at the stand level, it can contribute to additional landscape fragmentation when compared to even-aged methods. This finding, along with the additional costs associated with the construction of a more extensive road network, needs to be considered when balancing objectives through strategic forest management planning.

Our results also imply that choosing between even- and uneven-aged management involves a trade-off between the proportion of old forests in the landscape and their level of fragmentation. However, the consequences of this trade-off are closely linked to the specific even- and uneven-aged methods employed, the definitions used for fragmentation and habitat, the patterns of fragmentation resulting from natural disturbances, and the perceived effects of fragmentation on the landscape. Overall, our study indicates that uneven-aged management at the landscape scale, which can be considered as a land-sparing strategy, is not necessarily better than even-aged management, a land-sparing strategy, for conserving forest ecosystems. Hence, our study emphasizes the notion that over large spatiotemporal scales, no single forest management strategy is both economically and ecologically "better" than another (Puettmann et al. 2009; Nolet et al. 2018).

While neither even-aged nor uneven-aged management is without flaws, we anticipate that a mix of these two methods, implemented in the right place, could present the best compromise. Indeed, management scenarios that combined both methods presented intermediate values in all the measured variables, suggesting that their use could be fine-tuned to obtain the desired compromise between the conservation of certain forest habitats, and the construction of forest roads to maintain timber production. To further optimize such fine-tuning, management plans that strategically position areas harvested with uneven-aged management could reduce landscape fragmentation. For example, clustering areas managed near existing roads or organizing the landscape into zones of different harvesting intensities (as in the TRIAD approach) could reduce the need for additional roads when harvesting larger surfaces, thereby facilitating connectivity between sensitive or important habitats (Messier et al. 2009; Tittler et al. 2012).

6. Acknowledgments

We would like to thank Jérôme Garet of the MRNF for helping us gather valuable data to parameterize the FRS module.

7. Funding

Funding was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) through a Collaborative Research and Development grant awarded to C. Messier (RDCPJ: 498998-16) with the joint support of Resolute Forest Products, and a Discovery grant awarded to E.Filotas (RGPIN: 2018-06156).

8. Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

9. Author contributions

Clément Hardy: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization; **Christian Messier**: Conceptualization, Methodology, Resources, Writing – Review & Editing, Supervision, Funding Acquisition; **Yan Boulanger**: Software, Data Curation, Writing – Review & Editing; **Dominic Cyr**: Software, Data Curation, Writing – Review & Editing; **Elise Filotas**: Conceptualization, Methodology, Investigation, Resources, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

10. Data availability

The data concerning the preliminary simulations to calibrate certain parameters of LANDIS-II, all of the parameter files for all of the simulations, the scripts used to launch the simulations on Compute Canada's clusters, the raw results and the scripts used to analyze the results and produce the figures are all available on the following figshare private repository: https://figshare.com/s/1e84862cf4114b336a7f . The data of the repository will become public and identified with a DOI once the manuscript will be ready to be published.

11. Figures

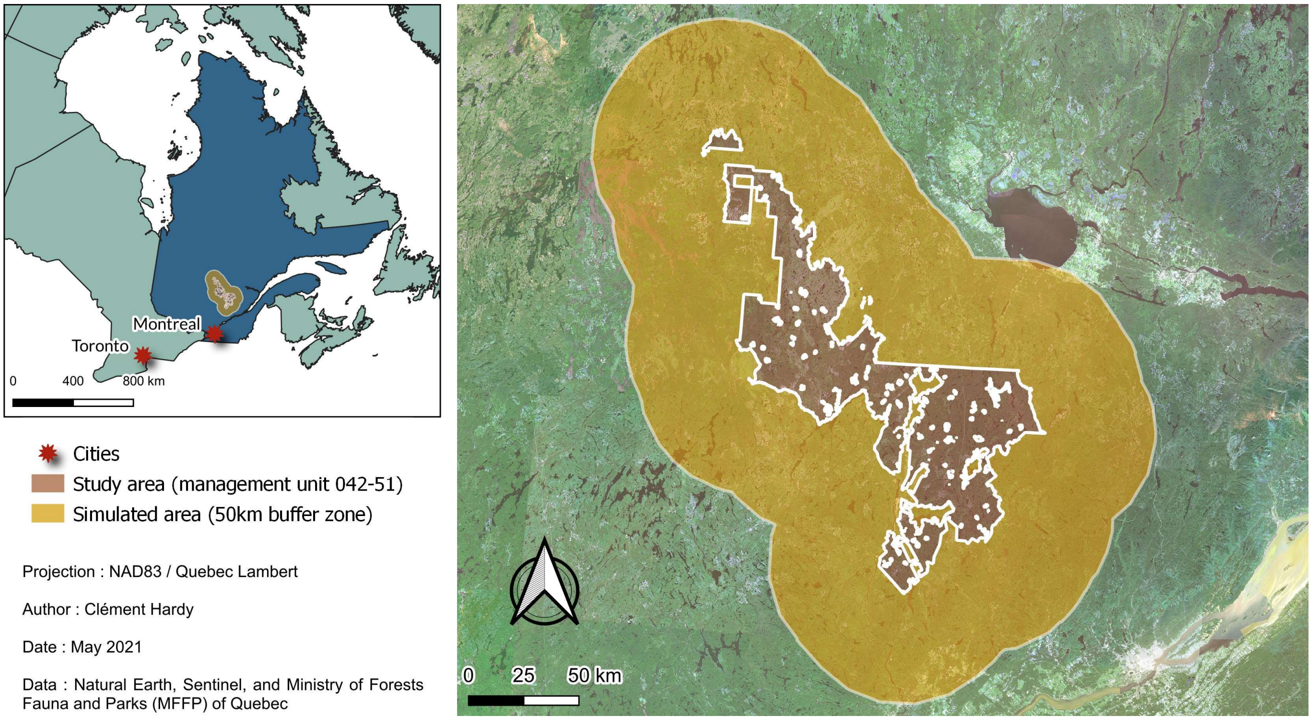
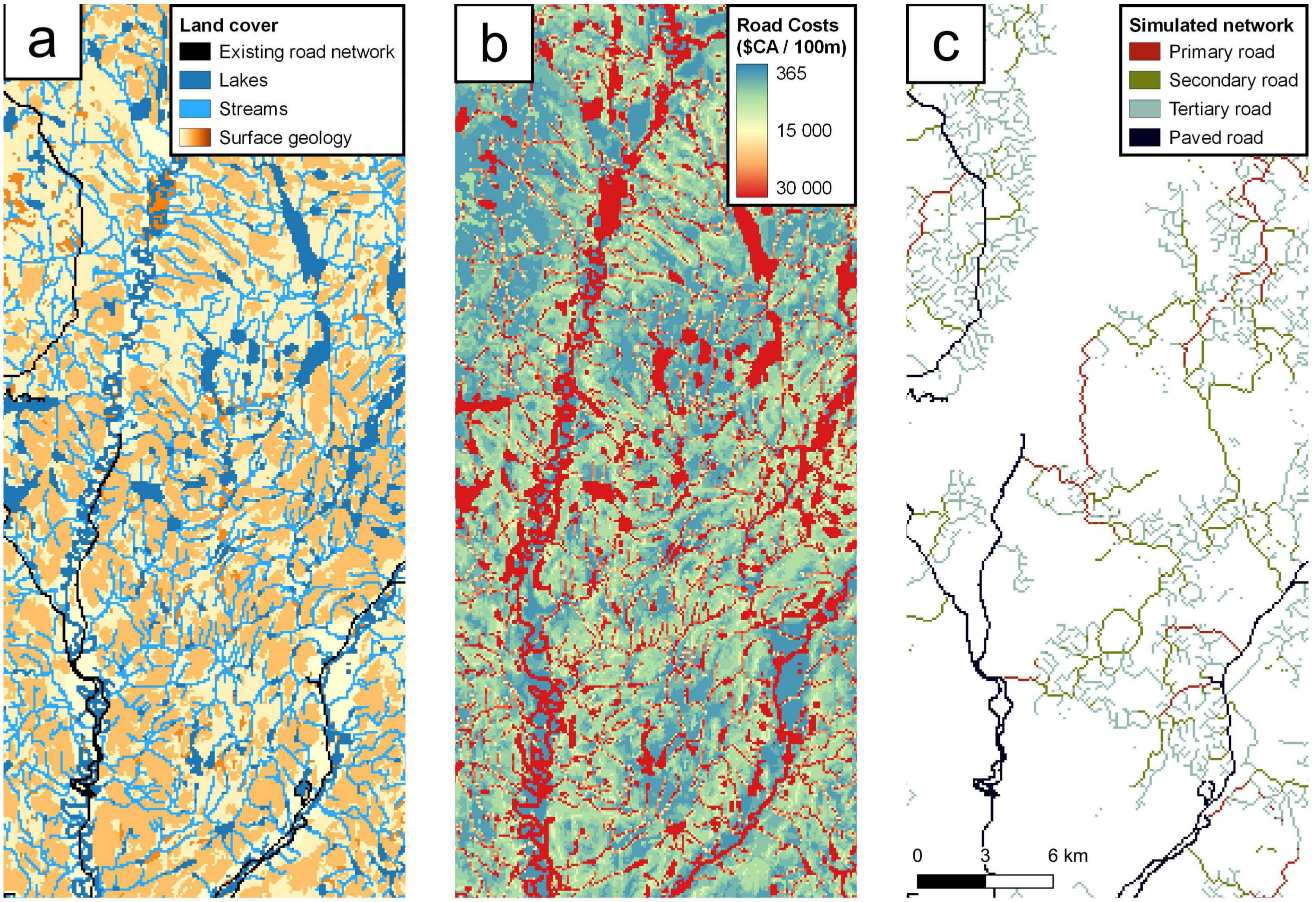


Figure 1 Map of study area (brick colour in the centre) and simulated area (gold) in Mauricie (Quebec, Canada). The northern part is located in the boreal coniferous forest whereas the southern part is located in the temperate mixed wood forest.



Projection : NAD83 / Quebec Lambert Author : Clément Hardy Date : May 2021

Figure 2 Three maps showing the same section of simulated landscape in the centre of our study area: a) Landscape features; b) Construction costs – computed by the FRS module based on topography, soils, water bodies, streams and existing roads; and c) Simulated network of roads after 150 years of simulations. In c), isolated road segments correspond to remains from old deteriorating roads.

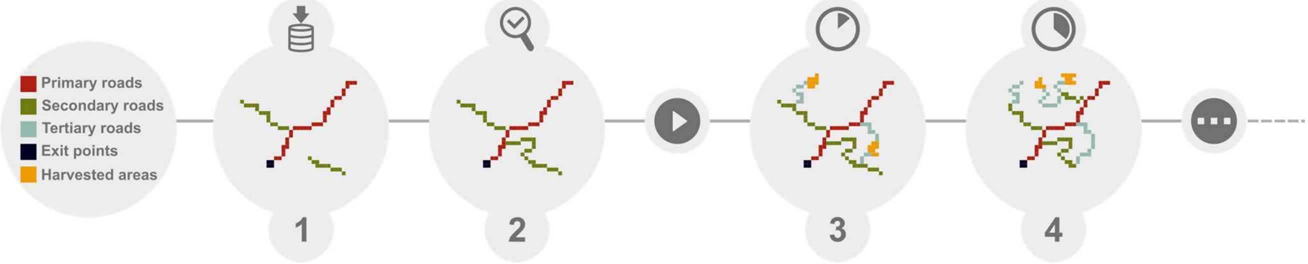


Figure 3 Diagrams showing the evolution of the forest road network simulated by the FRS module. Road pixels are coloured according to their size category. (1) Input data is read by the module; (2) the roads

that are not connected to an exit point (brown pixels; e.g., paved roads, sawmills, etc.) are detected and linked to the rest of the network in the initialization phase; (3 and 4) at each time step, the FRS module generates forest roads connecting the harvested areas to the rest of the network using the Dijkstra algorithm. Roads can form loops in the network, as shown in (3), where two roads connect the harvested area on the right. Additionally, the size category of a road may change with an increase in wood flux where two tertiary roads merge into a secondary road (4). Road aging is also simulated where two segments of secondary roads disappear from the network (4).

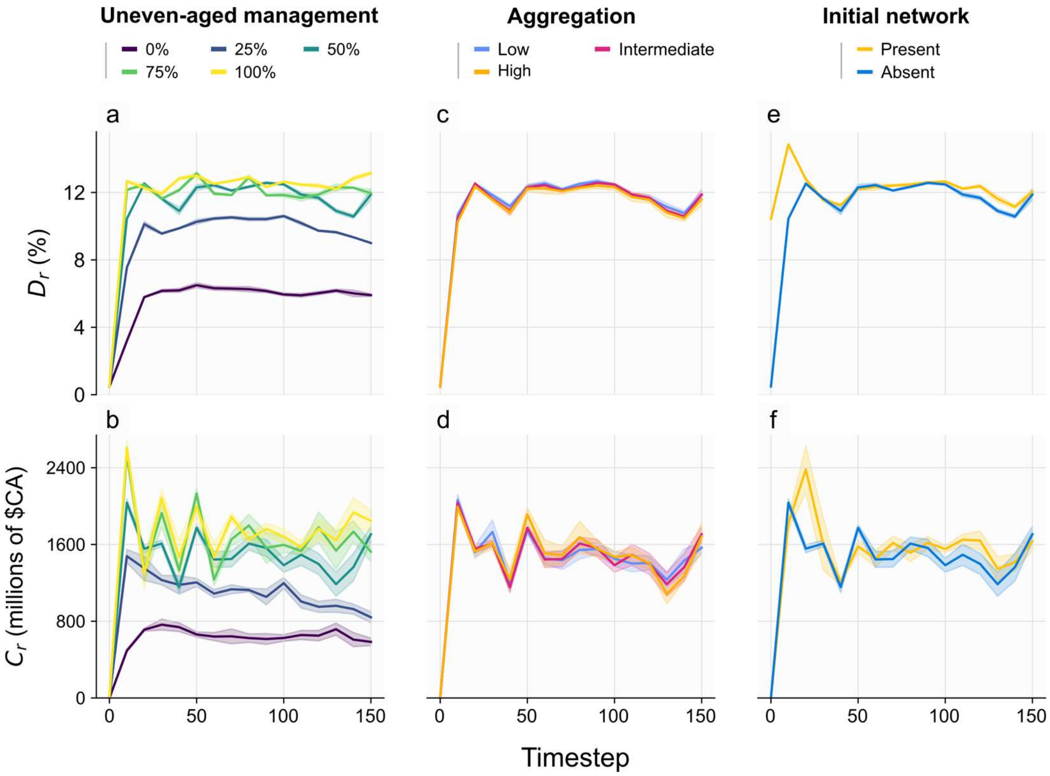


Figure 4 Time dynamics of the road density (Dr; top panel) and the costs of road construction and repair (Cr; bottom panel) for each factor: percentage of the biomass target harvested using uneven-aged management (a, b), aggregation level of harvested areas (c, d), and presence of an initial forest road network (e, f). Each factor (management, aggregation, initial network) is varied while keeping the other factors at their intermediate value. Curves correspond to the average of 5 simulation runs, and shaded areas correspond to the standard deviation across runs.

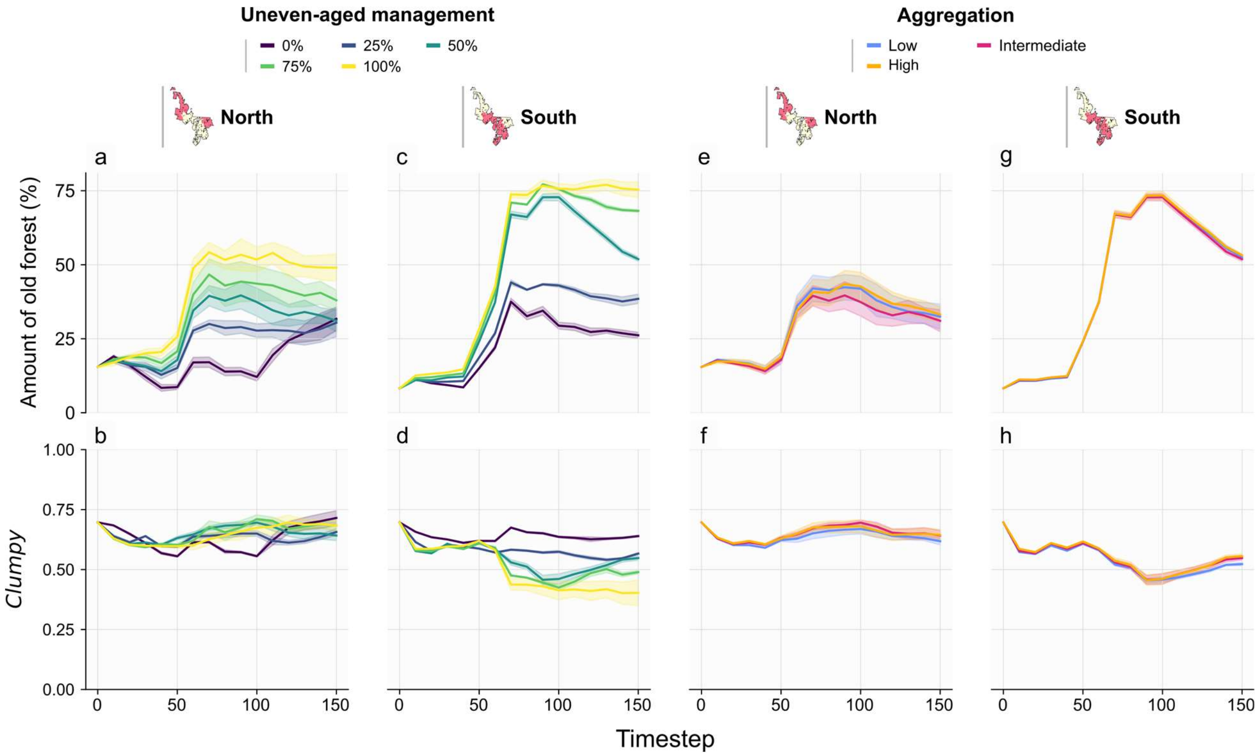
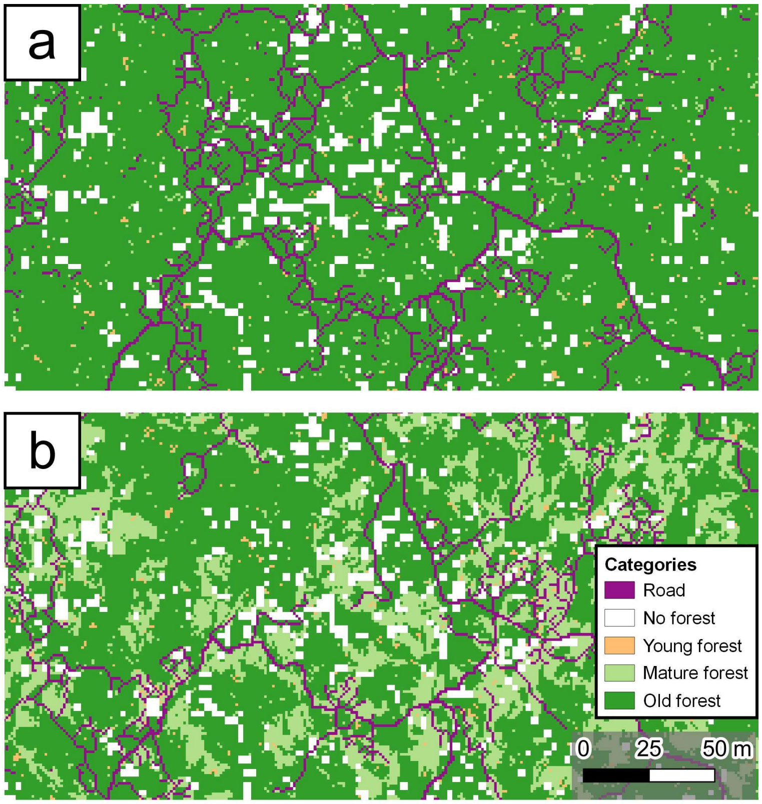


Figure 5 Effects of forest management and fire on the fragmentation of old forests measured by the amount of old forests (top panel, a, c, e, g) and the clumpiness index, *Clumpy* (bottom panel, b, d, f, h). The two columns on the left vary the proportion of uneven-aged management used for the northern region (1st column) and the southern region (2nd column) of our study area. The two columns on the right vary the aggregation level of cuts for the northern (3rd column) and southern (4th column) regions. Each factor (management, aggregation) is varied while keeping the other factors at their intermediate value. Curves correspond to the average of 5 simulation runs, and shaded areas correspond to the standard deviation across runs.



Projection : NAD83 / Quebec Lambert   Author : Clement Hardy   Date : May 2021

Figure 6 A section of our simulated landscape at t = 100 years during a simulation where a) only uneven-aged management is used, and b) only even-aged management is used. Young forests are defined as pixels with trees no older than 15 years; mature forests are pixels whose oldest trees range between 15 and 91 years of age; old forests are pixels comprising trees older than 91 years. It clearly appears that the fragmentation of old forests is associated with the extent of the road network under uneven-aged management (a) while it is also associated with the distribution of patches of younger forests under even-aged management (b).

12. Tables

Prescription	% biomass harvested	First harvest	Second harvest
Even-aged			

Clearcutting	90%	All age cohorts older than 10 years	None
Shelterwood	10%	90% of the biomass of all age cohorts older than 10 years	20 years later: all age cohorts older than 10 years
Uneven-aged			
Irregular Shelterwood	100%	30% of the biomass of all age cohorts 30 years and older	Same as the first, and repeated every 30 years

Table 1 Summary of the harvest prescriptions used in the simulated landscape.

Factor	**% of biomass target harvested with uneven-aged management**	**Aggregation of harvest cuts**	**Presence of an initial road network**
Levels of factor	0%	Low Maximum size of cuts is half of the historical maximum	Yes All roads from the AQReseau + database are initially present
	25%		
	50%	Historical maximum	
	75%	High Maximum size of the cuts is twice the historical maximum	No Only the main, paved roads are initially present
	100%		

Table 2 Summary of the variations of the three factors used to create scenarios. Each of the 30 scenarios corresponded to a unique combination of the three factors.

13. References

Adam M-C, Kneeshaw D, Beckley TM (2012) Forestry and road development: Direct and indirect impacts from an aboriginal perspective. Ecol Soc 17:

Adamic M, Diaci J, Rozman A, Hladnik D (2017) Long-term use of uneven-aged silviculture in mixed mountain Dinaric forests: a comparison of old-growth and managed stands. For Int J For Res 90:279–291. https://doi.org/10.1093/forestry/cpw052

Alain D, Boudreau J-F, Philibert Y, et al (2016a) Placettes-échantillons temporaires: normes techniques

Alain D, Boudreau J-F, Philibert Y, et al (2016b) Placettes-échantillons permanentes: normes techniques

Alexander RR, Edminster CB (1977) Uneven-aged management of old-growth spruce-fir forests: Cutting methods and stand structure goals for the initial entry. USDA For Serv 19

Beaudoin A, Bernier PY, Guindon L, et al (2014) Mapping attributes of Canada's forests at moderate resolution through kNN and MODIS imagery. Can J For Res 44:521–532. https://doi.org/10.1139/cjfr-2013-0401

Bergeron Y, Fenton NJ (2012) Boreal forests of eastern Canada revisited: old growth, nonfire disturbances, forest succession, and biodiversity. Botany 90:509–523. https://doi.org/10.1139/b2012-034

Bergeron Y, Leduc A, Harvey BD, Gauthier S (2002) Natural fire regime: A guide for sustainable management of the Canadian boreal forest. Silva Fenn 36:81–95

Betts MG, Phalan BT, Wolf C, et al (2021) Producing wood at least cost to biodiversity: integrating Triad and sharing–sparing approaches to inform forest landscape management. Biol Rev 96:1301–1317. https://doi.org/10.1111/brv.12703

Boudreault C, Zouaoui S, Drapeau P, et al (2013) Canopy openings created by partial cutting increase growth rates and maintain the cover of three Cladonia species in the Canadian boreal forest. For Ecol Manag 304:473–481. https://doi.org/10.1016/j.foreco.2013.05.043

Boulanger Y, Arseneault D, Boucher Y, et al (2019) Climate change will affect the ability of forest management to reduce gaps between current and presettlement forest composition in southeastern Canada. Landsc Ecol 34:159–174. https://doi.org/10.1007/s10980-018-0761-6

Boulanger Y, Gauthier S, Burton PJ (2014) A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. Can J For Res 44:365–376. https://doi.org/10.1139/cjfr-2013-0372

Boulanger Y, Taylor AR, Price DT, et al (2017) Climate change impacts on forest landscapes along the Canadian southern boreal forest transition zone. Landsc Ecol 32:1415–1431. https://doi.org/10.1007/s10980-016-0421-7

Brang P, Spathelf P, Larsen JB, et al (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. For Int J For Res 87:492–503

Bureau du forestier en chef du Quebec/ Quebec's Office of the Chief Forester (2013) Manuel de détermination des possibilités forestières, 2013-2018. Bureau du forestier en chef, Roberval, Québec

Burton PJ, Canada NRC (2003) Towards Sustainable Management of the Boreal Forest. NRC Research Press

Cameron EK, Bayne EM, Clapperton MJ (2007) Human-facilitated invasion of exotic earthworms into northern boreal forests. Ecoscience 14:482–490. https://doi.org/10.2980/1195-6860(2007)14[482:HIOEEI]2.0.CO;2

Carvalho Jr EAR, Nienow SS, Bonavigo PH, Haugaasen T (2021) Mammal responses to reduced-impact logging in Amazonian forest concessions. For Ecol Manag 496:119401. https://doi.org/10.1016/j.foreco.2021.119401

Clark WA (2011) Clarifying the spiritual value of forests and their role in sustainable forest management. J Study Relig Nat Cult 5:

Couillard P-L, Bouchard M, Laflamme J, Hébert F (2022) Zonage des régimes de feux du Québec méridional. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière

Curtis PG, Slay CM, Harris NL, et al (2018) Classifying drivers of global forest loss. Science 361:1108–1111. https://doi.org/10.1126/science.aau3445

Cushman SA, McGarigal K, Neel MC (2008) Parsimony in landscape metrics: Strength, universality, and consistency. Ecol Indic 8:691–703. https://doi.org/10.1016/j.ecolind.2007.12.002

Cyr D, Gauthier S, Bergeron Y, Carcaillet C (2009) Forest management is driving the eastern North American boreal forest outside its natural range of variability. Front Ecol Environ 7:519–524. https://doi.org/10.1890/080088

Cyr D, Splawinski TB, Pascual Puigdevall J, et al (2022) Mitigating post-fire regeneration failure in boreal landscapes with reforestation and variable retention harvesting: At what cost? Can J For Res 52:568–581

Dale VH, Joyce LA, Mcnulty S, et al (2001) Climate change and forest disturbances. BioScience 51:723. https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2

D'Amato AW, Bradford JB, Fraver S, Palik BJ (2011) Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. For Ecol Manag 262:803–816

Diaci J, Kerr G, O'hara K (2011) Twenty-first century forestry: integrating ecologically based, uneven-aged silviculture with increased demands on forests. For Int J For Res 84:463–465. https://doi.org/10.1093/forestry/cpr053

Duveneck MJ, Thompson JR (2019) Social and biophysical determinants of future forest conditions in New England: Effects of a modern land-use regime. Glob Environ Change 55:115–129. https://doi.org/10.1016/j.gloenvcha.2019.01.009

Edwards DP, Gilroy JJ, Woodcock P, et al (2014) Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Glob Change Biol 20:183–191. https://doi.org/10.1111/gcb.12353

Fahrig L (2017) Ecological responses to habitat fragmentation per se. Annu Rev Ecol Evol Syst 48:1–23

FAO (ed) (2016) State of the world's forests 2016. FAO, Rome

FAO, UNEP (2020) The State of the World's Forests 2020

FAO (2020) Global Forest Resources Assessment 2020. FAO

Fedrowitz K, Koricheva J, Baker SC, et al (2014) REVIEW: Can retention forestry help conserve biodiversity? A meta-analysis. J Appl Ecol 51:1669–1679. https://doi.org/10.1111/1365-2664.12289

Fischer J, Brosi B, Daily GC, et al (2008) Should agricultural policies encourage land sparing or wildlife-friendly farming? Front Ecol Environ 6:380–385. https://doi.org/10.1890/070019

Fletcher RJ, Didham RK, Banks-Leite C, et al (2018) Is habitat fragmentation good for biodiversity? Biol Conserv 226:9–15. https://doi.org/10.1016/j.biocon.2018.07.022

Frey SJK, Hadley AS, Johnson SL, et al (2016) Spatial models reveal the microclimatic buffering capacity of old-growth forests. Sci Adv 2:e1501392. https://doi.org/10.1126/sciadv.1501392

Gauthier S, Vaillancourt M-A (2008) Aménagement écosystémique en forêt boréale. PUQ

Gobster PH (1996) Forest aesthetics, biodiversity, and the perceived appropriateness of ecosystem management practices

Götmark F, Paltto H, Nordén B, Götmark E (2005) Evaluating partial cutting in broadleaved temperate forest under strong experimental control: Short-term effects on herbaceous plants. For Ecol Manag 214:124–141. https://doi.org/10.1016/j.foreco.2005.03.052

Gouvernement du Québec (2015) Adresses Québec: Guide de l'utilisateur. Qué Ministère L'Énergie Ressour Nat Dir Cartogr Topogr 60

Gouvernement du Québec (2018) Règlement sur l'aménagement durable des forêts du domaine de l'État

Graham-Sauvé L, Work TT, Kneeshaw D, Messier C (2013) Shelterwood and multicohort management have similar initial effects on ground beetle assemblages in boreal forests. For Ecol Manag 306:266–274. https://doi.org/10.1016/j.foreco.2013.06.019

Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the fate of wild nature. Science 307:550–555. https://doi.org/10.1126/science.1106049

Gronewold CA, D'Amato AW, Palik BJ (2010) The influence of cutting cycle and stocking level on the structure and composition of managed old-growth northern hardwoods. For Ecol Manag 259:1151–1160. https://doi.org/10.1016/j.foreco.2010.01.001

Groupe DDM, Ministry of Forests, Faune and Parks of Quebec (2020) Enquête sur les couts d'opération forestière dans les forêts du domaine de l'État ainsi que sur les couts et revenus de l'industrie du sciage du Québec 2019

Gucinski H (2001) Forest Roads: A Synthesis of Scientific Information. DIANE Publishing

Guldin JM (1996) The Role of Uneven-Aged Silviculture in the Context of Ecosystem Management. Western Journal of Applied Forestry 11:4–12

Haddad NM, Brudvig LA, Clobert J, et al (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci Adv 1:e1500052–e1500052. https://doi.org/10.1126/sciadv.1500052

Hardy C, Messier C, Valeria O, Filotas E (2023) A LANDIS-II extension for simulating forest road networks. Can J For Res. https://doi.org/10.1139/cjfr-2022-0306

Harvey BD, Leduc A, Gauthier S, Bergeron Y (2002) Stand-landscape integration in natural disturbance-based management of the southern boreal forest. For Ecol Manag 155:369–385. https://doi.org/10.1016/S0378-1127(01)00573-4

Haskell DG (2000) Effects of forest roads on macroinvertebrate soil fauna of the southern appalachian mountains. Conserv Biol 14:57–63. https://doi.org/10.1046/j.1523-1739.2000.99232.x

Hawley RC, Smith DM (1962) The practice of silviculture [by] David Martyn Smith. 7th ed. The continuation of a work published as a 1st ed. in Mar. 1921 by Ralph C. Hawley. Wiley, New York

He HS, Mladenoff DJ (1999) Spatially explicit and stochastic simulation of forest-landscape fire disturbance and succession. Ecology 80:81–99

Hesselbarth MH, Sciaini M, With KA, et al (2019) landscapemetrics: an open-source R tool to calculate landscape metrics. Ecography 42:1648–1657

Hilbert J, Wiensczyk A (2007) Old-growth definitions and management: A literature review. J. of Ecosystems and Management 8:18?

Himes A, Betts M, Messier C, Seymour R (2022) Perspectives: thirty years of triad forestry, a critical clarification of theory and recommendations for implementation and testing. Forest Ecology and Management 510:120103. https://doi.org/10.1016/j.foreco.2022.120103

Hunt LM, Lemelin RH, Saunders KC (2009) Managing forest road access on public lands: a conceptual model of conflict. Soc Nat Resour 22:128–142. https://doi.org/10.1080/08941920801922604

James ARC, Stuart-Smith AK (2000) Distribution of caribou and wolves in relation to linear corridors. J Wildl Manag 64:154–159. https://doi.org/10.2307/3802985

Joelsson K, Hjältén J, Work T, et al (2017) Uneven-aged silviculture can reduce negative effects of forest management on beetles. For Ecol Manag 391:436–445. https://doi.org/10.1016/j.foreco.2017.02.006

Kalabokidis KD, Wakimoto RH (1992) Prescribed burning in uneven-aged stand management of ponderosa pine/douglas fir forests. J Environ Manage 34:221–235. https://doi.org/10.1016/S0301-4797(05)80153-7

Karlsson J, Rönnqvist M, Frisk M (2006) RoadOpt: A decision support system for road upgrading in forestry. Scand J For Res 21:5–15. https://doi.org/10.1080/14004080500487102

Kneeshaw D, Gauthier S (2006) Accessibilité forestière accrue : panacée ou boîte de Pandore ? Téoros Rev Rech En Tour 25:36–40

Knorn J, Kuemmerle T, Radeloff VC, et al (2013) Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network. Environ Conserv 40:182–193

Koivula MJ (2005) Effects of forest roads on spatial distribution of boreal carabid beetles (coleoptera: carabidae). Coleopt Bull 59:465–487. https://doi.org/10.1649/815.1

Kuuluvainen T, Tahvonen O, Aakala T (2012) Even-aged and uneven-aged forest management in boreal fennoscandia: a review. Ambio 41:720–737. https://doi.org/10.1007/s13280-012-0289-y

Kuuluvainen T, Angelstam P, Frelich L, et al (2021) Natural Disturbance-Based Forest Management: Moving Beyond Retention and Continuous-Cover Forestry. Frontiers in Forests and Global Change 4:

Lexer MJ, Hönninger K (2001) A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. For Ecol Manag 144:43–65. https://doi.org/10.1016/S0378-1127(00)00386-8

Lindenmayer D, Franklin J, Lõhmus A, et al (2012) A major shift to the retention approach for forestry can help resolve some global forest sustainability issues. Conserv Lett 5:421–431

Lugo AE, Gucinski H (2000) Function, effects, and management of forest roads. For Ecol Manag 133:249–262. https://doi.org/10.1016/S0378-1127(99)00237-6

Luyssaert S, Schulze E-D, Börner A, et al (2008) Old-growth forests as global carbon sinks. Nature 455:213–215. https://doi.org/10.1038/nature07276

MacKinnon A (1998) Biodiversity and old-growth forests. Conserv Biol Princ For Landsc J Voller Harrison Ed Univ Br Columbia Press Vanc BC 146–184

Mansuy N, Thiffault E, Paré D, et al (2014) Digital mapping of soil properties in Canadian managed forests at 250m of resolution using the k-nearest neighbor method. Geoderma 235–236:59–73. https://doi.org/10.1016/j.geoderma.2014.06.032

Marsh DM, Beckman NG (2004) Effects of Forest Roads on the Abundance and Activity of Terrestrial Salamanders. Ecol Appl 14:1882–1891. https://doi.org/10.1890/03-5179

Marsh DM, Milam GS, Gorham NP, Beckman NG (2005) Forest Roads as Partial Barriers to Terrestrial Salamander Movement. Conserv Biol 19:2004–2008. https://doi.org/10.1111/j.1523-1739.2005.00238.x

Martin M, Boucher Y, Fenton NJ, et al (2020) Forest management has reduced the structural diversity of residual boreal old-growth forest landscapes in Eastern Canada. For Ecol Manag 458:117765. https://doi.org/10.1016/j.foreco.2019.117765

Matthews JD (1991) Silvicultural Systems. Clarendon Press

McGarigal K, Cushman SA, Ene E (2012) FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. Comput Softw Program Prod Authors Univ Mass Amherst Available Web Site Httpwww Umass Edulandecoresearchfragstatsfragstats Html

McMullin RT, Wiersma YF (2019) Out with OLD growth, in with ecological continNEWity: new perspectives on forest conservation. Front Ecol Environ 17:176–181. https://doi.org/10.1002/fee.2016

Merschel A, Vora RS, Spies T (2019) Conserving dry old-growth forest in Central Oregon, USA. J For 117:128–135

Messier C, Bauhus J, Doyon F, et al (2019) The functional complex network approach to foster forest resilience to global changes. For Ecosyst 6:21. https://doi.org/10.1186/s40663-019-0166-2

Messier C, Tittler R, Kneeshaw DD, et al (2009) TRIAD zoning in Quebec: Experiences and results after 5 years. For Chron 85:885–896

Meunier G, Lavoie C (2012) Roads as Corridors for Invasive Plant Species: New Evidence from Smooth Bedstraw (Galium mollugo). Invasive Plant Sci Manag 5:92–101. https://doi.org/10.1614/IPSM-D-11-00049.1

Ministry of Forests, Fauna and Parks of Quebec (2018a) Cartographie du 5e inventaire écoforestier du Québec méridional - Méthodes et données associées

Ministry of Forests, Fauna and Parks of Quebec (2018b) Plan d’aménagement forestier intégré tactique (PAFIT) 2018-2023 de l’Unité d’aménagement 042-51 de la Région de la Mauricie et du Centre-Du-Québec

Ministry of Forests, Fauna and Parks of Quebec (2016) Intégration des enjeux écologiques dans les plans d'aménagement forestier intégré de 2018-2023, Cahier 2.1 – Enjeu liés à la structure d'âge des forêts. Gouvernement du Québec

Mina M, Messier C, Duveneck M, et al (2020) Network analysis can guide resilience-based management in forest landscapes under global change. Ecol Appl e2221

Mori AS, Kitagawa R (2014) Retention forestry as a major paradigm for safeguarding forest biodiversity in productive landscapes: A global meta-analysis. Biol Conserv 175:65–73. https://doi.org/10.1016/j.biocon.2014.04.016

Moriarty KM, Epps CW, Betts MG, et al (2015) Experimental evidence that simplified forest structure interacts with snow cover to influence functional connectivity for Pacific martens. Landsc Ecol 30:1865–1877. https://doi.org/10.1007/s10980-015-0216-2

Moriarty KM, Epps CW, Zielinski WJ (2016) Forest thinning changes movement patterns and habitat use by Pacific marten. J Wildl Manag 80:621–633. https://doi.org/10.1002/jwmg.1060

Mortensen DA, Rauschert ESJ, Nord AN, Jones BP (2009) Forest Roads Facilitate the Spread of Invasive Plants. Invasive Plant Sci Manag 2:191–199. https://doi.org/10.1614/IPSM-08-125.1

Mosseler A, Major JE, Rajora OP (2003) Old-growth red spruce forests as reservoirs of genetic diversity and reproductive fitness. Theor Appl Genet 106:931–937. https://doi.org/10.1007/s00122-002-1156-1

Narayanaraj G, Wimberly MC (2011) Influences of forest roads on the spatial pattern of wildfire boundaries. Int J Wildland Fire 20:792–803. https://doi.org/10.1071/WF10032

Nolet P, Kneeshaw D, Messier C, Béland M (2018) Comparing the effects of even- and uneven-aged silviculture on ecological diversity and processes: A review. Ecol Evol 8:1217–1226. https://doi.org/10.1002/ece3.3737

O'Hara KL (2002) The historical development of uneven-aged silviculture in North America. Forestry 75:339–346. https://doi.org/10.1093/forestry/75.4.339

Ortega YK, Capen DE (1999) Effects of Forest Roads on Habitat Quality for Ovenbirds in a Forested Landscape. The Auk 116:937–946. https://doi.org/10.2307/4089673

Oswalt SN, Smith WB (2014) US forest resource facts and historical trends. United States Deparment of Agriculture, Forest Service

Paillet Y, Bergès L, Hjältén J, et al (2010) Biodiversity Differences between Managed and Unmanaged Forests: Meta-Analysis of Species Richness in Europe. Conserv Biol 24:101–112. https://doi.org/10.1111/j.1523-1739.2009.01399.x

Park A, Henschel C, Kuttner B, McEachern G (2005) A Cut Above - A Look at Alternatives to Clearcutting in the Boreal Forest. CPAWS - Wildlands League

Puettmann K, Coates KD, Messier C (2009) A critique of sylviculture: managing for complexity. Island Press, Washington

Pukkala T (2016) Which type of forest management provides most ecosystem services? For Ecosyst 3:9. https://doi.org/10.1186/s40663-016-0068-5

Reed RA, Johnson-Barnard J, Baker WL (1996) Contribution of Roads to Forest Fragmentation in the Rocky Mountains. Conserv Biol 10:1098–1106. https://doi.org/10.1046/j.1523-1739.1996.10041098.x

Régnière J, St-Amant R, Duval P (2012) Predicting insect distributions under climate change from physiological responses: spruce budworm as an example. Biol Invasions 14:1571–1586. https://doi.org/10.1007/s10530-010-9918-1

Regolin AL, Oliveira-Santos LG, Ribeiro MC, Bailey LL (2021) Habitat quality, not habitat amount, drives mammalian habitat use in the Brazilian Pantanal. Landsc Ecol. https://doi.org/10.1007/s10980-021-01280-0

Ribe RG (2005) Aesthetic perceptions of green-tree retention harvests in vista views: The interaction of cut level, retention pattern and harvest shape. Landsc Urban Plan 73:277–293

Robitaille A, Saucier J (1998) Paysages régionaux du québec méridional, Gouvernement du québec, ministère des ressources naturelles. Les publications du Québec

Ruel J-C, Fortin D, Pothier D (2013) Partial cutting in old-growth boreal stands: An integrated experiment. For Chron 89:360–369. https://doi.org/10.5558/tfc2013-066

Scheller RM, Domingo JB, Sturtevant BR, et al (2007) Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecol Model 201:409–419. https://doi.org/10.1016/j.ecolmodel.2006.10.009

Schütz J-P, Pukkala T, Donoso PJ, von Gadow K (2012) Historical Emergence and Current Application of CCF. In: Pukkala T, von Gadow K (eds) Continuous Cover Forestry. Springer Netherlands, Dordrecht, pp 1–28

Seidl R, Thom D, Kautz M, et al (2017) Forest disturbances under climate change. Nat Clim Change 7:395–402. https://doi.org/10.1038/nclimate3303

Shinneman DJ, Cornett MW, Palik BJ (2010) Simulating restoration strategies for a southern boreal forest landscape with complex land ownership patterns. For Ecol Manag 259:446–458. https://doi.org/10.1016/j.foreco.2009.10.042

Shorohova E, Kneeshaw D, Kuuluvainen T, Gauthier S (2011) Variability and dynamics of old-growth forests in the circumboreal zone: implications for conservation, restoration and management. Silva Fenn 45:. https://doi.org/10.14214/sf.72

Statistics Canada (2018) Human Activity and the Environment 2017: Forests in Canada

Stone I, Ouellet J-P, Sirois L, et al (2008) Impacts of silvicultural treatments on arboreal lichen biomass in balsam fir stands on Québec's Gaspé Peninsula: Implications for a relict caribou herd. For Ecol Manag 255:2733–2742. https://doi.org/10.1016/j.foreco.2008.01.040

Strittholt JR, Dellasala DA, Jiang H (2006) Status of mature and old-growth forests in the Pacific Northwest. Conserv Biol 20:363–374

Strukelj M, Brais S, Paré D (2015) Nine-year changes in carbon dynamics following different intensities of harvesting in boreal aspen stands. Eur J For Res 134:737–754. https://doi.org/10.1007/s10342-015-0880-4

Sturtevant BR, Miranda BR, Shinneman DJ, et al (2012) Comparing modern and presettlement forest dynamics of a subboreal wilderness: Does spruce budworm enhance fire risk? Ecol Appl 22:1278–1296. https://doi.org/10.1890/11-0590.1

Terry EL, McLellan BN, Watts GS (2000) Winter habitat ecology of mountain caribou in relation to forest management. J Appl Ecol 37:589–602. https://doi.org/10.1046/j.1365-2664.2000.00523.x

Thompson ID (1994) Marten Populations in Uncut and Logged Boreal Forests in Ontario. J Wildl Manag 58:272–280. https://doi.org/10.2307/3809391

Timoney KP, Peterson G (1996) Failure of natural regeneration after clearcut logging in Wood Buffalo National Park, Canada. For Ecol Manag 87:89–105. https://doi.org/10.1016/S0378-1127(96)03831-5

Tittler R, Filotas É, Kroese J, Messier C (2015) Maximizing Conservation and Production with Intensive Forest Management: It's All About Location. Environ Manage 56:1104–1117. https://doi.org/10.1007/s00267-015-0556-3

Tittler R, Hannon SJ, Norton MR (2001) Residual tree retention ameliorates short-term effects of clear cutting on some boreal songbirds. Ecol Appl 11:1656–1666

Tittler R, Messier C, Fall A (2012) Concentrating anthropogenic disturbance to balance ecological and economic values: applications to forest management. Ecol Appl 22:1268–1277

Tremblay JA, Boulanger Y, Cyr D, et al (2018) Harvesting interacts with climate change to affect future habitat quality of a focal species in eastern Canada's boreal forest. PLOS ONE 13:e0191645. https://doi.org/10.1371/journal.pone.0191645

Trumbore S, Brando P, Hartmann H (2015) Forest health and global change. Science 349:814–818

United States Department of Agriculture (1997) Draft Environmental Impact Statement - Kisatchi National Forest. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5391435.pdf

iVanlandeghem V, Drapeau P, Prima M, et al (2021) Management-mediated predation rate in the caribou–moose–wolf system: spatial configuration of logging activities matters. Ecosphere 12: https://doi.org/10.1002/ecs2.3550

Wagner CEV (1978) Age-class distribution and the forest fire cycle. Can J For Res 8:220–227. https://doi.org/10.1139/x78-034

Wang X, Blanchet FG, Koper N (2014) Measuring habitat fragmentation: An evaluation of landscape pattern metrics. Methods Ecol Evol 5:634–646. https://doi.org/10.1111/2041-210X.12198

Whittington J, Hebblewhite M, DeCesare NJ, et al (2011) Caribou encounters with wolves increase near roads and trails: a time-to-event approach: Wolf-caribou encounter rates. J Appl Ecol 48:1535–1542. https://doi.org/10.1111/j.1365-2664.2011.02043.x

Wirth C, Gleixner G, Heimann M (2009) Old-Growth Forests: Function, Fate and Value – an Overview. In: Wirth C, Gleixner G, Heimann M (eds) Old-Growth Forests: Function, Fate and Value. Springer, Berlin, Heidelberg, pp 3–10

Witmer GW, deCalesta DS (1985) Effect of forest roads on habitat use by Roosevelt elk. Northwest Science 59