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Article

A LANDIS-II extension for simulating forest road networks

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Abstract

Forest roads are an important part of forest management, both in terms of cost and impact on surrounding ecosystems. Existing tools to simulate the construction of forest roads have been designed for tactical or operational planning purposes, for relatively small areas (<10 000 ha) and small-scale topographic information. Hence, no forest road simulation tool properly exists to assist forest landscape ecology and management research. Here, we present the Forest Roads Simulation (FRS) extension for the LANDIS-II model—a spatially explicit landscape simulation model of forest succession and disturbances. The FRS extension simulates forest road networks via a least-cost path algorithm accounting for landscape structure, decision inputs, and forest road types. We demonstrate the accuracy with which the FRS extension reproduces several key characteristics of existing road networks in two managed regions in Quebec, Canada: road density, road position, and fragmentation of the landscape. The FRS extension is easy to parameterize, proposing many options for researchers to simulate forest road networks at a strategic level in managed landscapes. It can tackle new research questions investigating the effects of forest roads within management strategies, such as the cost of road construction and habitat fragmentation, across large management units and long planning horizons.

Key words: LANDIS-II, forest roads, road networks, forestry, spatially explicit modeling, forest ecology

1. Introduction

For several decades now, roads have been known to have important impacts on ecosystems such as increasing the loss and fragmentation of natural terrestrial and aquatic habitat (Bennett 2017; Li et al. 2003; Trombulak and Frissell 2000; van der Ree et al. 2011). Efforts to quantify the ecological effects of roads and reduce their negative impacts have even led to the creation of a separate field of study known as "Road ecology" (van der Ree et al. 2011). Forest roads are a particular type of road characterized by a low traffic volume, traffic mostly in one direction of long and heavy trucks, and often a surface of gravel or local soil (Sessions et al. 2016). Such roads are often abandoned or maintained for other purposes (fire-fighting, recreational activities, etc.) (Hunt et al. 2009; Thompson et al. 2021; Zhang et al. 2020). Despite having less traffic than main paved roads in more populated areas, forest roads can have many negative impacts on forest ecosystems (Boston 2016). Indeed, they have been shown to reduce the surrounding macroinvertebrate soil fauna (Haskell 2000) and the abundance of some beetles (Koivula 2005), to facilitate the spread of invasive plants (Mortensen et al. 2009), to alter the quality of habitat for some species of birds (Ortega and Capen 1999), and to fragment the landscape more than clearcuts (Reed et al. 1996). Forest roads also change the behavior of some large mammals: elk tend to avoid roads (Witmer and deCalesta 1985), whereas wolves tend to use them, increasing predation pressure on their prey (James and Stuart-Smith 2000; Whittington et al. 2011). It has even been suggested that forest roads could influence the spatial boundaries of forest fires, a key natural disturbance in boreal regions (Narayanaraj and Wimberly 2011; Yocom et al. 2019). In addition, forest roads can be an important source of water pollution and have impacts on the surrounding vegetation and soil conditions (Avon et al. 2010; St-Pierre et al. 2021; Zhou et al. 2020).

Forest roads are also a substantial operational expense for the forest industry, costing as much as half the harvest operations themselves (Epstein et al. 2006). This cost can, however, vary greatly among regions. For example, in several countries of Europe, costs related to forest roads represent 5%–10% of the total cost of forestry operations (Toscani et al. 2020), while in Chile these costs can reach 55% of the total operational cost (Epstein et al. 2006). In Quebec (Canada), forest roads represented between 10% and 18% of the total operational cost for the forest industry in 2019, depending on the type of forest harvested (Groupe DDM and MFFP du Québec 2020). Locally, cost can vary greatly due to soils, sub-soils, and slopes (Stückelberger et al. 2006). Approximately half of these costs is allocated to road construction themselves, while the other half is allocated to road repair and maintenance. Forest roads present several advantages, such as easier fire management and protection, and increased access to forests for economic or recreational purposes. Notably, forest roads provide greater access to several essential services to remote communities (e.g., indigenous nations) (Adam et al. 2012). However, because forest roads increase public accessibility to distant areas, their construction, maintenance, and removal is associated with land-use conflicts. Examples of socio-economic tensions related to forest roads include increased road traffic and recreational activities (hiking, fishing, motorized vehicles, etc.) in proximity to or within ancestral forests of indigenous communities, poor consultation with local communities in the planning of forest roads, and loss of access for recreational users following road decommissioning (Adam et al. 2012; Bourgeois et al. 2005; Hunt et al. 2009; Kneeshaw and Gauthier 2006).

Due to the diversity of economic, social, and ecological impacts associated with forest roads, there is an increased need to develop decision-making tools able to generate different scenarios of forest road network delineation and evaluate their trade-offs at a strategic level. Forest engineers rely on efficient software to plan forest road networks, such as Woodstock Road Optimizer (Remsoft 2019) or PLANEX (Epstein et al. 2006). These tools are used at the tactical and operational levels and focus on optimizing road design and harvest scheduling to reduce supply cost. However, these tools account for fine-scale constraints such as the skidding methods used or the position of timber landings, and, therefore, require detailed parametrization (Bont et al. 2015; Chung et al. 2004). Moreover, some of these tools are built with expensive proprietary software, making their use costly. In addition, these tools are not designed to explore the long-term and large-scale impacts of forest road networks. Finally, their stand-alone nature makes them inadequate to simulate forest roads along with forest succession, natural disturbances, and management options. Hence, to the best of our knowledge, no forest road model matches the needs of forest ecology and management research.

Here, we present the Forest Roads Simulation (FRS) extension, an extension for the LANDIS-II model. LANDIS-II (Scheller et al. 2007) is a spatially explicit and raster-based Forest Landscape Model (FLM) that has gained recognition in past years for its ability to study, through simulations, the interactions between management, natural disturbances, and climate change in North American forests (Mina et al. 2020; Molina et al. 2021; Tremblay et al. 2018). Hence, the FRS extension adds to the ability of LANDIS-II to simulate several key ecological (forest growth, succession, forest fire, etc.) and anthropogenic processes (harvesting or land-use changes), on large spatial and temporal scales. The FRS extension simulates the construction of forest roads at the landscape scale and interaction with the other processes simulated by LANDIS-II (harvesting, succession, and natural disturbances). The FRS extension thus differs from previous models simulating optimized forest road networks at the operational and tactical levels to focus, instead, on simulating forest roads at the strategic planning levels. Indeed, FLMs, like LANDIS-II and its other extensions, are not aimed at maximizing forestry or economic outputs but rather at determining the interactions between planned forestry strategies (harvest scheduling and operations) and ecological processes (succession and natural disturbances). Consequently, the FRS extension offers the possibility to explore research topics related to forest roads at larger spatial and temporal scales, including their effects on landscape fragmentation, carbon balance, animal movement, recreational access, fire management, timber harvesting cost, and social acceptability.

2. Methods

2.1. Model description

2.1.1. Design considerations

In developing the FRS extension, our main design objectives were to propose a model for simulating forest road networks at a strategic scale that (1) requires limited and available parametrization; (2) is able to replicate characteristics of real forest road networks (e.g., density of roads, extent and distribution, fragmentation level, and costs); (3) does not rely on low-level features of forest roads that have limited influence on the landscape-scale network (e.g., skidding methods, spacing and positioning of landings where the timber is stacked, etc.; see Chung et al. 2004 for examples); and (4) has a competitive performance (in run time) regarding other LANDIS-II extensions (i.e., under 30 min per time step; Sturtevant et al. 2004).

2.1.2. Goal of the extension

Forest road networks are built while attempting to minimize expenses (such as salaries of construction workers, equipment rental, cost of surface material, as well as costs related to the protection of the environment; Heinimann 2017), with lower standards than regular roads despite supporting heavy trucks (Légère 2001; Ryan et al. 2004). They are also developed sequentially rather than planned over a long-term horizon in an optimal manner, as forest industries construct new roads depending on available budget. Therefore, to capture the characteristics of existing forest road networks, the FRS extension focuses on designing roads to access harvested areas with a minimal cost of construction, but without necessarily minimizing the costs of construction across the entire network developed during the full planning horizon. Consequently, the main task of the FRS extension is to compute least-cost paths between a set of scheduled harvested areas to specific locations on the landscape where timber needs to be transported (e.g., main road network, sawmills). Note that the FRS extension does not solve what is called the "integrated forest harvest-scheduling model". This refers to the more complex problem of optimizing the forest road network design together with the choice of areas to be harvested (Heinimann 2017; Naderializadeh and Crowe 2020)—a problem solved by operational software such as Woodstock or PLANEX (Epstein et al. 2006).

Hence, the goal of the FRS extension is to solve the problem of connecting multiple known areas—a problem known as the Multiple Target Access Problem (MTAP) (Heinimann 2017). The MTAP is a predecessor to the larger problem of integrated forest harvest-scheduling and has been used several times in the context of forest roads (Heinimann 2017; Shirasawa and Hasegawa 2014). In essence, it can correspond to a minimum spanning tree problem (Shirasawa and Hasegawa 2014). While the MTAP is solvable, finding the optimal solution becomes extremely difficult for many targets (i.e., places that must be connected by roads such as harvested areas, sawmills, and the main road network) (Shirasawa and Hasegawa 2014). For a landscape covering millions of hectares, solving the MTAP becomes impossible, or requires an impractical amount of time. As an example, a fine-scale operational model can find optimal solutions to problems similar to the MTAP in up to 8 h of computation for an area of 4.3 km^2, making it inappropriate for landscapes used in simulation research, which can easily reach 10 000–100 000 km^2 (Bont et al. 2015).

The complexity of the MTAP in the context of forest road network design has led to the development of several heuristics (i.e., assumptions or simplifications) to reduce solving time (Shirasawa and Hasegawa 2014). However, using a heuristic implies that solutions are often approximations departing from the optimal solution to the MTAP. Hence, the choice of a particular heuristic can remarkably alter the resulting road network compared to the optimal MTAP solution (Anderson and Nelson 2004). Here, we developed the FRS extension by selecting three heuristics that are intuitive, reduce the extension's complexity for users, and improve execution time. These heuristics are also used in professional software like Remsoft Road Optimizer (Remsoft 2019). The three proposed heuristics rely on the same concept of "breaking" the MTAP into a set of Single Target Access Problems (STAP), that is, the problem of optimizing the path between two points. STAPs are in turn easy to solve via simple path-finding algorithms such as the Dijkstra algorithm (Anderson and Nelson 2004). Breaking down the MTAP into STAPs also replicates the sequential process used in the forest industry when constructing forest road networks. We propose two heuristics ("closest first" and "farthest first") used by Anderson and Nelson (2004) and tested by Shirasawa and Hasegawa, (2014), as well as a "random" heuristic. Heuristics are described in Section 2.1.5.2.

2.1.3. Structure

The FRS extension is an extension of the LANDIS-II model. LANDIS-II is itself an open-source project coded in C# made up of a core and a catalog of different extensions (Fig. 1) (Scheller et al. 2007). The FRS extension comes with its own documentation and Github repository, allowing any user to learn how to use it or to modify it if needed, with detailed information available in Hardy (2021).

The FRS extension operates after the harvest extension in LANDIS-II. Note that the FRS extension is compatible with any other extension of LANDIS-II, as it edits and reads a distinct spatial dataset that we name the "road landscape", without editing the forest landscape itself. The road landscape consists in a matrix of cells (or pixels): each cell is either empty or occupied by a road. In the latter case, the road category is also provided (primary, secondary, and tertiary; see Section 2.1.5.6). Moreover, the road landscape contains locations named "exit points" for the timber, which are defined by the user. These cells correspond to transit locations from which timber is further transported (e.g., main paved road network and train station), or final destinations where timber is processed (e.g., sawmill). Note that a cell containing a road remains available for harvesting. This assumption was made given that the widest forest roads rarely exceed 30 m and, therefore, remains smaller than the usual grain size used in LANDIS-II models (e.g., 1 ha).

2.1.4. Creation of the cost map

During the initialization phase of LANDIS-II, before the simulation starts, the FRS extension prepares the "cost map" that will be used by the least-cost path algorithm. The "cost map" is a matrix with the same dimensions as the simulated landscape that provides the cost for road construction within each cell. The cost map can take into account six types of landscape features known to influence the cost of forest road construction: existing roads (prevents the construction of new ones), elevation (slows down construction or requires adaptations), topographic obstacles (requires detours, e.g., cliffs or breaks), lakes and rivers (requires the construction of bridges), streams (requires the construction of culverts), and soils (influences the material needed, the amount of work required, and cost) (Fig. 2). These features need to be provided by the user in the form of raster files, and associated cost parameter values in a .txt file. However, the user must provide information about existing roads and elevation for the extension to function; the other features are optional but recommended to improve the extension predictions (Fig. 2). All raster files must have the same resolution and extent as the other raster files employed by LANDIS-II's core extension. The user must also input the "basal construction cost", corresponding to the minimal cost for building a forest road across a distance equal to the size of a cell and under ideal conditions (e.g., flat terrain, no water body, and good structural soil characteristic) in units of currency.

The total cost of construction of a forest road (eq. 1) on a single cell, C_{total}, is zero when a road already exists on the cell, otherwise it is calculated by adding all considered costs together:

$$(1)\quad C_{total} = R_{category} D_{obstacles} \times \left(C_{basal} + C_{slope} + C_{bridge} + C_{culvert} + C_{soil}\right)$$

where C_{basal} is the basal construction cost. C_{slope} is the additional cost due to the elevation. It is based on the average

Fig. 1. The LANDIS-II modeling structure. The forest landscape is simulated by the periodic and successive intervention of different extensions: succession and disturbances (e.g., harvesting, forest fire, and insect outbreaks). The Forest road simulation extension follows the harvesting extension.

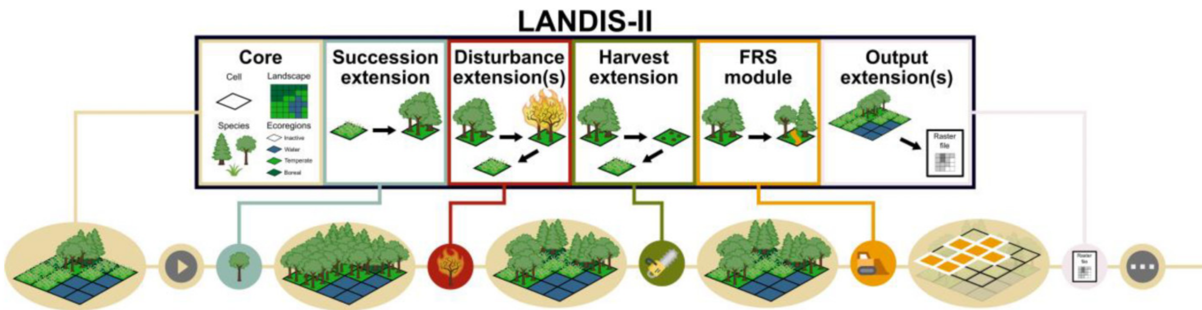
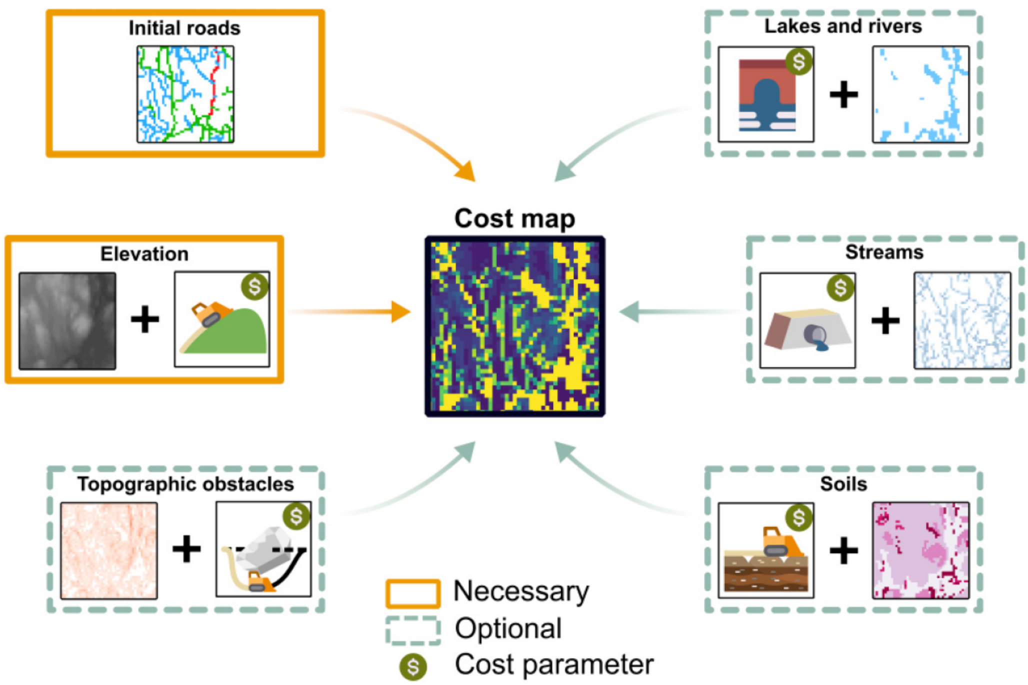


Fig. 2. The cost map constructed by the FRS extension during the initialization of LANDIS-II depends on six landscape features: the initial road network, the elevation (slope), the topographic obstacles, lakes and rivers, streams and soils. Features and their associated costs are fed to LANDIS-II in the form of raster and parameter text files at initialization step.



slope between the elevation of a cell and that of its immediate neighbors. C_{slope} is provided in a user-defined lookup table where an additional cost is associated to each class of slopes. C_{bridge} is the cost of constructing a bridge section across a cell that contains a water body. This cost does not depend on the presence of water bodies in surrounding cells. Hence, the total cost of building an entire bridge across a water body corresponds to the sum of costs for all cells along the bridge. $C_{culvert}$ is equal to the average cost of installing a culvert multiplied by the estimated number of culverts that would need to be installed within a cell. This estimation is made by using the total length of streams in a cell since several meandering streams may be present. We then assume that the number of needed culverts equals the ratio between this total length and the cell's diagonal length rounded to the next higher integer. For example, if 150 m of streams is present in a 1 ha resolution cell (100 m × 100 m), we estimated that two culverts would be needed. C_{soil} corresponds to the additional construction cost due to the local soil conditions. For example, C_{soil} can represent the cost of transporting gravel from afar or the cost of rock blasting. Finally, $D_{obstacles}$ is a multiplicative factor representing the increase in the overall cost of road construction due to topographic obstacles that require road detours within a cell. Whereas C_{slope} represents costs due to a change in the average elevation with the surrounding cells, $D_{obstacles}$ encompasses fine-scale topographic variabilities within the cell (holes, cliffs, breaks, etc.). We define $D_{obstacles}$ using the number of contour lines in a cell derived from a digital terrain model. A high number of contour lines would imply either a steep but homogeneous terrain, a flat but heterogeneous terrain, or a mix of both. A lookup table parameterized by the user

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assigned a multiplicative factor to different classes of contour line quantity (e.g., $D_{obstacles} = 1$, 2, or 3 for 0–1, 2–4, and 5 and more contour lines per cell, respectively.). The precise way in which these costs are calculated by taking into account both the topographical maps and the user-defined parameters is described in the user manual of the model (Hardy 2021).

These costs must be parameterized relative to a "reference" road category (e.g., primary roads). The estimation of the cost of construction for other road categories are then computed using the multiplicative value $R_{category}$ ($R_{category} = 1$ for the reference road category, $R_{category} < 1$ for less costly categories, and $R_{category} > 1$ for more costly categories). Hence, the multiplicative value $R_{category}$ adjusts the total cost as would be expected when building a road of larger or smaller width.

The values for these cost parameters can be obtained in different ways depending on data availability in the study region. The best estimates can be found from databases containing the measured costs of construction of existing forest road sections, from which prices per unit of distance can be extracted. In regions where such databases are not easily accessible to the public, parameterization could require expert opinion from forest engineers in logging companies or governmental agencies (Hardy 2021). However, irrespective of the methodology used, soil types, elevation, and construction costs are likely to be heterogeneous within a cell for higher spatial resolution (Stückelberger et al. 2006).

Following the creation of the cost map, the FRS extension checks whether the initial road network provided by the user contains road cells that are not connected to any exit point cells (either directly or via other roads). The presence of unconnected roads can be attributed to errors in the detection or registrations of roads, or by the destruction or deactivation of roads. The FRS extension then proceeds by creating new roads to connect those isolated road cells to exit point cells. This step completes the activation phase. During the simulation of the LANDIS-II model, the cost map is updated every time a road is built or destroyed, making it dynamic.

2.1.5. During the simulation

During a simulation of the model, LANDIS-II activates each extension selected by the user successively according to their respective return time (Fig. 1). As LANDIS-II can simulate disturbances that vary in their recurrence (e.g., harvesting every 5 years and insect outbreaks every 40 years), we recommend parameterizing LANDIS-II so that the FRS extension operates immediately following the selected harvest extension, and with the same recurrence.

2.1.5.1. Road aging

When the FRS extension is activated at a time step *t*, it starts by increasing the age of the forest roads in the landscape following the selected recurrence (if the option has been selected by the user) (Fig. 3, top). Indeed, each time a new road is "built" on a cell, the cell is given the "age" value 0. At the following activation of the FRS extension, the age of cells containing a road is updated by adding the time since its previous activation. If the age of a cell exceeds the maximum age of the road (determined by its road type; see below), then the road is considered unusable, and disappears from the landscape. This aging mechanism allows the landscape to escape the legacy of its initial state, as forest roads dynamically appear and disappear with time. However, crucial road cells can be considered repaired if they are re-created by the extension during the same time step. Moreover, permanent forest roads, such as main arteries, can be simulated by assigning them a high longevity. The age of all roads in the initial road network is currently initialized at 0. Initialization to real age values is nonetheless possible if these data are available.

2.1.5.2. Ordering of the recently harvested cells

Following road aging, the FRS extension identifies all cells harvested by the harvest extension since its last activation and orders them in a list according to the heuristic chosen by the user (Fig. 3, middle). Three heuristics are currently available: closest first, farthest first, or random. The closest first and farthest first heuristics order the recently harvested cells according to their Euclidean distance to the nearest existing road, while the random heuristic orders them randomly. The selected heuristic influences the order in which the forest roads will be created, and thus the shape of the resulting road network. While the three heuristics are available to the user, previous studies have shown that the closest first heuristic replicates the progression of a forest road network through a landscape and creates a network that is closest to an optimal one (Shirasawa and Hasegawa 2014).

2.1.5.3. Construction of new roads

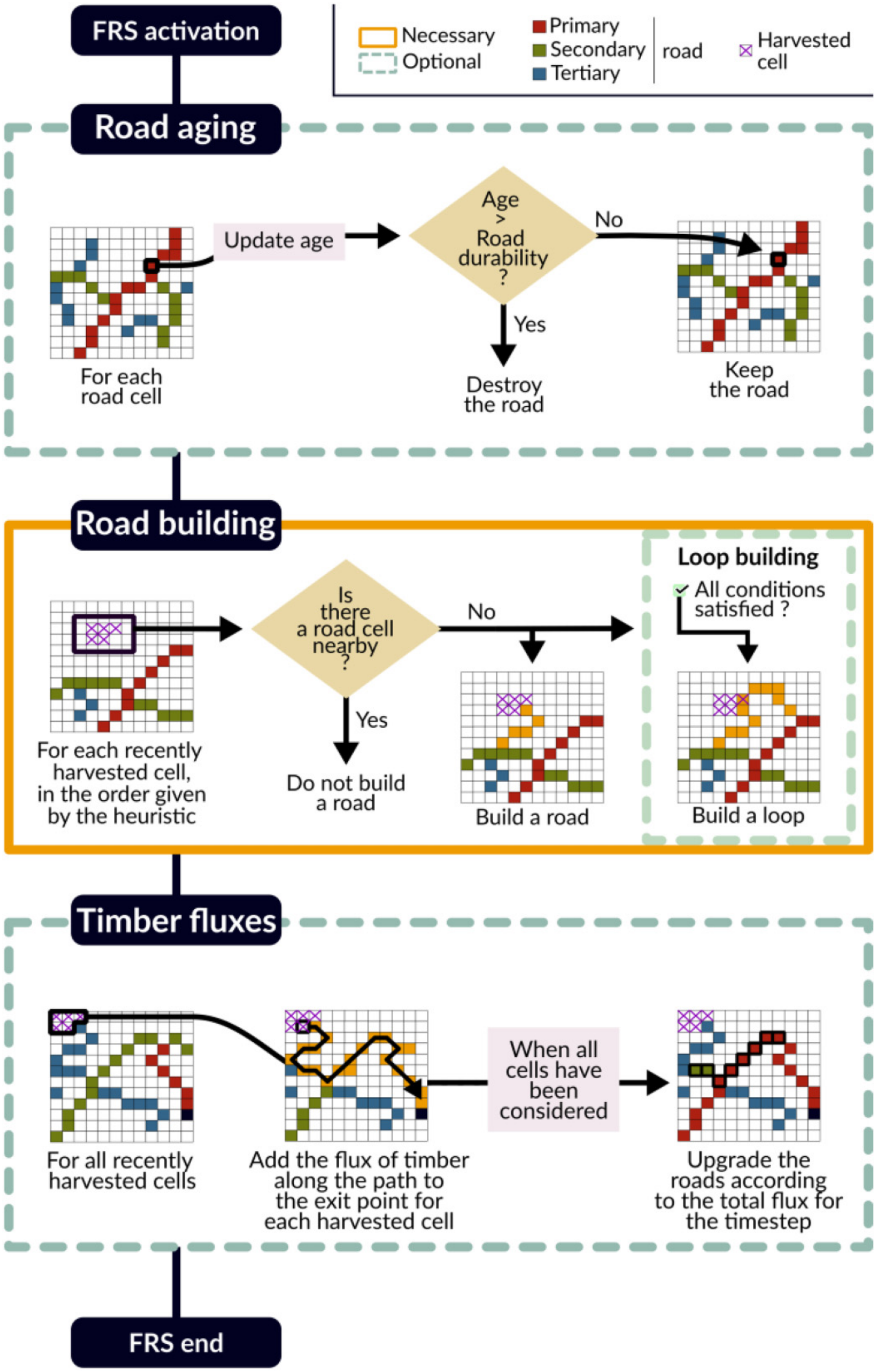
Road construction proceeds by considering each harvested cell one by one according to their ordering. First, the distance between the harvested cell and the closest existing road is computed. If this distance is less than the skidding distance parameter (Table 1), no new road is constructed as we consider that timber will simply be skidded toward the nearest road (Fig. 3, middle). If the distance is greater than the skidding distance, the Dijkstra algorithm (Dijkstra 1959) is used to solve the STAP. More precisely, the Dijkstra algorithm solves the "single-source many-targets shortest path problem", a special case of STAPs that finds the path between the harvested cell and one of multiple potential arrival points on the road network (Bast et al. 2003). The cost of the path is the sum of the construction costs, derived from the cost map, for each cell along the path. This cost is recorded by the extension for each road segment, and the sum of these costs is made available to the user in an output file.

In our model, the Dijkstra algorithm is allowed to move in a Moore neighborhood (nearest and next-nearest neighbors), with the cost of movement being weighted by the distance between cell centroids to avoid directional bias (Holland et al. 2007). We kept this simpler philosophy since approaches that consider more angles of movement (Stückelberger et al. 2007) generally result in increased computation time and complex interpretation of road configuration and costs.

2.1.5.4. Option to create road loops

The FRS extension also includes a "loop" algorithm to better replicate the occurrence of loop structures observed in

Fig. 3. Flow chart of the different stages followed by the FRS extension at time step t during a simulation in LANDIS-II: road aging (top), road building (middle), and simulation of timber fluxes (bottom).



existing road networks. A loop appears when more than one road connects two points of the landscape and surrounds a patch of forest. Loops occur for a variety of reasons and can be planned or not. For example, the harvested wood may need to travel to different mills along different roads. In addition, temporary disturbances such as a forest fire or flood that obstructs an existing road may require the construction of a new road leading to an eventual loop. Once constructed, they can increase the accessibility of certain forest areas for forestry vehicles or timber trucks, or increase the resilience of the network (i.e., the existence of multiple paths to a given place, increases the chances that one path will remain available if disturbances such as fire or flood obstruct other paths). However, it is hard to isolate a particular set of rules or probabilities that replicates the decision process by forest road engineers to create loops in the network.

Table 1. Description of the most important parameters of the Forest Roads Simulation (FRS) extension.

Parameter name	Optional	Units	Description
Time step	No	Years	Number of years between two activations of the FRS extension during a LANDIS-II simulation
Skidding distance	No	Meters	Maximum distance from a recently harvested cell to the nearest existing road across which timber is skidded to the existing road
Looping behavior	No	Boolean	Activates the looping algorithm
Looping—minimum distance	Yes	Meters	Size of the neighborhood around a recently harvested cell that must be free of road cells for a loop to be constructed
Looping—maximum distance	Yes	Meters	Size of the neighborhood around a recently harvested cell that must contain at least two road cells for a loop to be constructed
Looping—maximum road density	Yes	Percentage	Maximum number of road cells in the neighborhood of a recently harvested cell for a loop to be constructed. The size of the neighborhood is defined by the maximum looping distance
Looping—maximum cost ratio	Yes	No unit	Maximum ratio between the cost of the second segment and the cost of the first segment of the loop
Looping—probability	Yes	No unit	Probability that a loop is constructed if all the other loop conditions are respected
Basal distance cost	No	Monetary units	Minimum cost to build a road across a single cell
Coarse elevation costs	No	Monetary units	Table of additional construction costs due to the elevation for different ranges of slope value
Fine elevation costs	Yes	Monetary units	Table of multiplicative construction costs due to detours needed to avoid topographic obstacles for different ranges of fine elevation values in a cell
Bridge cost	Yes	Monetary units	Average cost to build a bridge across a single cell
Culvert cost	Yes	Monetary units	Average cost to build a culvert across a single cell
Soil costs	Yes	Monetary units	Additional construction costs due to the type of soil present in the cell
Simulation of road aging	No	Boolean	Enables road aging
Simulation of the wood flux	No	Boolean	Enables the simulation of the wood flux through the roads
Lower and upper wood flux thresholds	Yes	Age cohorts transported by year	Associates ranges of wood flux values to types of forest road (e.g., primary, secondary, etc.)
Multiplicative cost values	No	No unit	Indicates how the cost of construction of a given road type is increased or decreased compared to a reference type
Maximum ages before destruction	Yes	Years	Indicates how long a road of a given type can last without any repairs or upgrades before it gets destroyed by wear

The loop algorithm of the FRS extension creates a loop stochastically by building a second road segment, with a given probability, from a recently harvested cell to the rest of the network, in contrast to building a single road by default. Four conditions must be met for a loop to be constructed (Table 1): (1) no existing road cell should be too close to the harvested cell of interest (minimum looping distance); (2) at least two existing road cells should be present in the vicinity of the harvested cell (maximum looping distance); (3) a maximum number of existing road cells in the vicinity of the harvested cell should not be exceeded (maximum road density); and (4) the second road to be built should not be too costly (maximum cost). The looping algorithm therefore controls the size, distribution and quantity of loops without having to explicitly simulate the complex decisions of forest engineers. More details on the loop algorithm can be found in the user guide of the FRS extension (Hardy 2021).

2.1.5.5. Planned return to harvested cells

Some harvest prescriptions require a return to harvested cells for a second cut (e.g., shelterwood), or for repeated, periodic cuts (e.g., selection system). However, if road aging is activated, a road constructed to reach a particular cell may have disappeared at the time of the next prescribed harvesting. Hence, when a new road is built to a recently harvested cell, the FRS extension computes and selects the least expensive option between (1) building a low-cost road that may need to be re-built when returning to the cell, or (2) building a higher-grade road that will last for the next access. To that end, the FRS extension takes advantage of the fact that the user can input different road categories associated with a different longevity (e.g., primary, secondary, or tertiary road).

2.1.5.6. Computation of the wood flux

Once all forest roads necessary to access recently harvested cells have been created, the FRS extension simulates the timber flux transported through the road network (if the option has been selected by the user) (Fig. 3, bottom). The timber from each harvested cell is transported across all road cells that connect its cell of origin to an exit point in the landscape. The timber flux thus "flows" across the road network (as water does in a watershed) and increases upon converging with other roads. As a result, the timber flux in a given road cell at a particular time step is simply the sum of the amount of timber going through this road cell. The amount of timber leaving a recently harvested cell is estimated by the number of age cohorts (i.e., groups of trees of the same age) harvested in the cell at the current time step. We used age cohorts as they represent a unit shared between different extensions of LANDIS-II, allowing for more compatibility. Moreover, since an increasing amount of harvested age cohorts necessarily implies an increasing amount of harvested biomass, age cohorts constitute a good proxy for the amount of harvested timber.

The FRS extension can then use the timber flux to inform of potential "upgrade" to a higher category of a forest road. Each road category can accommodate a timber flux up to a maximum level above which a higher category is required (primary > secondary > tertiary, etc.) (Nevečerel et al. 2007). Integration of road category into FRS is important for studies that focus on the impact of road traffic on fauna or estimate degradation over time (Girardin et al. 2022), for example. Updating the category of a road also involves a higher cost. This cost of upgrade is computed for every road cell, adding to the costs of maintenance of the forest road network ($R_{category}$ in eq. 1). Additionally, when a road cell is upgraded, its age is reset to 0.

2.1.6. Computing performance

We improved the computing performance of the extension by using two open-source C# NuGet packages. More details about these packages, as well as how they improved the computing performances of the extension are detailed in Appendix A. The employed packages reduced the computing time of the FRS extension to less than a minute when executing a single iteration on a landscape of 4 million active cells and about 5% harvested cells, with a 2.60 GHz Intel i7 4 cores-CPU and 16GB of RAM.

2.2. Model testing

We tested the ability of the FRS extension to reproduce key structural characteristics of forest road networks: the density of roads in the landscape, the fragmentation level of the landscape, and their approximate location. These road network properties are important indicators of the impacts that roads have on forest landscapes (Bennett 2017; Forman 2005; Karlson and Mörtberg 2015). We limited our tests to these main properties due to the difficulty of finding data regarding existing forest roads, their construction date, their precise construction cost, and their original destination. As such, other forest road properties simulated by the FRS extension (e.g., road age, road category, road costs, and the precise location of roads) could not be validated, as reliable estimates for these measures could not be obtained from existing data in our study areas.

2.2.1. Study area

We tested the forest road network simulated by the FRS extension in two different forested regions in the province of Quebec, Canada (Fig. 4), the Mauricie and the Côte-Nord regions. The region in Mauricie covers 5 million hectares and extends above the 46° parallel north from the mixed to the boreal forests. Only a small proportion of its surface (<2%) is non-forested—mainly agricultural areas in the south—and there is a high quantity of "main" paved roads (e.g., highways). It also contains many lakes, rivers and streams, with the Saint-Maurice River being the largest and dividing the landscape into two parts. The region in Côte-Nord covers 13 million hectares going from N48° to N52°, and extends across the boreal forest. Whereas multiple paved roads are present in its southern part, only a single paved road (route 389) reaches the northern limit of this region, representing a vital artery of transport through the area. The Manicouagan River and the Outardes River run north to south in the Côte-Nord region. This region is more hilly and mountainouswith around 15% of its area at an elevation above 1000 m, compared to 5% for the Mauricie region. Both regions contain a high density of forest roads resulting from decades of forest harvesting, with 13.5 and 6.73 meters of roads per hectare in the Mauricie and Côte-Nord regions, respectively.

The road networks were simulated to connect existing areas of forestry operations to the main road network in their respective regions. Areas of operations were identified from Quebec's 5th forest inventory which includes forest operations at times dating back as far as the beginning of the 20th century (MFFP 2018). We compared the simulated networks with those contained in the governmental database, "AQReseau+", of all terrestrial transport routes in Quebec, including forest roads (Gouvernement du Québec 2015). The LANDIS-II model and the FRS extension were parameterized for both regions. The Mauricie region was modeled using a 100 m × 100 m cell resolution and the Côte-Nord region was modeled using a 250 m × 250 m cell resolution.

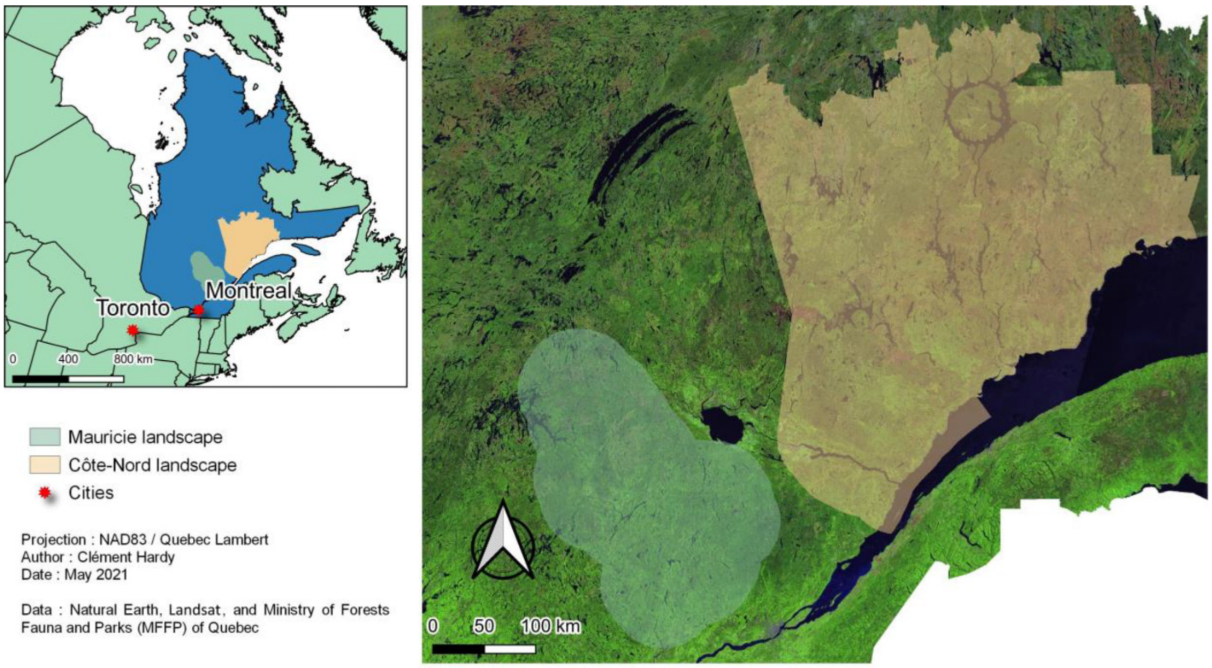
2.2.2. Parameterization

For both case studies, the FRS extension was parameterized with data provided by the Ministry of Forest, Fauna and Parks (MFFP) of Quebec. Terrain data (elevation, hydrology, and soils) are publicly available through "Données Québec", and data related to cost parameters (e.g., influence of elevation on construction cost, cost of culverts, etc.) were acquired from MFFP internal studies and expert opinions. Cost parameters obtained from expert opinions were then adjusted, within the range of existing values, to obtain the best concordance in replicating the characteristics of the existing forest road network.

2.2.3. Rasterization and data cleaning

The FRS extension generates the road network in raster format. Therefore, the first step in our comparison protocol was

Fig. 4. Map of the two landscapes used to test the FRS extension, in Quebec province, Canada. Polygons of countries (top left) and cities locations are both from the Natural Earth dataset (https://www.naturalearthdata.com/). Satellite imagery is from the Landsat project, and accessed through the data portal of the Ministry of Forests, Fauna and Parcs of Quebec (https://geoegl.msp.gouv.qc.ca/ws/mffpecofor.fcgi?request=GetMetadata&layer=lsat_mos2020). Study area extent for the Côte-Nord region (orange) comes from Labadie et al. (In preparation).



to convert the AQReseau + data, consisting of shapefile objects (Fig. 5*a*), to a raster layer. This rasterization process was performed using an 8-neighbors rule. More precisely, we rasterized the vector roads going from any point A to a point B by keeping only the raster cells on the shortest path from A to B. This path was based on a movement in 8 directions through cells that intersected the vector road (Fig. 5*b*). This effectively kept the location of the existing roads. While other rules can be used to rasterize line strings, such as "keep all cells intersecting the line" or "keep all cells with a centroid close enough to the line", they may over- or under-estimate the presence of roads. The chosen rule confers an adequate compromise between insuring that rasterized road segments are free of discontinuities while limiting the number of redundant cells. This, in turn, reduces potential biases coming from the rasterization process.

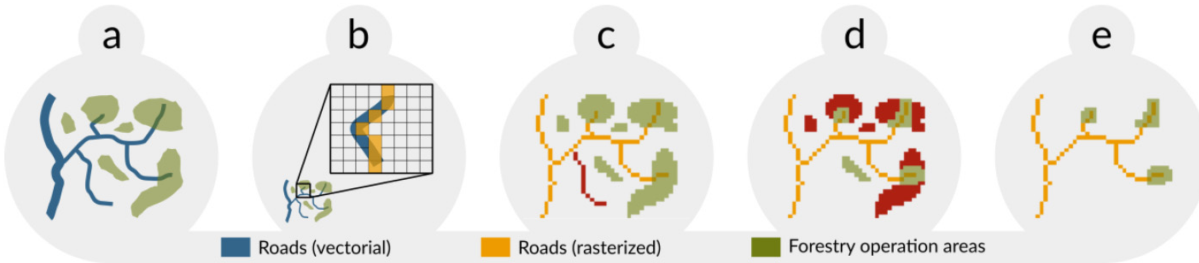
Following the rasterization process, we cleaned the obtained raster map by eliminating existing roads that were irrelevant for the validation protocol (Fig. 5*c*). Indeed, the FRS extension can only simulate forest roads leading to areas of forestry operations, as it is currently not designed to create roads for purposes other than timber transport. On the other hand, many forest roads reported in AQReseau + did not lead to any registered harvested areas. The construction date of some forest roads and their associated harvested areas were also unreliable or nonexistent. Therefore, in the raster map of existing roads, we only kept roads connecting harvesting zones to the main paved road network and removed all other roads. To that end, we first gathered the areas of all the forest operations ever recorded by the MFFP (e.g., cuts, thinning, plantations, etc.) in the two landscapes. We then retained all road cells within these areas as well as the road cells needed to connect them to the main paved road network through the shortest path (Fig. 5*c*). This procedure eliminated 9.6% and 9.8% of all road cells in the Mauricie and the Côte-Nord regions, respectively.

Moreover, the FRS extension simulates roads to every harvested pixel associated with forestry operation areas. As such, harvested cells will always be accessible by roads following a simulation of the FRS extension. However, the AQReseau + database is not entirely complete, as some forest roads are unregistered and undetected, and hence absent from the record even if the presence of a forestry operation areas implies their existence. Therefore, we removed harvested cells that were unconnected by a road or at a distance greater than 250 m away from an existing road, which corresponds to a selected maximum skidding distance for the harvest timber (Fig. 5*d*). From this final step, we obtained a rasterized road network composed of roads leading to forestry operation areas, and forestry operation areas connected to roads (Fig. 5*e*).

2.2.4. Measurements

We simulated forest roads with the FRS extension ten times for each study region to account for the stochasticity present in the loop algorithm, and compared the resulting road networks with the existing road network in each region. We measured key structural characteristics of road networks

Fig. 5. The 5-step process by which the vector data from the AQReseau + database were transformed to be compared with the outputs of the FRS extension: (*a*) the initial vector data, (*b*) the rasterization of the road network, (*c*) the removal of forest roads that did not lead to forestry operation areas, (*d*) the removal of forestry operation areas not reached by roads, and (*e*) the final, transformed data. Features that were removed during the transformation process appear in red in the illustration.



using standard metrics from landscape ecology that capture their impacts on forested landscapes: road density, number of forest patches, and level of fragmentation generated by roads. These metrics provide a quantitative assessment of the extent, density, and spatial distribution of road networks, allowing for a reliable discrimination between the real and simulated networks. We computed the total area of forest in the landscape as well as four indices of fragmentation of forest area: the number of forest patches delimited by non-forest areas (N), the clumpy index (Clumpy), the Total Core Area index (TCA), and the perimeter-area fractal dimension index (PAFRAC) (McGarigal et al. 2012) (equations for the indices appear in Appendix B). These distinct indices were chosen because they represent different aspects of fragmentation. The number of forest patches indicates the degree of subdivision of a forest landscape. Inversely, Clumpy captures the level of aggregation of habitat patches. TCA quantifies the total amount of core habitat area in the landscape where the core of a patch is the interior area at a given distance from its edge; here, we used a distance of 1 pixel (i.e., 100 m for the Mauricie region and 250 m for the Côte-Nord region). Finally, PAFRAC represents the fractal dimension of the habitat patches and is used to measure the complexity of their shape (Wang et al. 2014). Moreover, TCA is highly correlated to habitat amount, while Clumpy and PAFRAC are not (Wang et al. 2014). All indices were computed using the R package *landscapemetrics* (Hesselbarth et al. 2019). We assumed that all forest pixels in our landscape, regardless of their age and species composition, consisted of habitat.

In addition, we evaluated the superposition of simulated and existing roads at a local scale. This approach allowed us to assess the capacity of the FRS extension to simulate the presence of existing roads without requiring them to occupy the exact same location. To that end, we computed the percentage of simulated road pixels that was located 500 m or less from existing road pixels. The 500 m distance was chosen to be neither too permissive nor restrictive when comparing the location of existing and simulated roads. We carried out this analysis for roads within and outside forestry operation areas, as road segments outside management areas had fewer constraints on their position and, therefore, represented a greater challenge for the extension to replicate.

3. Results

Measures of road density and fragmentation indices are presented for each study region as the percentage error between the variables measured on both simulated and existing road networks (Fig. 6). Our results show that the FRS extension was able to reproduce the equivalent road density of the existing road network with small differences in both regions (error less than to 1%) (Fig. 6). Moreover, most fragmentation patterns were reproduced with relatively small differences in the Mauricie region (error less than 10% for all indices; Fig. 6) and in the Côte-Nord region (error less than 10% for TCA and PAFRAC), despite Clumpy presenting an error of around 13% (Fig. 6). Clumpy and TCA were both underestimated by the FRS extension in the two regions, indicating that simulated roads tended to fragment forest patches more than existing roads do (Fig. 6). On the other hand, PAFRAC was higher in both regions under simulated roads than in the AQReseau + database, indicating that the shape of habitat patches was more complex and less smooth when roads were generated by the FRS extension (Fig. 6).

Table 2 shows the local correspondence between the location of simulated and existing road pixels. In both regions, the percentage of simulated road pixels located at a distance smaller than 500 m from existing roads pixel was high when all road pixels were considered (approximately 90%). However, this percentage decreased by about 40% when only the roads located outside forestry operation areas were considered.

4. Discussion

Overall, the FRS extension was able to reproduce the characteristics of two AQReseau + database forest road networks with small differences. In particular, the extension was able to reproduce the density of roads in the landscape, their fragmentation of forest habitat, and their position. The replication is remarkable, given the complexity of the interactions between different agents and factors at play in the construction of forest roads: methodology and decision of forest road engineers, existing legislation, forest planning, future forestry activities, presence of protected areas, and so on. Our extension considered some of these factors by

Fig. 6. Percentage error (%) between the 10 simulated road networks and their existing counterparts, for the road density, the total area of forest, the number of forest patches and the three fragmentation indices for the Mauricie region (green) and the Côte-Nord region (yellow). Black bars indicate the standard error of the mean.

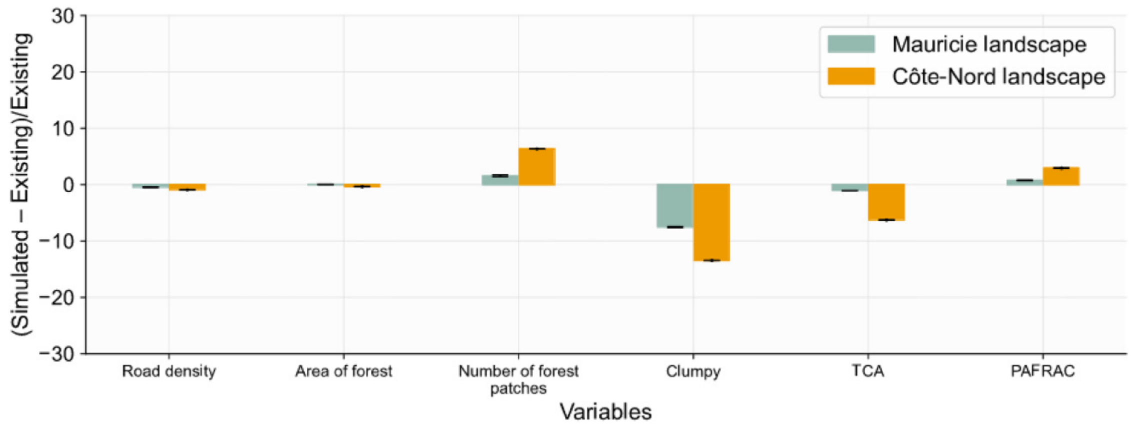


Table 2. Percentages of simulated road pixel that are 500 m or less from existing road pixels for the two landscapes. Standard error is indicated for the ten simulations.

	For all roads	For roads outside of managed forest areas
Mauricie landscape	97.1% ± 0.0	60.5% ± 0.2
Côte-Nord landscape	89.3% ± 0.1	44.7% ± 0.1

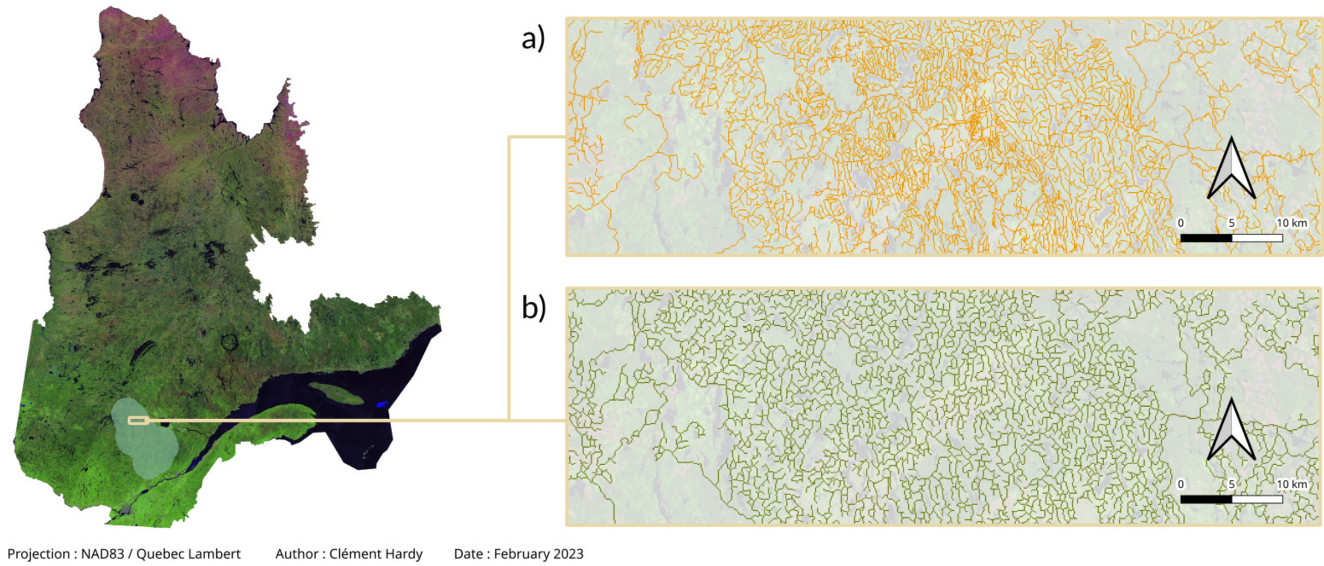
implementing cost layers based on landscape features, such as soils, and topographic and hydrographic obstacles, along with road categories based on food fluxes, road aging, and the possibility of building loops. The implementation of these factors can explain the performance of the FRS extension in replicating existing road networks.

Our results show that our extension reproduced generally well the four measured aspects of habitat fragmentation: subdivision (Number of patches), aggregation (Clumpy), core area (TCA), and shape (PAFRAC) of forest patches. Some variations between the existing and simulated landscapes were observed, especially for Clumpy, even though the FRS extension successfully reproduced the density of road pixels and the total amount of forest pixels in the landscapes (Fig. 6). Hence, the deviation in the fragmentation of forest patches is not caused by differences in the quantity of forest pixels, but by differences in their distribution across the existing and simulated landscapes. A qualitative comparison between the existing road network in a section of the Mauricie region (Fig. 7*a*) and one simulated road network in that same section (Fig. 7*b*) provides insight into the differences in the measured fragmentation properties. We observe that in the simulated network, roads maintain a regular spacing across the landscape, which is explained, in part, by the constant skidding distance employed in the FRS extension. On the other hand, in the existing network, the separation between roads is not uniform and even closer than in the simulated networks. This heterogeneity in the spatial distribution of roads influence the division, the aggregation, and the shape of forest patches.

Together, the differences in the number of patches, Clumpy and TCA suggest that forest pixels were less aggregated in landscapes with simulated roads. This resulted in a higher number of patches with a generally smaller core area than in existing road landscapes. Moreover, the larger values of PAFRAC in the simulated landscapes indicates that shape of forest patches tended to depart from simple squares toward more convoluted shapes with a longer perimeter or outside edge. This, in turn, is also supported by the decrease in TCA which implies that forest patches have less core area and more edge.

Globally, our results showed notable local correspondence between the location of simulated and existing road pixels. The superposition of pixels within a 500 m radius was especially high for road pixels located inside forest operation areas, whereas this correspondence decreased by about 40% for road pixels located outside forest operation areas (Table 2)—representing between 10% and 30% of all road pixels in the landscapes. The poor overlap between existing and simulated road pixels outside forest operation areas is due to reduced constraints and hence greater freedom with which the FRS extension could position forest roads. A possible reason to explain this divergence is that FRS operates at the strategic scale, whereas existing roads are ultimately constructed at the operational scale. The strategic scale of forest management considers long-term and large-scale objectives such as the annual allowable cut, conservation objectives, or aggregation of forest harvesting. In contrast, the operational scale takes into account small scale and short-term factors such as the position of employee accommodations and timber landings, temporal constraints influencing the durability requirements of roads, the precise order in which forest operations will be executed, etc. Had the actual FRS extension considered these more operational factors, there might have been greater concordance between existing and simulated

Fig. 7. Comparison of the road pixels corresponding to (*a*) existing forest roads and (*b*) forest roads simulated by the FRS extension, at a particular location in the Mauricie landscape used to test the extension. Satellite imagery is from the Landsat project, and accessed through the data portal of the Ministry of Forests, Fauna and Parcs of Quebec (https://geoegl.msp.gouv.qc.ca/ws/mffpecofor.fcgi?request=GetMetadata&layer=lsat_mos2020).



road pixels outside forest operation areas. While some factors could be integrated into future versions of the FRS extension (e.g., temporal constraints associated with each forestry activity), this increased precision would require more specific data that is rarely available. Moreover, some factors (e.g., timber landings) could never be considered in a model such as LANDIS-II because this would require fine-scale data related to the operational scale (e.g., fine topographical elements, technology available, etc.). Such fine-scale data could not be implemented in LANDIS-II without requiring many more parameters and input data, but also much longer simulations times due to the finer spatial and temporal resolution required. In addition, such efforts would always be limited by the discrete nature of space and time in the functioning of LANDIS-II. Hence, studies that focus on the precise location of forest roads outside forestry operation areas (e.g., roads that cross the habitat of an endangered species) should recognize that the FRS extension does not simulate forest roads at an operational level.

In the end, our results show that the FRS extension can be used in modeling studies that are interested in landscape-scale measures of road density and fragmentation, or that explore ecological or economic issues influenced by the spatial distribution of forest roads at a strategic level. However, these results must be interpreted in light of the transformations that we made on the existing road networks (rasterization, elimination of inadequate roads and forest operation areas; see Section 2.2.3). Still, we believe that these transformations did not alter our results in an important way, as only a small portion of existing roads (around 10%) were deleted in the process. Moreover, the FRS extension employs a uniform skidding distance across the simulated landscape and should be used with caution in contexts where local features of the landscape (i.e., topography, soils, etc.) can influence the skidding distance. In these situations, the FRS extension might over- or under-estimate fragmentation or road density measures, depending on how the parametrization was made. In such cases, we recommend that users explore the sensitivity of their results to important parameters including the skidding distance or those used by the loop algorithm.

Additionally, in hilly terrain, the presence of steep slopes increases the complexity of road construction, which is represented in our model (Stückelberger et al. 2007). Our two regions did not contain steep slopes (>10%) in large quantity, preventing us from measuring the performance of the FRS extension in hilly terrain. However, as the model discourages road construction in cells with a steep slope or topographic obstacles (cliffs, etc.) by increasing their cost of construction, we expect that it will be able to provide adequate estimates of the position of roads in most hilly terrains. In a broader context, studies that focus on the precise location of forest roads could integrate appropriate cost layers at a smaller resolution than those used here (250 m and 100 m). Thanks to the open-source and collaborative nature of the FRS extension, we expect that future contributions will improve the precision of our model. Finally, the FRS extension also provides other measures and outputs that could not be tested here. In particular, the estimated construction cost of the road network can be used to compare different management scenarios that vary the economic incentives or obstacles to road construction for the forest industry.

5. Conclusion

We presented the FRS extension, a new extension for the LANDIS-II FLM that simulates the construction of forest road networks. We showed that the FRS extension has few essential parameters and many options, allowing researchers to simulate the evolution of forest road networks with different levels of details. In its simplest form, the extension only requires a single raster map (elevation) and two cost parameters (basal distance cost and an additional cost due to the slope). More advanced options can integrate other spatial features of the landscape (e.g., streams or soils), roads aging, and timber flux through the road network. The execution time of the FRS extension is very fast and does not increase the simulation time of the LANDIS-II model by more than a few minutes at each iteration of the extension, for a landscape of 5 million active cells.

The FRS extension will enable researchers to include the construction of roads in forest management, furthering our understanding of its impacts on forest ecosystems. Consequently, it will offer the possibility to explore or re-explore research questions relative to forest roads including their impact on landscape fragmentation, animal movement, recreational access, fire management, social acceptability of timber harvesting, and cost at larger spatial and temporal scales. Simulating forest roads is crucial at a time when forests are perceived as providers of important ecosystem services, like carbon storage via afforestation and substitution, which can be affected by the construction and usage of forest roads.

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Data availability

The source code, binaries and user guide of the FRS extension are all available at https://github.com/Klemet/LANDIS-II-Forest-Roads-Simulation-extension.

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Competing interests

The authors declare there are no competing interests.

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Appendix A: packages used to optimize performances

We improved the computing performance of the module by using two open-source C# NuGet packages: "Supercluster.KDTree" (Regina 2015) and "OptimizedPriorityQueue" (BlueRaja 2015). The first package allows to partition the recently harvested cells and the exit points into a particular binary tree data structure called a "k-d tree" (Bentley 1975). This tree is made by repeatedly splitting a multi-dimensional space (with a number "k" of dimensions) on the position of points in that space (here, the cells centroïd). At each split, the remaining points (not used for splits) are categorized in one part of the split or the other, effectively creating a binary tree. Using a k-d tree, a fast nearest-neighbor search can be performed using the tree's structure to find the exit point closest, in Euclidean distance, from any harvested area of interest. Once that the closet exit point is found for every harvested area, these can be ranked according to the "closest first" or "farthest first" heuristics. Hence, the k-d tree dramatically improves the computation time of the module by eliminating the need to compute the Euclidean distance for every pair of recently harvested cells and exit points at each time step.

The second package, "OptimizedPriorityQueue", contains a priority queue object optimized for the C# language which improves the speed of the Dijkstra algorithm. The algorithm work by successively integrating cells into the "frontier" of its search space by considering the neighbors of the cells at the frontier. Each cell integrated into the frontier is given a "priority" value, which is used to determine which cell will be considered at the next iteration. In the case of the Dijkstra algorithm, this priority value is the least-cost path from the starting point of the search to this cell, with lower values being prioritized. The optimized priority queue proposed by the package takes advantage of the object-oriented structure of the C# language to reduce the number of operations needed to order a new cell (and its corresponding value). This, in turn, make the Dijkstra algorithm much faster.

Appendix B: equations of the fragmentation indices

B1. Clumpy

The Clumpiness Index (Clumpy; McGarigal et al. 2012) for the patch type (class) i is given in the following equation:

$$CLUMPY_i = \begin{bmatrix} \dfrac{G_i - P_i}{P_i} for\, G_i < P_i \,\&\, P_i < 0.5;\; else \\ \dfrac{G_i - P_i}{1 - P_i} \end{bmatrix}$$

where

$$G_i = \left(\frac{g_{ii}}{\left(\sum_{k=1}^{m} g_{ik}\right) - \text{min-e}_i} \right)$$

and:

1. g_{ii} is the number of like adjacencies between pixels of patch type (class) i based on the double-count method.
2. g_{ik} is the number of adjacencies between pixels of patch types (classes) i and k based on the double-count method. Here, k are the other existing patch types (class) in the landscape.
3. min-e$_i$ ist he minimum perimeter (in number of cell surfaces) of patch type (class) i for a maximally clumped class.
4. P_i is the proportion of the landscape occupied by patch type (class) i.

Clumpy corresponds to the deviation of the proportion of like adjacencies between pixels of type (class) i, when compared with a random distribution of those pixels. It varies between −1 and 1. When Clumpy approaches 0, the pixels of type i are aggregated as they would be if they were distributed randomly. When Clumpy approaches −1, the pixels of type i are distributed in a way that they are less aggregated than in a random distribution. When Clumpy approaches 1, the pixels of type i are aggregated more than in a random distribution.

B2. TCA

The Total Core Area (TCA; McGarigal et al. 2012), for the patch type (class) i is given in the following equation:

$$TCA_i = \sum_{j=1}^{n} a_{ij}^{core} * \left(\frac{1}{10000} \right)$$

where:

- a_{ij}^{core} is the core area of the patch j of the patch type (class) i. In our study, the core area pixels are defined as pixels that have no neighbors different than their own class; if not, they are considered on the edge of the patch.

As the quantity of core area of patches of type (class) i in the landscape increases, TCA increase too. It varies from 0 (no core area), and is only limited by the total size of the landscape.

B3. PAFRAC

The Peremiter-Area Fractal Dimension (PAFRAC, McGarigal et al. 2012) for a patch of type (class i) is given in the following equation:

$$\frac{2}{\dfrac{\left[n_i \sum_{j=1}^{n} \left(lnp_{ij} \cdot lna_{ij}\right)\right] - \left[\left(\sum_{j=1}^{n} lnp_{ij}\right)\left(\sum_{j=1}^{n} lna_{ij}\right)\right]}{\left(n_i \sum_{j=1}^{n} lnp_{ij}^2\right) - \left(\sum_{j=1}^{n} lnp_{ij}\right)^2}}$$

where:

- a_{ij} is the area of patch *j* of the patch type (class) *i*.
- p_{ij} is the perimeter of patch *j* of the patch type (class) *i*.
- n_i the total number of patches of the patch type (class) *i* in the landscape.

PAFRAC varies from 1 to 2. As its value departs from 1 and approaches 2, the shape of the patches of type (class) *i* depart from a Euclidean geometry, and take more complex shapes. Therefore, PAFRAC approaches 1 for patches with very simple shapes (perimeter) such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Appendix References

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