Forest Roads Simulation v1.3.1
LANDIS-II Extension
User Guide

Clément Hardy[1]

[1]Université du Québec à Montréal

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1 Introduction

This document describes the Forest Roads Simulation or "FRS" extension ('plug-in') for the LANDIS-II model. Users should read the *LANDIS-II Model User's Guide* prior to reading this document.

The FRS extension is described and tested in an article by Hardy et al. (to be published), that we recommend to users for further reading.

The FRS extension was formerly called "FRS module". Know that the two terms are interchangeable, and describe the same software.

1.1 Terminology used in this guide

In this guide, **the terms "pixel", "cell" or "site" are used interchangeably**. They are all used to describe the discrete spatial units of the LANDIS-II model. Additionally, **we use the terms "forest roads" and "roads" in two distinct ways**. "Forest roads" will refer to roads that the FRS extension is capable of creating (or destroying); while "roads" will refer to both the forest roads and to the main, paved road network of the simulated landscape.

1.2 Necessity of using a harvest extension

The Forest Roads Simulation extension simulates the evolution of forest roads in the LANDIS-II landscape. These forest roads are used to access zones to harvest simulated by another LANDIS-II extension that manages harvesting disturbances (e.g. "Base Harvest" or "Biomass Harvest"). Therefore, **the FRS extension works in tandem with a harvest extension**. Without one, the FRS extension will simply be inactive.

1.3 Roads in the landscape of LANDIS-II

Currently, the forest roads built by the FRS extension do not influence the vegetation of the LANDIS-II landscape. Therefore, it is as if the FRS extension edits a landscape parallel to the main landscape used in the LANDIS-II simulation. **We call this landscape the "road landscape"**. Data related to this road landscape is available in the outputs of the FRS extension.

1.3.1 Sites without roads

For each LANDIS-II site, the "road landscape" contains a value that describes if the site contains a road or not. Sites without roads have no value, or a value of "0". While they do not contain roads, these sites can present another disturbance simulated by another LANDIS-II extension (harvested or burned).

1.3.2 Sites with exit points

Exit points are defined as sites containing structures where the harvested timber should be transported to, via the use of forest roads, in order to be sold, used, or transported further. For example, exit points can contain sawmills, or paved roads that are part of the main road network of the landscape. **Exit points are static throughout the simulation** (they are not created or deleted through time). In addition, **the road landscape must contain at least one exit point for the FRS extension to function**. The site values of the road landscape corresponding to exit points are defined by the user (see below).

1.3.3 Sites with forest roads

Forest roads are used to transport timber from recently harvested areas to a nearby exit point (see above). They can be of different types defined by the user (e.g. primary, secondary, etc.). The site value corresponding to each road type is defined by the use (see below). The FRS extension simulates the construction (and, optionally, the destruction) of these forest roads.

1.4 Determining the type of forest roads

Forest roads can be described as different categories, relative to their dimensions, their materials, and so on. In reality, forest roads of higher categories are often constructed to facilitate the transport of timber as they are costly to build (Nevečerel et al. 2007). However, to our knowledge, no clear guideline exists on this subject.

In order to determine the type of forest roads to build in a way that is both realistic and easy to understand, we used an approach that inspires from the study of hydrological networks. In this approach, the forest road network is perceived as a watershed, with the "water" being timber coming from the harvested sites. This timber is transported by timber trucks, which follow the shortest path through the forest roads, from a harvested site to an exit point.

To determine the type of each forest road, this “flux” of timber is simply calculated for each segment of the forest road network by addition from segment to segment. The user can then indicate thresholds of timber flux by time step for which a certain forest type must be built to allow for transportation of this flux.

1.5 Tracing of the forest roads via the least-cost path

1.5.1 Construction cost of a forest road at the site level

In order to create realistic forest roads, the path of the forest roads built by the FRS extension depend on their cost of construction. The FRS extension act according to the hypothesis that the right tracing for a given forest road is going to be the cheapest one, monetary speaking. This is because forest roads represent an important cost associated with forest management, which foresters try to reduce (Heinimann 2017). In this way, the extension will avoid constructing forest roads at expensive locations, or in expensive ways.

To determine the cost of constructing a forest road on a site, the extension can consider different information about the topography of the landscape that are relevant for creating a forest road: distance, slope (elevation), obstacles (e.g. cliffs, breaks, etc.), existing bodies of water (rivers, lakes), streams, and soils. This way, the extension can favor the best conditions for road building, but also give a broad estimate of the costs of construction of the roads.

In addition to the topography of the landscape, the cost of building a forest road is influenced by the type of the road (e.g. primary, secondary, etc.; see above). The FRS extension accounts for this by using “cost multipliers” for different the different types of roads defined by the user, relative to a “reference” type (see sections 4 and 5.3.4).

The cost of construction of a road through a cell is given by the following formula:

$$\text{If a road is present} : C_{total} = 0$$
$$\text{Else} : C_{total} = M_{type} D_{obstacles} \left(C_{basal} + C_{slope} + C_{bridge} + C_{culvert} + C_{soil} \right)$$

With M_{type} being the multiplication parameter for the type of road to construct (see section 5.3.4); $D_{obstacle}$ being the multiplicative parameter for potential detours due to obstacles in the cell (see sections 3.4 and 4.3); C_{basal} being the basic distance cost (see section 4.1); C_{slope} being the additional cost due to the slope (see sections 3.3 and 4.2); C_{bridge} being the cost of having to construct a bridge if the cell presents a body of water (see sections 3.5 and 4.4); $C_{culvert}$ being the price of building culverts if the cell contains streams that must be crossed (see sections 3.6 and 4.5); and C_{soil} being the additional cost due to the type of soil in the cell (see section 3.7).

1.5.2 Optimizing the cost of the forest road network

A great number of methods exist in order to determine the least-cost path between two given points. The resolution of this problem is called, in the context of forestry, the “Single Target Access Problem” (STAP; Chung et al., 2008). It is quite simple to resolve. However, the design of a forest road network represent a more complex optimization problem, called the “Multiple Target Access Problem” (MTAP), for which optimization of a solution is much harder to deal with (Chung et al. 2008; Heinimann 2017).

To solve a MTAP, current software for designing forest road networks such as REMSOFT’s Road Optimizer (Remsoft 2019) uses a heuristic coupled with a path-finding algorithm. In essence, this solves the MTAP as a sequence of STAPs, which ordered via the heuristic. For example, the heuristic can be “build roads to the harvested sites farthest from current roads first”. Then, in sequence, the STAPs are solved with the path-finding algorithm.

With this method, the chosen heuristic will influence the shape of the forest road network. In addition, the forest road network generated by this method will not be perfectly optimized (e.g. the cheapest possible). However, different heuristics can be used successively to identify differences or similarities between the generated networks.

The FRS extension makes use of this method by proposing three heuristics to the user: Random, closest first, farthest first. The least-cost path algorithm used by the extension is the Dijkstra algorithm (Dijkstra 1959).

1.6 Major Releases

1.6.1 Version 1.0 (October 2020)

Features:

- All of the essential functions of the model present
- Code cleaned up

1.6.2 Version 1.1 (March 2021)

Features:

- Implementation of the looping algorithm 2.0

1.6.3 Version 1.2 (June 2021)

Features:

- Temporary fix for a problem in the planning of a return to a harvested cell (see this issue)
- Fix in the parsing of cost parameters and rasters; now, if one writes "none" as the location for a cost raster, there is not need to indicate an entry for the associated parameter.

1.6.4 Version 1.3 (August 2021)

Features:

- The loop algorithm now uses the random number generator of the LANDIS-II core. Hence, different simulations using the loop algorithm with the a similar LANDIS-II scenario seed will give the exact same road network as a result, which was not the case before.

1.7 Minor Releases

1.7.1 Version 0.5 (August 2019)

First pre-release for testing purpose. Features:

- Detection of an installed harvest extension
- Reading of a raster containing the initial road network
- Completion of the initial road network
- Construction of roads
- Creation of an output raster at each time step

1.7.2 Version 0.9 (October 2019)

Pre-release for research purposes. Features:

- Construction of roads influenced by several different features of the landscape
- The user can now enter customized types of roads in the parameter file.
- Simulation of the flux of wood
- Output of rasters showing the flux of wood
- Simulation of road aging
- Output of a log containing the cost of construction at every tim estep

1.7.3 Version 0.95 (November 2019)

Pre-release for research purposes. Features:

- Huge improvements to performances and simplification of the code.

1.7.4 Version 0.96 (January 2020)

Pre-release for research purposes. Features:

- Updated functions for getting the "TimeSinceLastEvent" variable for harvest events.
- Performance improvements.

1.7.5 Version 0.97 (June 2020)

Pre-release for research purposes. Features:

- Implementation of the first version of the looping algorithm
- Consideration of the need to return to the harvested cell for repeated harvests
- Fixed a bug concerning the wood fluxes that resulted in some incoherent forest road types.

1.7.6 Version 0.98 (June 2020)

Pre-release for research purposes. Features:

- Fix a bug during the initialization phase that was due to the extension trying to gather non-initialized variables at that time.

1.7.7 Hotfix 1.2.1 (July 2020)

Features:

- The FRS extension is now packaged with a more recent version of `Landis.Library.SiteHarvest-v2.dll`, which should avoid this issue.

1.7.8 Version 1.3.1 (June 2020)

Features:

- Fixing the printing of the message "Testing if prescription is repeat harvest." that would display in certain cases.

1.8 References

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1.9 Acknowledgments

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I deeply thank the LANDIS-II foundation for their incredible work toward providing an easy to use, and easy to program model.

2 Basic input parameters

These parameters should be at the beginning of the parameter `.txt` file (see section 6 for an example)

2.1 LandisData

This parameter's value must be `" Forest Roads Simulation"`.

2.2 Time step

This parameter is the extension's time step. **To avoid errors or inconsistencies, it should be the same as the harvest extension**. In addition, **the FRS extension should be activated right after the harvest extension**. To that end, **please avoid using a random order for disturbance extensions in your scenario files**. Not doing so would result in temporal inconsistencies in the outputs of the FRS extension. Value: integer > 0. Units: years.

2.3 Heuristic for network construction

This parameter determine which heuristic will be used to determine the order in which roads to recently harvested cells will be built (see sub-section 1.5.2). It can take three different values: "`Random`", "`ClosestFirst`", "`FarthestFirst`".

With the "Random" value, at each time step, forest roads will be built to the recently harvested sites in a random order. With the "`ClosestFirst`" value, the sites closest to existing roads will be connected first. The opposite will happen with the "`FarthestFirst`" value.

Previous testing from our part seem to have shown that the "`ClosestFirst`**" heuristic provided the most realistic results** when compared to existing forest road networks. However, we recommend the user to try different simulations with different heuristics to account for the existing variability between these options.

2.4 Skidding distance

The skidding distance indicates the maximal distance on which timber can be "skidded" towards a nearby forest road. Hence, if a recently harvested cell is at a skidding distance from a cell containing a road, no road will be built to that harvested cell. Instead, it will be supposed that the timber from the harvested cell will be skidded toward the existing road. If the opposite is true, then a forest road will be built to reach this harvested cell. The skidding distance is calculated between the centroïd of each cells. Value: integer > 0. Units: meters.

2.5 Looping behavior

If a single road is created to the harvested cells that must be reached, then the resulting road network will resembles a tree whose branches never touch. In such a structure, there cannot be a “complete” surrounding of patches of habitat by the way of “loops” of roads. Such “loops” can however be observed in real forest road networks, as they result from roads that make redundant paths toward the same place. This discrepancy can heavily influence the value of fragmentation indices such as the effective mesh size (Jaeger 2000), which are very sensitive to the existence of well-defined patches of habitat.

Hence, the FRS extensions contains a “looping algorithm” which uses 5 parameters in order to control when and where loops will be created in the landscape. These parameters create 4 conditions that must be respected so that the a second, redundant road be created to a harvested cell, creating a loop. The looping algorithm will create a first road to the harvested cell of consideration (as described in section 1.5). Then, it will design the path of a second road linking the harvested cell to another part of the existing road network. However, this second road will only be built if all conditions are validated (see below).

To activate the looping algorithm, the user must associate the value “`yes`” to the parameter “`LoopingBehavior`”, or use “`no`” to disable it. If the looping algorithm is activated, the following 5 parameters must be provided:

- The “`LoopingMinDistance`” parameter is a distance around the harvested cell of consideration under which no road cells must exist. If one does exist, the second road will not be built. This avoids loops that are too small. Value: integer > 0. Units: meters.
- The “`LoopingMaxDistance`” represent a distance around the harvested cell of consideration under which at least two road cells must exist. If less than two exist, the second road will not be built. This avoids loops that are too big. Value: integer > 0. Units: meters.

- The “`LoopingMaxPercentageOfRoads`” parameter is a percentage of roads existing around the harvested cell of consideration, at a distance corresponding to the “`LoopingMaxDistance`” parameter. If this percentage is exceeded, the second road will not be built. This avoids over-crowding a local road network that is already dense in roads. Value: 100 >= integer >= 0. Units: percentage.
- The “`LoopingMaxCost`” parameter is the maximum ratio that can be reached between the cost of the second road, and the cost of the first road. Above it, the second road will not be built. This avoids building a second road that is too costly. Value: integer > 0. Units: none.
- The “`LoopingProbability`” parameter is a probability threshold representing the chance of building the second road if all of the other 4 conditions are respected (see above). The closer it is to 100, the more chances there are to build the second road if all other conditions are validated. This fine-tunes the quantity of loops in the landscape. Value: 100 >= integer >= 0. Units: percentage.

2.6 Location of the outputs rasters

This parameter indicates where the user wants the output rasters generated at each time step to be saved. It can be expressed as a relative or an absolute path. The name of the output rasters must be indicated, including the `.tif` extension (e.g. `./output/roadsRasters/roadNetwork.tif`). The name of the raster file will automatically contain the number of the time step at which it was generated at its end (e.g. `roadNetwork-10.tif`).

2.7 Location of the summary log of the construction costs

This parameter indicates where the user wants the summary log of the construction costs of roads to be located. This summary log will contain the construction costs of all of the forest roads constructed during the simulation, the number of road cells constructed at each time step, the time that the extension took to execute at this time step, and the number of harvested cells that needed to be reached at this time step.

3 The input rasters

To function, the FRS extension requires spatial information about the topography of the landcape. This information is fed to the extension by the use of different input rasters. These rasters have to be in a certain format to be read and understood by the extension. In this section, you will find details and indications to generate those rasters easily. More examples can be found in the article of Hardy et al. (2021).

Only three rasters are essential to run the FRS extension: the raster of buildable zones, the initial road network raster, and the coarse elevation raster. The others raster are optional, but they will improve the realism of the roads generated by the extension. **Each input raster must have the same resolution and extent as the other rasters used as inputs for LANDIS-II**. In addition, as with any input raster of LANDIS-II, each raster should be formatted in the `int` format (`int16` or `int32`).

3.1 The raster of buildable zones

This raster indicates where forest roads can or cannot be built in the landscape. Any pixel with a value different of `0` is considered “buildable”. Consequently, any pixel with a value of `0` is considered “non-buildable”. No forest road will be built on non-buildable pixels during the simulation.

3.2 The initial road network raster

This raster indicates the state of the roads in the landscape at the beginning of the simulation. Values equal or inferior to `0` are reserved for sites without roads on them. Positive values should correspond to a road ID or the ID of an exit point defined by the user later in the parameter file (see sections 5.3.3 and 5.4 below).

If the value for a pixel is neither negative, nor 0, nor one of the road type ID, the FRS extension will return an error when reading the raster. The initial road network raster must contain at least one exit point for the FRS extension to function. The values used in this raster to represent cells with or without roads are also used in the output rasters of the FRS extension.

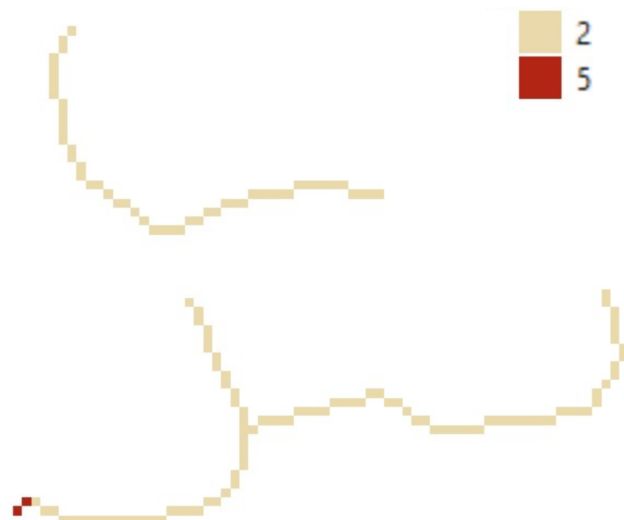
Here is an example of values for the initial road network raster:

Raster pixel value	Road type
>= 0	No road
1	Primary forest road
2	Secondary forest road
3	Tertiary forest road
4	Winter/temporary forest road
5	Sawmill
6	Main road network (paved)

Any other value	Not valid (unknown)

To create the initial road network raster, you can use the free GIS software "Quantum GIS" (QGIS). If your initial road data is in vectorial format (lines), you can modify the attribute table of the layer to associate each line with the correct road type ID that you defined for the type of the line. Then, you can use the "Vector to Raster" tool to "burn" the attribute field you just created (containing integer values) with the right resolution and extent. At this point, it is recommended that you define the "No Data Value" of the raster at 0, and that you use the advanced parameter to save the raster's values as "int16".

Here is a very simple example raster following such instructions:



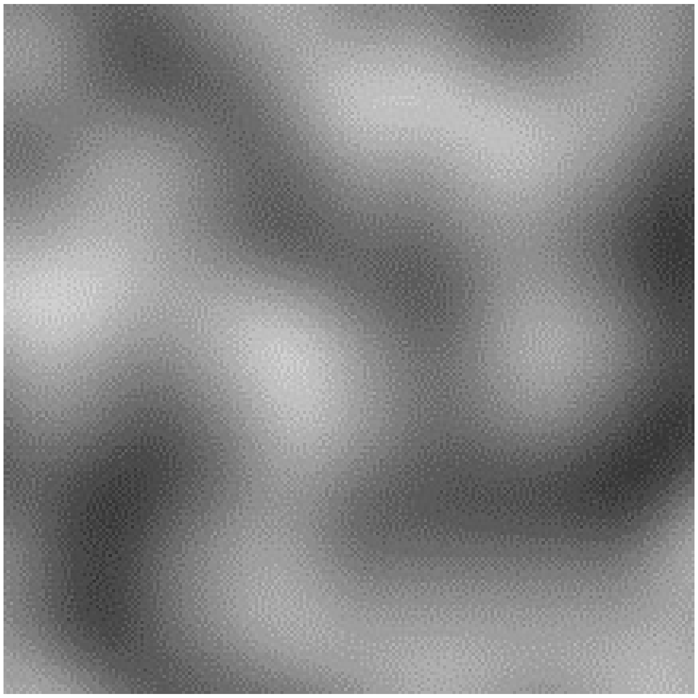
As you can see, this example raster only contains two pixels/sites indicated (in the example classification displayed above) as a sawmill (5), and pixels/sites indicated as secondary forest roads (2). The rest will be sites without roads (0 or No Data).

3.3 The coarse elevation raster

Because the resolution of LANDIS-II too low to take into account the presence of cliffs or breaks inside a cell, we separated the topography of the landscape into two rasters of different resolution, containing two distinct (albeit related) information. The “coarse” elevation raster describes the mean elevation of each pixel of your landscape, while the “fine” elevation raster describes the presence of topographical obstacles. In essence, the coarse elevation raster is a Digital Elevation Model. It is one of the three rasters that are essential for the FRS extension to function, as the slope is one of the main factors influencing the path of roads in reality.

In this raster, each pixel should contains the value of the mean altitude associated with the pixel/site. To create such a raster, we recommend the use of a Digital Elevation Model (DEM), and to change the resolution and the extent of the DEM to the one used for your LANDIS-II rasters. **The elevation should be in meters**, to adapt to the formula used in the FRS extension to compute the slope between two pixels.

When displayed in software like QGIS, the coarse elevation raster should look like this:



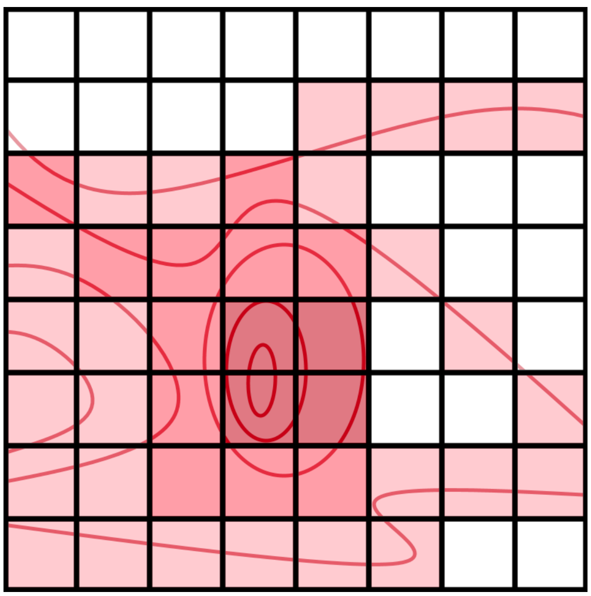
3.4 The fine elevation raster

This raster contain information pertaining to small changes in the topography that might become an obstacle for the construction of the forest road.

These obstacles can requiring detours, or an increase of road distance to traverse the pixel/site (e.g. cliffs, breaks, ditches, etc.). The values contained in the raster will depend on the methodology used to create it. For example, it can contain value related to the quantity and closeness of contour lines in the cell.

To create a fine elevation raster based on vectorial contour lines, one can use the free QGIS software. It can be done by using 3 tools: first, the “grid” tool to create a polygonal square grid with the same extent/resolution than the desired raster. Secondly, the “Sum line length” tool to fill an attribute field of this vectorial grid with the length or quantity of the contours lines that cross each square polygon of the grid. Thirdly, the “Raster to Vector” tool to “burn” the attribute field created previously into a raster with the correct resolution, extent and value format (int16; see sub-section 3.1). We recommend that a measure in meters should be used, to keep a uniformity among the values used by the extension.

Here is a representation of what the fine elevation raster looks like, with the red lines corresponding to contour lines, and redder pixels representing higher values in the raster:



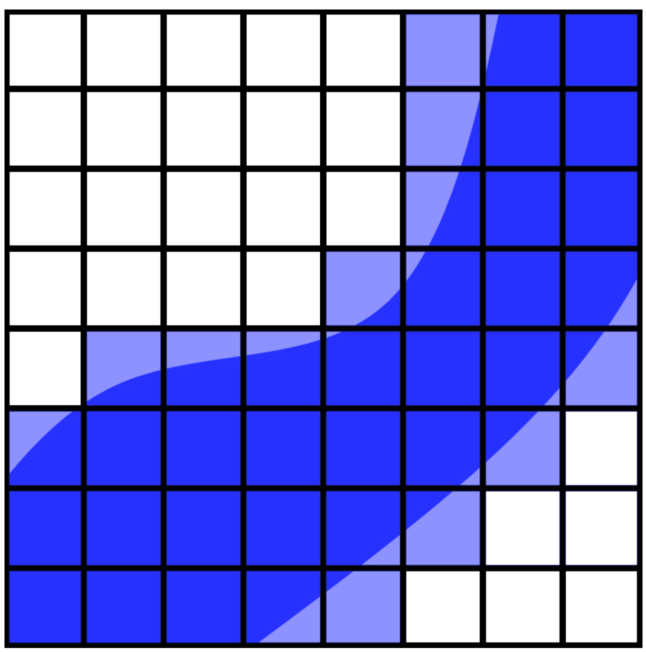
3.5 The coarse water raster

As with the raster pertaining to elevation, information related to the presence of water bodies and stream is split in two different rasters for the FRS extension to use. The “coarse” water raster contains information about large bodies of water (lakes, rivers, etc.) requiring a bridge to be crossed. In contrast, the “fine” water raster contains information about streams, requiring only a culvert to cross. In the coarse water raster, value inferior or equal to 0 indicate that no surface of water is present in the pixel. In contrast, values superior to 0 will indicate the presence of a surface of water in the pixel.

The coarse water raster can be created easily, by “rasterizing” a vectorial layer about surfaces of water into a raster. However, users should remain careful about small rivers (smaller in width than the pixel size) which might not be properly rasterized at some places during the rasterization process. This can create “gaps” that the pathfinding algorithm of the FRS extension will use to cross them, instead of paying the price to make a bridge.

To avoid this issue, we recommand using the “rasterization” tool of QGIS, and indicate the “-at” parameter (corresponding to the words “ALL_TOUCH” for the GDAL engine) in the “additional command-line parameters”.

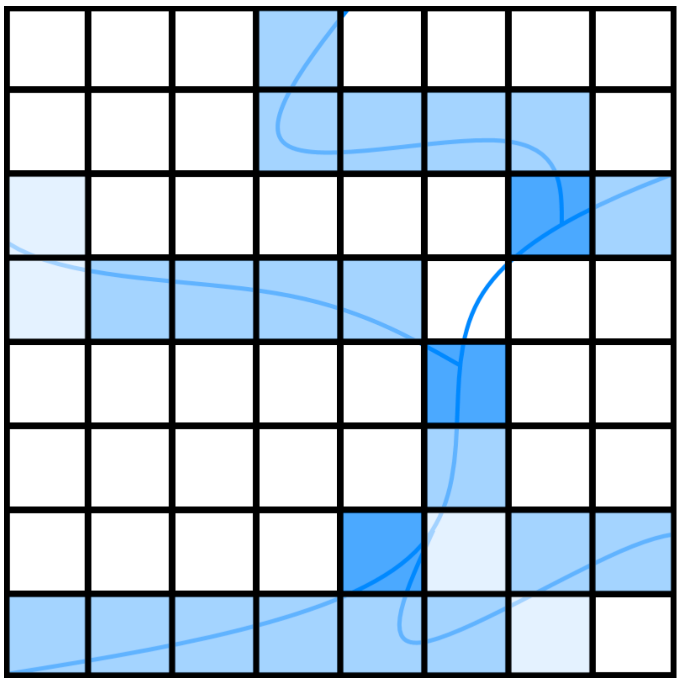
Here is a representation of what the coarse water raster should look like, with the dark blue shape being a polygon corresponding to a body of water, and light squares representing pixels with a value superior to 0 in the resulting coarse water raster:



3.6 The fine water raster

This raster contains information about streams. It should contain, in each pixel, a measure of the length of streams present in that pixel. Hence, we recommend to create it with the same tools as those advised for the fine elevation raster (see section 3.4), but this time by using lines that describe the position of streams in the landscape. As the length of streams in the pixel/site increase, the probability of having to cross at least one increase too, indicating that one or multiple culverts will have to be installed to cross it, leading to increased cost of constructions.

Here is a representation of what the fine water raster should look like, with blue lines representing streams, and bluer pixels representing higher values in the raster:



3.7 The soil raster

This raster contains information concerning the soils of the landscape. Soils can be important for the construction of forest roads, especially if they allow the builders and engineers to use local material (gravel, etc.) to build the roads. In contrast, if the materials used to make the road have to be imported to the location, the construction costs will increase.

Each pixel of this raster should be an integer corresponding to an additional construction cost related to the type of soil present in the pixel. This additional cost can be determined using a linear model applied on construction costs of real forest roads (see section 4 below). In that way, the intercept of the model will contain the effect of a “reference” soil type. We recommend that this “reference” soil type is the type of soil for which the cost of construction is the lowest. Hence, every over soil type will be associated to a positive additional cost. The intercept of such a linear model will then become the basal distance cost parameter (see section 4 bellow more detailed examples).

4 The cost parameters

Following the location of each of the input rasters must be a set of parameters that indicates the cost associated with the content of the rasters. We recommend that all of the costs represent real values in the monetary unit chosen by the user. That way, both the inputs and outputs of the extension are grounded in values that are easy to discuss or relate too. This makes the parametrization and the interpretation of results easier with both modelers and non-modelers.

These costs will be expressed for one chosen type of forest road type (e.g. primary, secondary or tertiary, etc.). This road type will be considered as the "reference" type. A multiplication parameter will be applied when forest roads of lower or higher type are constructed, to increase or reduce the cost when compared to the reference type (see section 5.3.4).

4.1 Distance cost

This parameter must follow the location of the initial network raster, and is essential to the functioning of the FRS extension. It represents the irreducible cost of building a forest road of the reference type, on the distance of a side of a site. For example, if sites have a side of 100m, then this cost must be the irreducible cost of building 100m of forest road on the best conditions possibles for forest road construction (e.g. 0% slope, the best soil type, etc).

This parameter can be estimated using a linear model applied to real construction cost of forest roads. If done so, the basic distance cost will be the intercept, containing only the effect of the "best" level for those factors (e.g. 0% slope, best soil type for construction, etc.).

The parameter should be a single value superior to 0.

4.2 Coarse elevation costs

These parameters correspond to additional construction costs that are due to the slope of the terrain. The user can input this additional cost for several ranges of slope percentage. The slope percentage for a pixel will be equal to the biggest slope percentage among its 8 neighboring pixels. The percentage is calculated using the pixel size indicated to LANDIS-II, and the information of the coarse elevation raster.

These costs take the form of a table indicating a lower threshold and an upper threshold in percentage of slope. For each row, there should be an associated cost for values of slope percentages between those two thresholds. Thresholds must be continuous and encompass all of the possible slope values in the landscape. An example is given in the example parameter file (see section 6).

The cost associated to each slope range should be a single value superior to 0.

4.3 Fine elevation cost

These parameters corresponds to a multiplication of the cost of construction of the forest road on the cell. This multiplication is due to possibility that the road will have to slalom in order to avoid finer topographic elements (cliffs, depressions, etc.). This will increase the length of forest road that will have to be constructed in order to pass through the given site, increasing the total construction cost.

These parameters take the form of a table of values with three columns: Lower topography threshold, upper topography threshold, and multiplication value for this range of values. The thresholds should correspond to thresholds in the values of the fine elevation raster.

The thresholds should be values ranging between 0 and the maximum topography value existing in the fine elevation raster. The first lower threshold must be smaller than the smallest fine elevation value in the raster. The multiplication values should be superior to 0.

4.4 Coarse water cost

This parameter correspond to the cost of building a section of a bridge, on a body of water equal to the length of the site where it is present. For example, if the price of a basic bridge over 200m of water is around 2 000 000$, and if the side of a site in the LANDIS-II landscape is of 100m, then this cost should be of 1 000 000$. While the price of bridges can vary according to the type of bridge and the material used, the coarse water cost is mostly used to discourage the path-finding algorithm from crossing large bodies of water.

The parameter should be a single value superior to 0.

4.5 Fine water cost

This parameter correspond to the cost of constructing a culvert, which is a structure that channels water from a passing stream beneath the road. The number of culverts that will have to be created by crossing the given site will be dependent on the probability of having to cross a stream. This probability depends on the length of streams present in the given site, as indicated by the fine water raster.

The number of culverts to be created by crossing the cell will be the result of the division of the length of streams in the site and the length of the diagonal of the site, rounded at the superior number. For example, if the cell has a diagonal of 140m, and if 300m of streams are present in the cell; then given the probability of crossing the streams, the algorithm will take into account that 2 culverts would have to be constructed to cross it.

The parameter should be a single value superior to 0.

5 Road type thresholds and cost multiplication values

As indicated in sub-section 1.4, the FRS extension can construct different types of forest roads. The type of road to construct, or to upgrade to, is deduced by an algorithm that considers the forest road network as a kind of watershed. Once all of the forest roads have been created at the current time step, each recently harvested site are considered as a source of timber at the considered time step. The amount of timber coming from a site is currently measured by the number of age cohorts harvested in the site, so as to adapt to all existing succession and harvest extensions.

Then, the algorithm will make the timber from the harvested sites “flow” from road cell to road cell, until it reaches an exit point. In consequence, the type of the forest roads (which are always initially constructed from the “lowest”, cheapest road type) will be upgraded to the one determined by the road type thresholds (see section 5.3.1 and 5.3.2). For a given forest road, if the flux of timber that goes through this road at the current time step is between the flux thresholds of a certain road type, this road will then be upgraded to become this road type if the current road type is of “lower” type. For example, a tertiary forest road (not very large) will be upgraded to become a secondary forest road (larger than tertiary) at a given time step if the wood flux for this road cell at the time step correspond to the “secondary” forest road type.

Once the type of a forest road is determined, the cost of the upgrade is calculated. This upgrade cost is the cost of construction of the higher road type (reference cost for the cell * multiplication value for the road type) minus the cost of construction for the current road type (see section 5.3.4). Those multiplicative costs must be relative to the reference forest road type chosen to describe all of the cost parameters (see section 4 and further below for more details).

5.1 Simulation of road aging

The FRS extension can simulate the aging of the forest roads as time goes by, and their potential destruction if they are not maintained. To that end, the user must input `yes` to this parameter. If so, the user must also indicate a `maximum age before destruction` value for each type of forest roads in the table of road types (see section 5.3 below).

If activated, at each time step, the forest roads will be “aged”; when their age reach a number superior to the maximum age before destruction for their category, they will be destroyed. They can be rebuilt if the algorithm identifies the pixel as the cheapest way to go to connect to a certain harvested area.

Currently, the age of the forest roads is reset when they are constructed, or upgraded via the algorithm of wood flux.

5.2 Simulation of wood flux

The extension can simulate the flux of wood going through the roads as the harvesting unfolds, and can also upgrade the type of the forest roads according to this flux (see introduction of section 5). To that end, the user must input `yes` to this parameter. If so, the user must also indicate lower and upper thresholds of wood flux for every type of road in the table of road types (see section 5.3 below).

5.3 Table of forest road types

This table contains the information relative to the different forest road type that the user wants to use in their landscape.

The table should contain at least a forest road type ID, a multiplicative cost value, and a road name for each forest road type. If the wood flux is simulated (see previous section 5.2), it should contain thresholds for the wood flux for each forest road type. If the aging of forest roads is simulated (see previous section 5.1), it should contain the maximum age before road destruction for each forest road type.

5.3.1 Lower wood flux threshold (Optional, if wood flux is simulated)

This threshold corresponds to the minimal value of wood flux that requires the corresponding type of forest road. Currently, the wood flux is expressed in number of harvested age cohorts in order to accommodate to all succession and harvest extensions. As the flux is calculated at each time step, the threshold should be expressed in age cohorts harvested by time step. The lower threshold is inclusive, meaning that any wood flux equal to a lower threshold will get included in the road type for this threshold.

5.3.2 Upper wood flux threshold (Optional, if wood flux is simulated)

This threshold corresponds to the maximal value of wood flux that is needed before using a higher type of forest road than the corresponding type. Currently, the wood flux is expressed in number of harvested age cohorts in order to accommodate to all succession and harvest extensions. As the flux is calculated at each time step, the threshold should be expressed in age cohorts harvested by time step. The upper threshold is not inclusive, meaning that a wood flux equal to an upper threshold will get included in the road type of the category above this threshold.

5.3.3 Forest road type ID

The forest road type ID corresponds to an integer associated with the corresponding type of forest road. These IDs should correspond to the ones that are found in the initial road network raster (see section 3.2), and will be the ones found in the output rasters (see section 2.6),

It can be any positive integer, as values inferior or equal to 0 correspond to the absence of roads. However, the forest roads types ID should not correspond to any exit point road type ID (see section 5.4), and vice versa.

5.3.4 Multiplicative cost value

This parameter is used to compute the cost of construction of a forest road type different from the “reference” type. As all cost parameters are relative to the reference forest road type (see section 4), the multiplicative cost value is used to increase or decrease the cost of construction of a road type relative to the cost calculated for the reference type.

For example, if the cost rasters and the cost parameters all concerned forest roads of type “secondary road” (that thus serves as the “reference” type of forest roads), then the multiplicative cost value for this type will be 1; the multiplicative cost values for smaller forest roads (e.g. tertiary forest roads) will be inferior to 1, and superior to 1 for bigger road types (e.g. primary forest roads).

These multiplicative cost values can be obtain from real road cost data, by comparing the average cost of construction of different road types, relative to a “reference” type.

The multiplicative cost value must be superior to 0 for each forest road type.

5.3.5 Maximum road age before destruction (Optional, if road aging is simulated)

This value corresponds to the number of years that the corresponding forest road type is supposed to last before being destroyed by wear. It must be superior to 0.

5.3.6 Road name

A string of characters without any spaces corresponding to the name of the corresponding forest road type.

5.4 Table of exit points for the wood

This table contains every information necessary to the extension in order to take into account different exit points for the wood (e.g. sawmills, main paved road network, warehouse, etc.).

The table must only contain IDs and names associated to exit points for the road. These are crucial, as the algorithm will need to connect to them in order to successfully reach a harvested area. At least one of these exit points must be present in the initial road raster (see section 3.2). The IDs for the exit points must be different from IDs used forest roads, but also from values equal or inferior to 0 which are indicative of the absence of roads in cells.

6 Example parameter file

```
>> To be read properly, the parameter file must contain the parameters in this order.
>>-----------------------------------------------------------------------
>> BASIC PARAMETERS

LandisData "Forest Roads Simulation"
Timestep 10
HeuristicForNetworkConstruction Closestfirst
SkiddingDistance 450

LoopingBehavior Yes
LoopingMinDistance 500
LoopingMaxDistance 3000
LoopingMaxPercentageOfRoads 50
LoopingMaxCost 10
LoopingProbability 90

OutputsOfRoadNetworkMaps ./output/disturbances/roads/roadNetwork.tif
OutputsOfRoadLog ./output/disturbances/roads/

>>-----------------------------------------------------------------------
>> INPUT RASTERS AND COST PARAMETERS
>> Only the initial road network raster and the distance cost are
>> essential. If you do not want to use one of the cost for the path-
>> -finding, just indicate "none" as the parameter value for the raster
>> location, and "0" for the value of the associated cost.

RasterOfBuildableZones "../../sharedRasters/buildable_zones.tif"
InitialRoadNetworkMap "../../sharedRasters/initial_road_network.tif"
DistanceCost 674.17

CoarseElevationRaster "../../sharedRasters/coarse_elevation.tif"

CoarseElevationCosts
>> Lower elevation      Upper elevation        Additional
>>    threshold            threshold             value
          0                  9                   0
          9                  16                  365
          16                  41                 778
          41                 10000               100000

FineElevationRaster "../../sharedRasters/fine_elevation.tif"

FineElevationCosts
>> Lower elevation      Upper elevation      Multiplication
>>    threshold            threshold             value
          0                 300                   1
          300               600                   1.5
          600               1000                  2
          1000              10000                 10

CoarseWaterRaster "../../sharedRasters/coarse_hydrology.tif"
CoarseWaterCost 1400000

FineWaterRaster "../../sharedRasters/fine_hydrology.tif"
FineWaterCost 20000

SoilsRaster "../../sharedRasters/soils_cost.tif"
>>-----------------------------------------------------------------------
>> ROAD TYPE THRESHOLDS AND MULTIPLICATION VALUES
>> These parameters are all essential to the functioning of the
>> extension.
SimulationOfRoadAging Yes
SimulationOfWoodFlux  Yes

RoadTypes
>> Lower Wood Flux   Upper Wood Flux     Road type     Multiplicative     Maximum age      Road Type
>>    threshold         threshold           ID          Cost Value      Before destruction    Name
          0                70               6              1                 1          Winter_roads
          70               105              5              1.5               3          Class_05
          105              3000             4              2.15              10         Class_04
          3000             40000            3              3.57              15         Class_03
          40000            70000            2              9.19              25         Class_02
          70000            100000           1              13.38             25         Class_01
          100000           1000000000       7              15.06             50         Out_of_norm

RoadTypesForExitingWood
```

```
>> Road type   Road Type
>>    ID        Name
      8         Sawmill
      9         MainRoadNetworkPaved
```