Faculté des bioingénieurs

Study of spatial analysis methods for characterizing the green infrastructure of Louvain-la-Neuve

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Année académique 2021-2022

Mémoire de fin d'études présenté en vue de l'obtention du diplôme de Bioingénieur : sciences et technologies de l'environnement

Remerciements

Je tiens à remercier en premier lieu mon promoteur Pierre Defourny et mon co-promoteur Julien Radoux pour leurs précieux conseils, retours, suggestions d'amélioration et écoute au long de ce travail.

Je remercie également Baptiste Delhez pour sa disponibilité et l'aide qu'il a pu apporter pour résoudre les différents troubles qui sont survenus durant ce quadrimestre.

Ensuite, je voudrais remercier mes proches pour m'avoir soutenu tout au long de l'année, avec une reconnaissance toute particulière pour ceux qui m'ont aidé lors de la relecture de ce travail et des ajustements finaux.

Enfin, merci aux lecteurs qui m'accordent de leur temps pour lire ce mémoire.

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List of abbreviations

GIS	Geographic Information System
GUI	Graphical User Interface
LLN	Louvain-la-Neuve
SGIB	Great Biological Interest Site

1. Introduction

In the European Union, as well as at national and regional levels, biodiversity has become a matter of concern. Human activities such as urbanization, agriculture, and the development of road infrastructures have caused land use and land cover changes, leading to habitat loss. Habitat fragmentation and habitat loss have been known to have negative impacts on biodiversity. These processes cause isolation of populations, affecting regular movements of individuals (food, shelter), as well as migratory or seasonal movements, dispersal movements between fragments, breeding success, and predation rate (Fahrig, 2003; Bennett & Saunders, 2010). Moreover, small and isolated populations become more vulnerable to stochastic processes, such as variation in demographic parameters, loss of genetic variation, fluctuations in the environment, and catastrophic events.

For many organisms, the detrimental effects of isolation can be partly reduced by habitat components that enhance connectivity within the landscape (e.g., continuous corridors or “stepping stones” of habitat) (Bennett & Saunders, 2010). These corridors are linear landscape elements that provide for survivorship and movement between habitats, and sometimes even contribute to species’ habitat and natality (McGarigal, 2015).

The town of Louvain-la-Neuve (LLN) has evolved a lot since the end of the 20th century and its creation in 1971. What used to be agricultural fields 50 years ago have now been replaced by buildings and artificial surfaces, in addition to the development of roads that ensue from this urbanization (Figure 1). The *Bois de Lauzelle* (top) and the *Bois des Rêves* (bottom*)* were already there although not exactly the same, but with the construction of the town, these two habitats are more isolated than before.

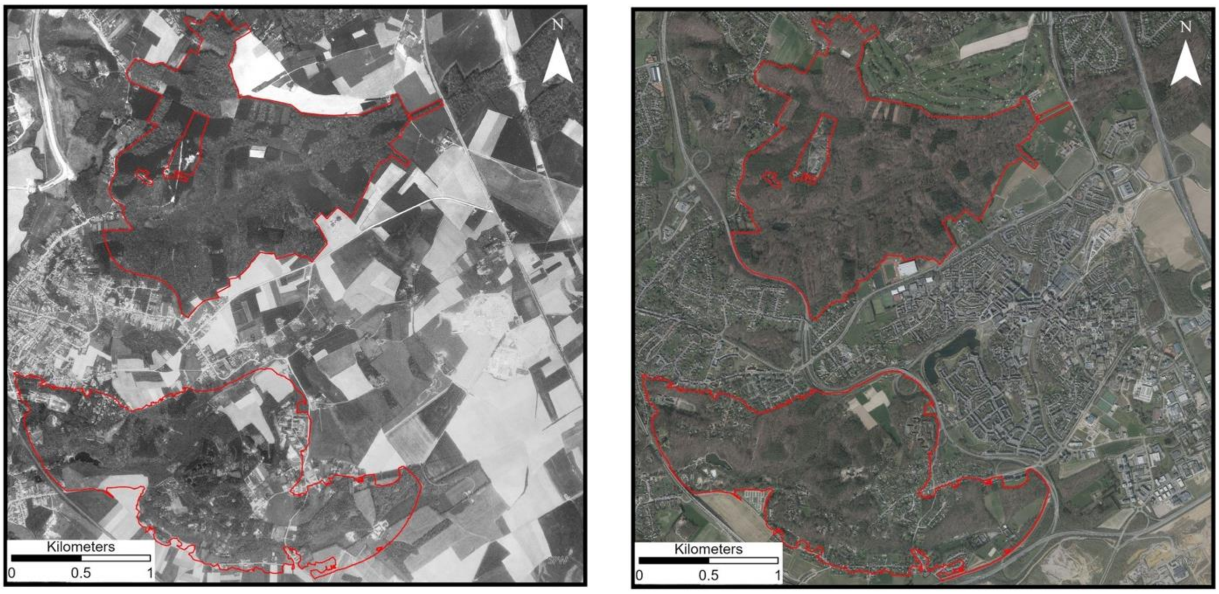

Figure 1 : Orthoimage of LLN in 1971 (left) and 2021 (right) (Orthophotos : la Wallonie vue du ciel, n.d.).

Furthermore, with the planned construction of the new *Athéna-Lauzelle* district adjacent to the *Bois de Lauzelle*, connectivity between habitats in LLN is a matter of increasing concern.

Monitoring and assessing the connectivity of habitats appear crucial for land use planning and have been facilitated by the development of remote sensing and Geographic Information Systems (GIS). The different software and theories used for connectivity analysis in landscapes have also been greatly developed and the distinction between one another or their possible applications is sometimes unclear.

2. Literature review

2.1. Green infrastructure

The green infrastructure can be defined as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation, and climate mitigation and adaptation" (What is green infrastructure?, 2021). Although this definition provides insight into the concept, it misses a key point, which is the role that green infrastructure holds in ecology. The Countryside Agency (2006) is arguably more comprehensive in its definition, defining the concept as "the provision of planned networks of linked multifunctional green spaces that contribute to protecting natural habitats and biodiversity, enable more sustainable and healthy lifestyles, enhance urban liveability and wellbeing, improve the accessibility of key recreational and green assets, support the urban and rural economy and assist in the better long-term planning and management of green spaces and corridors".

As the definition states, the green infrastructure is a network of linked green spaces. In a broader context and taking into consideration the reality on the ground, these interacting green spaces form, to some extent, landscapes. A landscape is an area where a cluster of interacting ecosystems is repeated in a similar form, characterized by its specific dynamics, and organized at a higher degree than the ecological level. (Forman & Godron, 1981; Burel & Baudry, 2003). The connectivity between these areas can be assessed using certain metrics, which are the cornerstone of landscape connectivity analysis. Certain metrics useful to assess this connectivity and the steps prior to their usage are described in the sections below.

2.2. The relevance of scale

Apart from Figure 2, all the information from sections 2.2 to 2.4, quotations included, is taken from the FRAGSTATS complete description (McGarigal, 2015).

It is meaningful to define the scale at which the study area is monitored from the perspective of the organisms under consideration. It is indeed critical that the extent and grain represent the studied organism to the uppermost degree, otherwise the landscape patterns detected might lead to incorrect conclusions due to the pattern having little meaning. In other words, it is meaningless to define grain at a much greater or lesser unit than the resolution of the habitat patches the organism perceives and responds to (Figure 2). Nevertheless, it is safer to choose a finer grain than what is believed to be important, as it is always simpler to dissolve to a coarser grain than the contrary. Patches represent discrete areas of relatively homogeneous environmental conditions where the distinction made between the patch and its surroundings depends on the species under consideration.

Note that GIS' technical capabilities regarding image resolution often exceed the remote sensing equipment capabilities. It is therefore possible to generate GIS images at a too fine resolution regarding the resolution of the acquired data, resulting in a more complex representation of the landscape than can truly be obtained using this data.

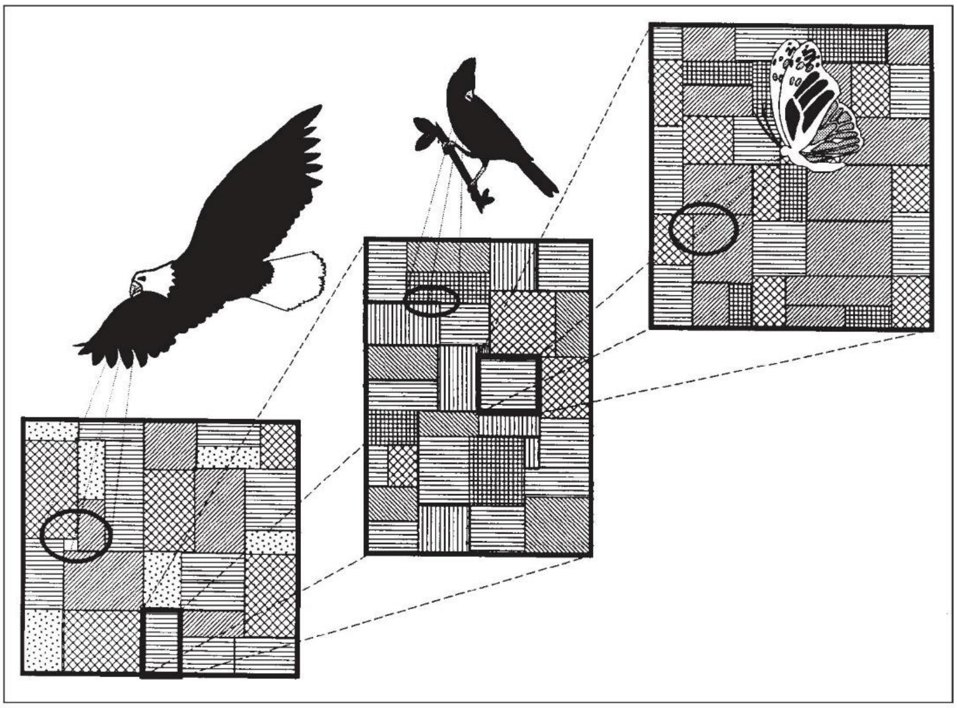

Figure 2: Multiscale view of "landscape" from an organism-centered perspective. Because the eagle, cardinal, and butterfly perceive their environments differently and at different scales, what constitutes a single habitat patch for the eagle may constitute an entire landscape or patch-mosaic for the cardinal, and a single habitat patch for the cardinal may comprise an entire landscape for the butterfly that perceives patches on an even finer scale (McGarigal & Marks, 1995).

Data may be available at various scales which could lead to data extrapolations from one scale to another or integration of information represented at different scales. Data can be transferred across scales if both extent and grain are specified, although it is unclear whether landscape metrics obtained at different scales can be compared, and how the observed landscape patterns vary in response to extent and grain adjustments. The uncertainty regarding scale differences compels comparison between different scale landscapes to be done cautiously.

2.3. Assessing the landscape context

Landscapes are always embedded among larger landscapes, which are within other larger landscapes as well, and so on. Simply put, landscapes are never isolated. They are always dependent on a larger territory, independently of the chosen scale. This means that landscape context is essential when organisms or phenomena studying, as the observed data will largely be affected by broader-scale processes. However, the importance of the landscape context varies according to the "openness" of the landscape relative to the phenomenon under consideration. Say, from a hydrological standpoint, a landscape could be defined by a watershed, which would be a relatively "closed" landscape, as exchanges with external landscapes are rather limited. From the perspective of the population of an animal species though, e.g., a large mammal, the watershed delineation has little to no influence on the movement of the population through the territory. Furthermore, local mammal abundance patterns may be a result of population dynamics or events elsewhere in the species' range. Consequently, the landscape whose boundaries are delineated by the watershed might be considered relatively “open”, from the perspective of a mammal.

Landscape metrics are used to quantify patterns of the landscape within the delineated boundaries. Therefore, an awareness of the landscape context and openness relative to the considered phenomenon is necessary to interpret the calculated metrics. This is particularly true for nearest-neighbor metrics, as an open system might be highly influenced by a patch located outside of the landscape boundaries, but would not be considered by that metric. Thus, the results of this metric would likely be misleading. The severity of this issue depends on the landscape scale, as increasing the size of the landscape relative to the scale at which the considered organism reacts to the environment would diminish the likeliness of outer patches affecting the metric. In general, the larger the extent to grain ratio, the less likely are metrics to be ruled by boundary effects.

2.4. Hierarchical levels of heterogeneity

Habitat patches shape the foundations of categorical maps or patch dynamics. Their composition can be characterized by variables calculated within them. Yet, once patches have been defined, they tend to be disregarded in terms of within-patch heterogeneity, as they have been attributed a nominal class value representative of their composition. Therefore, the selected metric must be defined at the appropriate level for its application. Whereas individual patches possess few spatial characteristics, a set of patches may have a variety of properties as a result of the aggregation of individual patches. Landscape metrics can hence be defined at four levels, corresponding to the hierarchical organization of spatial heterogeneity in patch mosaics.

2.4.1. Cell-level metrics

These provide the finest spatial unit of resolution when characterizing spatial patterns using raster images. The spatial characteristics of each cell are calculated without particular regard for affiliations at higher levels in the hierarchy. Although the ecological neighborhood is characterized by the patch mosaic surrounding the cell, these metrics are specific to each cell and are not patch-centric.

2.4.2. Patch-level metrics

Similar to the metrics mentioned previously, patch metrics characterize the spatial character and context of individual patches. Patch metrics usually serve as a computational basis for class or landscape metrics. Computed values acquired for each individual patch generally have little interpretive value, yet these indices can be informative in landscape-level examinations (e.g., the considered species requires a minimum patch size for its habitat). Ultimately, the utility of the patch metrics will depend on the objectives of the investigation.

2.4.3. Class-level metrics

Class metrics are integrated over all the patches of a given type, or class. They may be integrated by simple averaging, or via a weighted-averaging scheme. The latter allows attributing a greater contribution from larger patches to the overall index. Class metrics possess properties resulting from the aggregation of patches across the landscape, forming unique configurations. The amount and distribution of patches constituent of a particular class is often the primary interest of class-level metrics applications. For example, habitat fragmentation could be investigated using such metrics. A suitability index for the habitat of a species or several species could be assigned to a set of classes. Patches would be classed according to their characteristics, thus depicting the habitat fragmentation in the landscape relative to the considered species and set classification.

2.4.4. Landscape-level metrics

These metrics are integrated over all patch classes included in the entire landscape. Landscape metrics may be integrated by a simple or weighted averaging, comparably to class metrics. However, landscape metrics may also reflect the aggregate properties of the patch mosaic. In many applications, the primary interest is in the pattern of the landscape mosaic, which can be quantified using landscape-level metrics.

It is important to note that while these metrics may be somewhat equivalent, their interpretations might be different. “Cell metrics represent the spatial context of local neighborhoods centered on each cell. Patch metrics represent the spatial character and context of individual patches. Class metrics represent the amount and spatial distribution of a single patch type and are interpreted as fragmentation indices. Landscape metrics represent the spatial pattern of the entire landscape mosaic and are generally interpreted more broadly as landscape heterogeneity indices because they measure the overall landscape structure.” It is therefore important to interpret each metric in a manner appropriate to its level.

In addition, it is important to note that although most metrics at higher levels are derived from patch-level attributes, not all are defined at all levels. In particular, patch collections at the class and landscape levels have aggregate properties that are not defined at lower levels. Many metrics are correlated, as most higher-level metrics are derived from the same patch level. Therefore, they provide similar and possibly redundant information.

Lastly, although class and landscape metrics are typically computed for the entire extent of the landscape, they can also be computed for a local window placed over each cell individually. This moving window would register the value of the class or landscape metric into a new grid, where each cell represents the “local neighborhood structure”. This is like the cell-level metrics previously described, although these cell metrics employ unique algorithms defined at the cell level, while the metrics here described are simply the same initial metrics disaggregated to a cell level.

2.5. Analyzing landscape connectivity

With the progress achieved in computer technology and the public concern regarding biodiversity, a variety of tools and software packages for landscape connectivity modeling, planning, and assessing were developed.

2.5.1. Circuit theory

Some connectivity analysis software packages use circuit theory to assess connectivity in landscapes. Circuit theory connectivity models are applied to graphs, which originate from graph theory (McRae et al., 2008).

2.5.1.1. Basic concepts

Circuit theory uses analogous properties of random walks and electrical theory to model animal movement and gene flow across a resistance surface (Doyle & Snell, 1984; Koen et al., 2014).

Circuits are networks of nodes, such as habitat patches, connected by resistors. The resistors are components that conduct current through the circuit board (i.e., the landscape), which therefore influences the intensity of the current passing through that pathway (McRae et al., 2008). In circuit theory, the current is considered as the flow of a species and is used to predict movement probabilities for these random walkers through each pathway of the circuit. An area with higher current would then imply a higher probability of animal flow in that zone.

Graphs permit pictorial representation of networks. They are sets of nodes (or focal nodes) connected by edges, which are functional connections between the nodes (Urban & Keitt, 2001; McRae et al., 2008). The edges can be weighted to reflect the resistance between two nodes (Figure 3).

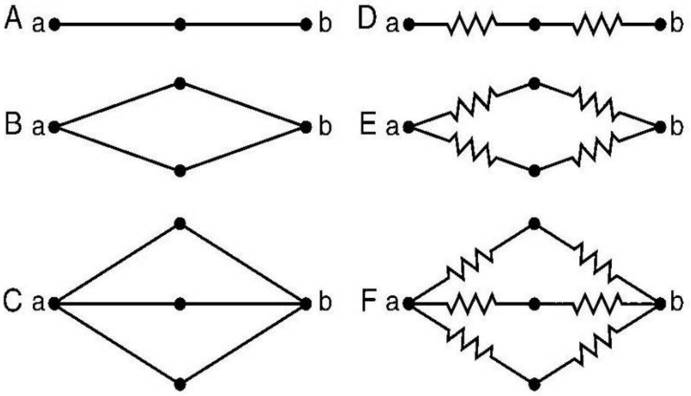

Figure 3: Three graphs to the left (A, B, C), with edge weights of 1. Traditional shortest path or geodesic distance, d, between nodes a and b is identical (d = 2) in all three cases. To the right (D, E, F), edges have been replaced with unit resistors to create analogous circuits. Effective resistance, $\hat{R}$, measured between nodes a and b decreases from top to bottom ($\hat{R}$ = 2, 1, and 2/3, respectively), reflecting additional contributions from multiple pathways (McRae et al., 2008).

Resistance can be defined as the opposition of a habitat type to the movement of organisms. The voltage can be considered as the source population of species, which can thus be used to predict the probability that walkers leaving any node on a graph will reach a given destination before another (Figure 4).

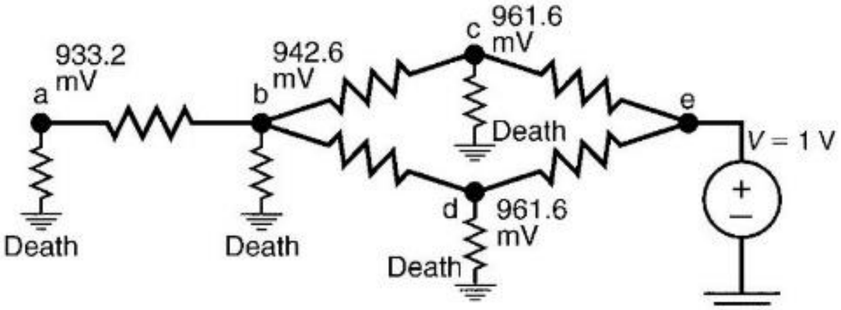

Figure 4: Circuit with a voltage source (V) of one volt at node e. All random walkers must pass across the first branch, but half would be expected to take the upper pathway, and half the lower. Resistances connecting nodes were set to 1 ohm for this simple example. Ground resistors are added to reflect a 1% probability of mortality as the random walker passes through each node. To achieve this, resistances to the ground for nodes a–d were set to 99, 33, 49.5, and 49.5 ohms, respectively. Node voltages reflect the probability that a random walker, starting at each node, will successfully reach node e. For example, the proportion of dispersers leaving node a expected to successfully reach node e is 0.9332 (933.2 mV equivalent). Deaths at each node exceed 1% because nodes are visited multiple times by random walkers, with the highest numbers of deaths observed in nodes with the highest numbers of visits. Only one possible dispersal destination was included here, but the method can accommodate as many dispersal destinations as desired. Although the destination node is tied directly to the ground, resistors could be added between destination nodes and ground, with their conductances set to reflect a finite probability that a walker would settle rather than continue walking once reaching a node (McRae et al., 2008).

Ohm’s law ($I = V/R$) allows a good understanding of circuit theory applied to connectivity in landscapes. The current I that flows through a resistor depends on the voltage V applied and the resistance R. The flow of a species is therefore proportional to its source population divided by the encountered resistance along its path.

Resistance distance is frequently used in practice and is defined by the effective distance between a pair of nodes where edges are replaced by analogous resistors. It includes multiple pathways connecting nodes and is thus decreasing when more connections between nodes are added. In other terms, the resistance distance incorporates least-cost distance, i.e., the distance between the source and target that costs the least for the species under consideration, as well as availability of alternative pathways (Figure 3) (McRae et al., 2008).

2.5.1.2. Circuit theory tools

i. Circuitscape

Circuitscape is an open-source connectivity analysis software package useful to predict connectivity in heterogeneous landscapes using circuit theory algorithms. These algorithms provide predictions for movement, gene flow, and genetic differentiation among plant and animal populations. To achieve this, Circuitscape uses a raster grid and a list of points, called focal nodes, which are potential starting and ending points for animal flow, such as habitat patches (Anantharaman et al., 2020). Each cell of the raster grid is assigned a value (e.g., quality of habitat), thus creating a resistance surface, where cells with the lowest quality of habitat possess the highest resistance. The grid can then be represented as a graph, where nodes illustrate grid cells and edges are weighted proportionately to movement probabilities. The software can produce current and voltage maps, through a series of computations (Figure 5). The resistance between pairs can also be calculated.

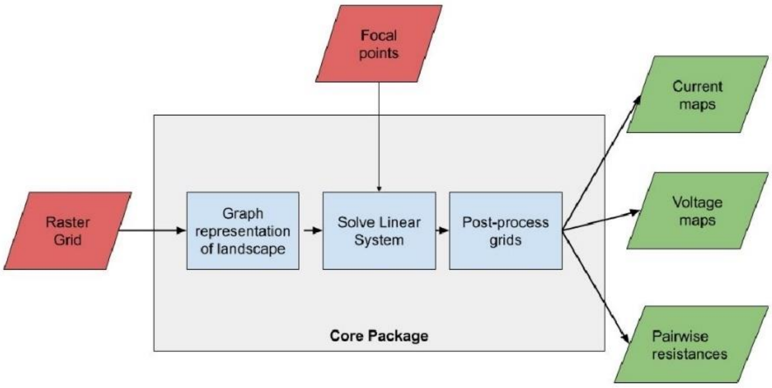

Figure 5: Stages of computation and inputs/outputs. The input raster grid is usually assembled and produced using a GIS software package, and the output current maps are often exported to a GIS software package for postprocessing (Anantharaman et al., 2020).

Circuitscape offers four modeling modes: pairwise, one-to-all, all-to-one, and advanced. For the first, connectivity is calculated between each possible pair of focal nodes, where one node is arbitrarily connected to a 1-amp current source, and the other is connected to the ground (McRae, Shah, & Mohapatra, 2013). The advanced mode allows for simultaneously activating user-picked current sources and grounds in the landscape file, and models connectivity between each other. The all-to-one and one-to-all modes are rather similar. In the latter, one focal node is connected to a 1-amp source while all remaining nodes are connected to ground. The all-to-one mode does the contrary, i.e., one node is connected to ground and the remaining to a 1-amp source. These two methods measure connectivity across all focal nodes in the raster file in a single iteration and allow to reduce computation time.

When using the pairwise mode, Circuitscape produces current maps for each pair of focal nodes and a cumulative current map that combines each current map into one.

The software allows picking between connecting cells to their four (four cardinal) or eight (four cardinal and four diagonal) immediate neighbors for the current flow maps.

Circuitscape has no dispersal limit which might lead to overestimating dispersal distances for short-ranged species (Nordén, 2016).

Since 2009, Circuitscape has known an increasing number of applications in peer-reviewed journal articles, reaching nearly 100 applications in 2020, and totaling 572 since its launch (Hall et al., 2021). These applications cover a wide range of topics (Figure 6).

The different articles cited in the Hall et al. (2021) paper describe studies conducted on diverse animal species in various landscapes and locations, such as sage-grouses in the western United States (Reinhardt et al., 2017), little penguins in a marine environment in southeast Australia (Afán et al., 2015) or African elephants between Kenya and Tanzania (Osipova et al., 2018).

Although Circuitscape can be applied to a variety of species, its use in marine environments is more challenging. Because the resistors are isotropic, i.e., the resistance to current flow is the same for whichever direction, it limits applications for marine ecology where directional currents play a large role in dispersal rates (McRae et al., 2008). In addition, the resistance values are derived from sea surface current azimuths, which makes the resistance surface arguably more challenging to create than assigning resistance values to lander cover classes (Afán et al., 2015).

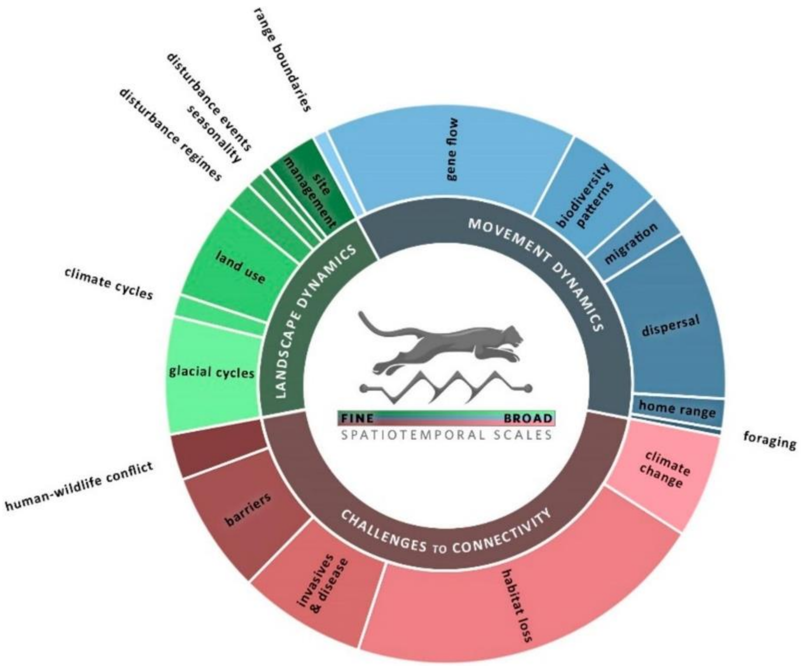

Figure 6: Distribution of 572 Circuitscape applications grouped into three broad categories (inner circle), and then arranged in categories that range from finer scale (spatial or temporal) studies in darker shades, to applications at larger scales and/or longer focal time periods (lighter shades) (Hall et al., 2021).

ii. Omniscape

Omniscape applies Circuitscape iteratively through the landscape in a moving window to predict omni-directional connectivity (Landau et al., 2021). This offers a “coreless” approach and allows a more comprehensive analysis of the connectivity in natural habitats that may be defined as cores using Circuitscape. The algorithm requires a resistance raster, and a source strength raster, that is, the relative amount of current to be injected into every pixel of the landscape. The source raster can be derived from the resistance file. In that case, a resistance threshold must be specified to determine which elements can be identified as sources. All pixels above that threshold are assigned a source value of 0, whereas all the pixels below that threshold are identified as a source. Moreover, a certain block size can be specified to restrict the number of target pixels in the grid. The block size determines the number of pixels forming a square where only its center can be considered as a target pixel, whose source strength is equal to the sum of all the block pixels’ strength (Figure 7). This also allows to greatly reduce computation times.

The radius of the moving window is user specified and can be linked to the dispersal distance of the species.

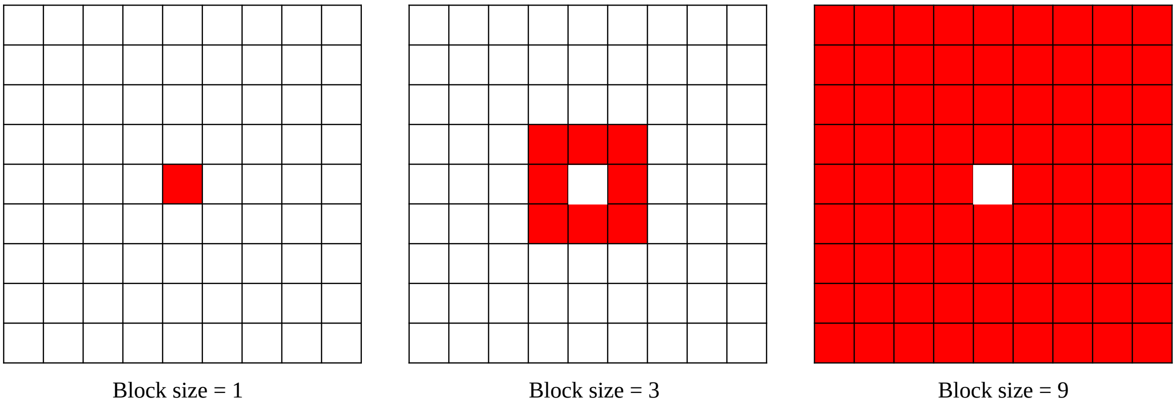

Figure 7: Block size examples for Omniscape

Just like Circuitscape, Omniscape allows picking between four or eight-neighbors connectivity.

Operating in a series of four steps, the algorithm will establish a current map for every potential target pixel in the landscape. These current maps are then summed to get a single cumulative current flow map. In addition, flow potential (current flow under null resistance) and normalized flow current (cumulative current flow divided by flow potential) can be acquired using Omniscape. The latter helps to identify the areas where the current is either impeded by the high resistance barriers, or channelized. As it is calculated by dividing cumulative current by flow potential, high values would mean that the current flow with a resistant landscape is higher than it would be without, which implies that the current is channelized due to physical constraints (Landau et al., 2021). This allows pinpointing areas that are under pressure by their surroundings.

Launched in 2016, Omniscape does not yet match the popularity of Circuitscape, with applications of the software being discussed in 11 research articles in 2020 (compared to approximately 100 for Circuitscape).

Omniscape was used in a recent study to model pathways between present and future Californian habitats in prevision of climate changes that will force animal species to change their ranges (Schloss et al., 2022). Rather than modeling connectivity for a certain species, the study computed pathways between natural lands and their future climate analog, which encompasses a wide range of species instead of focusing on one in particular. Another study was conducted in Washington State using a resistance surface created for wildlife in general, without focusing on a single species (Gallo et al., 2019). Connectivity in a landscape can also be assessed for several focal species, the outputs for each species can then be aggregated in a single connectivity map (Jennings, Zeller, & Lewison, 2020). The studied focal species were puma, bobcat, southern mule deer, wrentit, big-eared woodrat, and California mouse, in a 540 km^2 area in San Diego County.

iii. GFLOW

This software program allows large-extent and fine-grained connectivity analyses based on a circuit-theoretic approach (Leonard et al., 2017). GFLOW offers connectivity analysis for selected pairs of nodes, but also between random nodes, which allows users to calculate connectivity between nodes whose properties are unknown (Leonard et al., 2017).

GFLOW operates many iterations to explore complex landscape connectivity dynamics on various spatial and temporal scales (Figure 8) (Leonard et al., 2017). Therefore, the software was developed to operate in a high-performance computing environment but can also be deployed on desktop computers with reduced performance (Leonard, 2017).

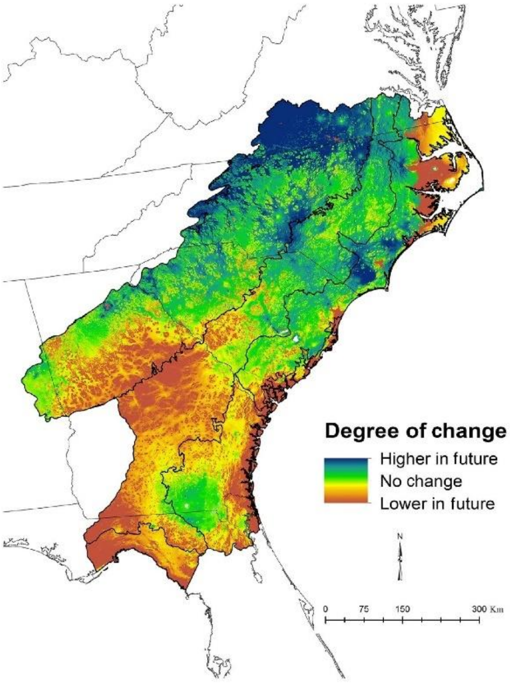

Figure 8: Circuit theory-based connectivity analysis using GFLOW to predict changes in landscape connectivity patterns into the year 2100 based on a composite of multiscaled habitat connectivity models for six individual species in the south-eastern United States. Degree of change is represented by the relative distribution of values with the assumption that future values, although lower than contemporary values, will still be important to dispersing animals (Leonard et al., 2017).

GFLOW was used for several large extent studies, located near the Appalachian Mountains forming a 592 192 km^2 area (Leonard, Baldwin, & Hanks, 2017), for the entirety of the Province of Alberta (Marrec et al., 2020), and in a Master thesis modeling connectivity for amphibian species at the Switzerland scale (Amherd, 2017).

The main reason for choosing GFLOW over another circuit theory tool, such as Circuitscape, is its operability on large extent landscapes (Amherd, 2017; Marrec et al., 2020).

iv. Condatis

Condatis models habitats using circuit theory and concepts such as voltage, current, and resistance (How Condatis works, n.d.).

The software links the time of travel between habitat cells with the resistance. The strength of the linkage between these cells is thus greater if the speed of dispersal is faster, i.e., flowing through a lower resistance. Taking the dispersal distance and reproductive rate of the species under consideration, the software will then calculate the flow from source to target and the portion passing through each cell (How Condatis works, n.d.). Condatis can also map the "bottlenecks" of the habitat network by highlighting the links of highest strain, i.e., links with the highest flow of species and distance traveled.

Accounting for the reproduction of the species allows for assessing the range shifts of a species due to climate change, as the distance traveled is greater than what an individual could travel in its lifetime (Travers et al., 2021). Furthermore, Condatis allows prioritization analysis or "Dropping". Potential habitat cells are ranked by their contribution to the speed of the species' movement. The lowest-ranking cells are "dropped", and after multiple repetitions, only the cells contributing the most to the flow are left, indicating where restoring or preserving the habitat would be most relevant (How Condatis works, n.d.).

Condatis calculates the distribution of dispersers in a manner such that it declines with distance traveled. Although this simplification does not model the difficulty of moving through the landscape matrix, it allows for analyzing more extensive networks and representing long-term processes of range expansion (Travers et al., 2021).

The software's ability to model multi-generational movement makes it a preferred option when studying species movement in reaction to climate change (Butlin, 2018; Iwanda et al., 2019; Travers et al., 2021), but also allows calculating the conductance across a landscape, i.e., the rate of colonization (Travers et al., 2021; Mancini, Hodgson, & Isaac, 2022).

2.5.2. Network theory

Network theory applies graph theory with a focus on the relationship between the network structure and function (Rayfield, Fortin, & Fall, 2011). Networks are graphs weighted by node size or link weight which can be used to study functional dispersal processes.

2.5.2.1. Network theory tools

i. Graphab

Graphab is a software application for modeling landscape networks (Foltête, Clauzel, & Vuidel, 2012). The tool identifies habitat patches from a raster file containing a landscape map using an algorithm based on a four or eight neighborhood principle. Unlike Circuitscape and Omniscape which allow picking between these two options to model connectivity between the nodes, Graphab only uses this principle to identify the habitats. Links between these patches are then defined and can be weighted using Euclidean distance, least-cost distance (cost unit), or the least-cost path distance (metric unit). Graphab can either create a complete graph, containing links between all core habitats, or a minimum planar graph, where only the neighboring patches are linked (Foltête, Clauzel, & Vuidel, 2012). Metrics in Graphab are computed at global, by component, or local levels. Metrics such as probability of connectivity and flux can be calculated. The graph and exogenous point data set (field data) can be linked. This connection offers analysis possibilities at patch level (data associated with the points documents the patches) or point level (patch level metrics are extrapolated to each point).

Results from Graphab are relatively easy to interpret, as the modeled graph only displays links between core habitats, i.e., the fewer the links, the more isolated core habitats are (Nordén, 2016). However, an isolated patch could very well have a low-cost link to a nearby habitat that presents more connections to other patches. As the results contain fewer details, Graphab can be used for large landscape areas without sacrificing too much time. Areas of interest could then be analyzed with other tools giving more detailed results, such as Circuitscape (Nordén, 2016).

Like many other tools, Graphab relies on cost values for graph modeling. Such cost values are often derived from expertise, which may raise concerns about their validation (Foltête et al., 2021).

The software is widely used for landscape analysis applications, as it appeared in 49 articles in 2022 alone. Graphab was used to assess the contribution of green roofs to tree canopy connectivity in a highly urbanized area (Kim & Kang, 2022) and to improve connectivity between protected areas bordering an urban area based on forest bird species (Ribeiro, de Mello, & Averna Valente, 2022). Another study constructed the ecological networks of agro-pastoral areas for terrestrial species, highlighting the importance of agricultural areas very straightforwardly thanks to the simplicity of Graphab outputs (Shi et al., 2020).

ii. LandScape Corridors

LandScape Corridors requires a raster map containing a resistance surface, and another locating the nodes to be connected (Ribeiro et al., 2017). The software package allows simulating corridors between all node pairs or to pick the connected pair for each simulation.

LandScape Corridors uses least-cost path algorithms, but also four different methods to simulate multiple-path corridors, namely MP, MLmin, MLavg, and MLmax (Ribeiro et al., 2017). The MP method adds random variation to each pixel of the resistance surface map using a variability parameter. This parameter represents uncertainty in the values used to create the resistance map, but also the tendency of different species in using alternative paths, as they perceive the landscape differently. The ML methods operate similarly but consider biological information by including landscape metrics, i.e., by accounting for neighboring non-resistance pixels. The resistance surface pixels are replaced by the minimum (MLmin), average (MLavg), or maximum (MLmax) values of the surrounding pixels within a radius defined by the user, which is the perceptual range of the monitored species (Ribeiro et al., 2017).

The methods described allow connectivity modeling for generalist species (MP, MLmin, MLavg), which tend to disperse more easily through the landscape, and for specialist species (MLmax).

Note that resistance surface maps often derive from expert knowledge of species characteristics, and therefore add uncertainty around these values (Ribeiro et al., 2017).

By modeling multiple least-cost paths between habitats, LandScape Corridors provides alternative outputs to other least-cost path tools which usually compute a single route. Its links are however different from results obtained via circuit theory software which model flow values for each cell of the landscape but not delineated pathways. This feature was used to assess habitat loss, fragmentation, and connectivity for small mammal, amphibian, reptile, and butterfly species in Luxemburg (Babi et al., 2019). The software was also applied to a wide extent area of 207 024 km^2 in the Brazilian Atlantic Forest to evaluate the capacity of forest fragments to sustain connectivity for four carnivorous mammals: three big cat species and the Tayra (Diniz et al., 2021). The multiple least-cost corridors feature in LandScape Corridors was used to assess landscape permeability for forest bird species in an urban environment, taking advantage of the ML methods to define the influence of the surrounding landscape on the species' perception (Bhakti et al., 2021).

iii. FunConn

FunConn is a toolbox operable in ArcGIS used to create habitats and landscape network models (Hamilton, 2014). It allows graph theoretic analyses, but also network-type such as least-cost path between designated nodes. The toolbox is used to calculate node-edge interactions, as well as the minimum spanning tree, i.e., the shortest length tree that includes every node in the graph (Urban & Keitt, 2001).

FunConn only requires a land cover surface and additional inputs (e.g., minimum patch size) weighted by the user and allows integration of spatial data, such as anthropogenic disturbances or topography. The low volume of needed data makes this tool attractive for wildlife managers with limited time and resources (Evangelista, Norman, & Swartzinki, 2012).

Launched in 2006, only one article using FunConn could be found on Google Scholar. The software was used to analyze the ecological network of 66 terrestrial faunal species in southern Italy, located in a 15 600 km^2 study area (Modica et al., 2021).

iv. TerrSet

The TerrSet Geospatial Monitoring and Modeling System incorporates the IDRISI GIS as well as Image Processing tools to offer a wide range of monitoring and modeling applications of the earth system (Eastman, 2016).

The Planning tab included in the Habitat and Biodiversity Modeler provides a corridor planning tool for biological corridors modeling. The Corridor Planning Panel requires a map of the two terminal regions to be connected, in addition to a habitat suitability map with values on a 0.0–1.0 scale. Optional maps of development suitability, conservation value, and protected lands can be added to incorporate the human dimension in corridor planning. After the aggregation of the suitability maps, the modeler creates corridors using a least-cost path algorithm. The number of desired branches can also be specified, where the first branch has the least cost distance (Eastman, 2016).

Due to the large variety of features available in TerrSet, the software is widely used for geospatial monitoring and modeling. However, this also makes it very difficult to find articles related specifically to the Corridor Planning tab and it is unclear if the lack of studies using that tool is caused by it being unpopular in comparison to the other features proposed by TerrSet.

2.5.3. Pros and cons of circuit and network theory

Circuit theory algorithms usually measure isolation by resistance, rather than isolation by distance. The latter is based on a least-cost distance approach, where there is only one optimal route between two nodes, which is the chain of edges with the lowest sum of resistances (Anantharaman et al., 2020). The disadvantage of this approach is that the result depends on the choice of start and end points and doesn't allow the exploration of alternative routes that should be restored or preserved. Isolation by resistance takes account of all possible pathways between the two nodes. This provides a more comprehensive understanding of landscape connectivity as it expresses the potential of populations to follow random pathways (Dickson et al., 2018; Anantharaman et al., 2020).

Software modeling least-cost links between habitats are useful to pinpoint the most crucial paths to preserve, as they are the least costly to animal movement. However, these links are often calculated based on the present land cover and do not take account of alternative pathways that could be relevant for connectivity or could have a lower cost after small modifications in the landscape. On the other hand, current flow maps obtained using circuit theory show all possible pathways between habitats, which also include paths that are not the least costly but would still be suitable for animal movement. For these reasons, tools using least-cost path algorithms are relevant for corridor conservation, while circuit theory is useful to find multiple pathways that could be taken advantage of.

Both circuit and network theory rely on expertise to assign cost and resistance values, causing uncertainty around these values. Data derived from empirical studies or from models which proved to be effective must therefore be privileged whenever possible (Ribeiro et al., 2017; Foltête et al., 2021).

It seems accepted in the scientific community that circuit theory is useful to predict gene flow patterns in heterogeneous landscapes (McRae & Beier, 2007; McRae et al., 2008; Leonard et al., 2017; Hall et al., 2021) but the opposite was found in a study by Schwartz et al. (2009).

Another study (Coulon et al., 2015) claims that a better alternative to least-cost path and circuit theory exists, namely the use of individual-based models and a "stochastic movement simulator". Least-cost path algorithms assume that the individuals moving through the landscape are omniscient, that is, have a perfect knowledge of the landscape that allows them to follow the least costly path between the source and target (Coulon et al., 2015). Circuit models are based on Markovian random walks i.e., each movement is independent (McRae et al., 2008). This means that changes in movement behavior with time are not acknowledged, but also that these random walkers can retrace their steps indefinitely, which would inflate mortality rates. Moreover, these movement rules are not behaviorally realistic for individuals, which tend to make a series of sequential movement decisions rather than moving randomly through the landscape (Coulon et al., 2015).

2.6. Synthesis

2.6.1. Key points

The resolution of the data acquired for landscape analysis should be related to the organism or phenomenon under consideration, but it is always safer to pick a resolution too fine and convert it to a coarser one, than the contrary. The landscape should be defined by taking account of the patterns within, and the context relative to the studied organisms and how they perceive the landscape. Moreover, metrics can be applied to the landscape at four different levels, corresponding to a hierarchical organization of spatial heterogeneity. The choice of the level of heterogeneity depends on the monitored phenomenon.

While connectivity characterizing using least-cost path or circuit theory presents some similarities, the obtained information and purpose of use are different. Current flow maps computed using circuit theory show probability of movement for every single cell in the landscape, whereas least-cost path only displays a single pathway between the habitats.

3. Objectives

The main objective of this thesis is to compare landscape analysis and corridor planning tools applied to the town of LLN, in order to study and compare each tool and underlying algorithms, operating processes, outputs, and limitations.

Moreover, the purpose of this work is to assess the aim of use of each tool, to allow for a better understanding of their application possibilities considering the landscape context and desired result.

Lastly, to a lesser extent, the goal is to characterize the connectivity at a fine scale in a town under high real-estate and development pressure, neighboring several wildlife suitable habitats. As this work offers a generic approach to connectivity modeling, a single animal species isn't being considered but rather a broad group of small mammals which include species such as red squirrel (*Sciurus vulgaris*) or wood mouse (*Apodemus sylvaticus*), living in areas with needleleaved or broadleaved trees.

The software packages relying on circuit theory algorithms that will be used are Circuitscape (Anantharaman et al., 2020) and Omniscape (Landau et al., 2021). GFLOW is more suitable for wider study areas, requiring a high-performance computing environment. Condatis, on the other hand, is useful for multigenerational movement of species and is therefore not appropriate for this thesis. Although the use of LandScape Corridors would have been relevant, its code hasn't been updated since 2018 and it isn't operable.

Graphab (Foltête, Clauzel, & Vuidel, 2012) and TerrSet (Eastman, 2016) are the network theory tools that will be further addressed. As FunConn does not seem to have been updated recently, nor does it have a functioning download link, its use has been precluded.

4. Study area

The study area is located in LLN, in the Walloon Brabant, a province of Wallonia located south of Brussels, in Belgium (Figure 9). The town of LLN hosts the university campus of the *Université Catholique de Louvain* since its creation in 1972 (Historique, n.d.).

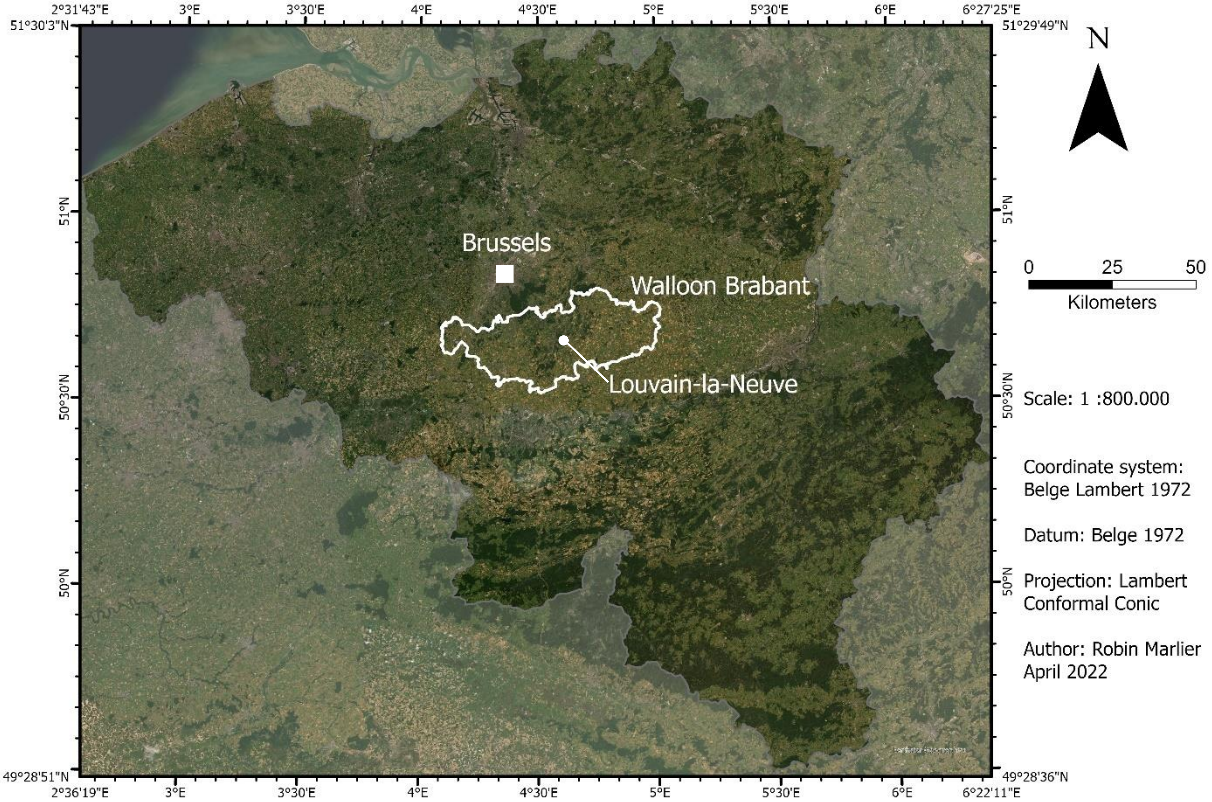

Figure 9: Location of LLN in Belgium

The objective is to connect different habitats surrounding the town, for which animal movement between one another could necessitate navigating through LLN or being physically restricted by it. The suitable habitats are patches of needleleaved or broadleaved trees or shrubs with an area of 3 ha or more (Attuquayefio et al., 1986).

By analyzing the landscape around LLN via satellite imagery and a land cover map (Figure 10), four habitats can be delimited:

1. The *Bois de Lauzelle*, a 233 ha great biological interest site (SGIB)
2. The *Bois des Rêves*, whose limits were extended further to the east, as the forest patches are relatively uninterrupted until reaching the trunk road. This adds to the 57 ha SGIB of the *Bois des Rêves*, to form a 200 ha habitat
3. An 8 ha patch, located east of the town
4. A 15 ha habitat patch, separated from habitat 2 by the trunk road

The extent of the study area is delineated in a manner that it comprises the habitats that were selected, and forms a 17 km^2 rectangle around LLN, as visible in Figure 10.

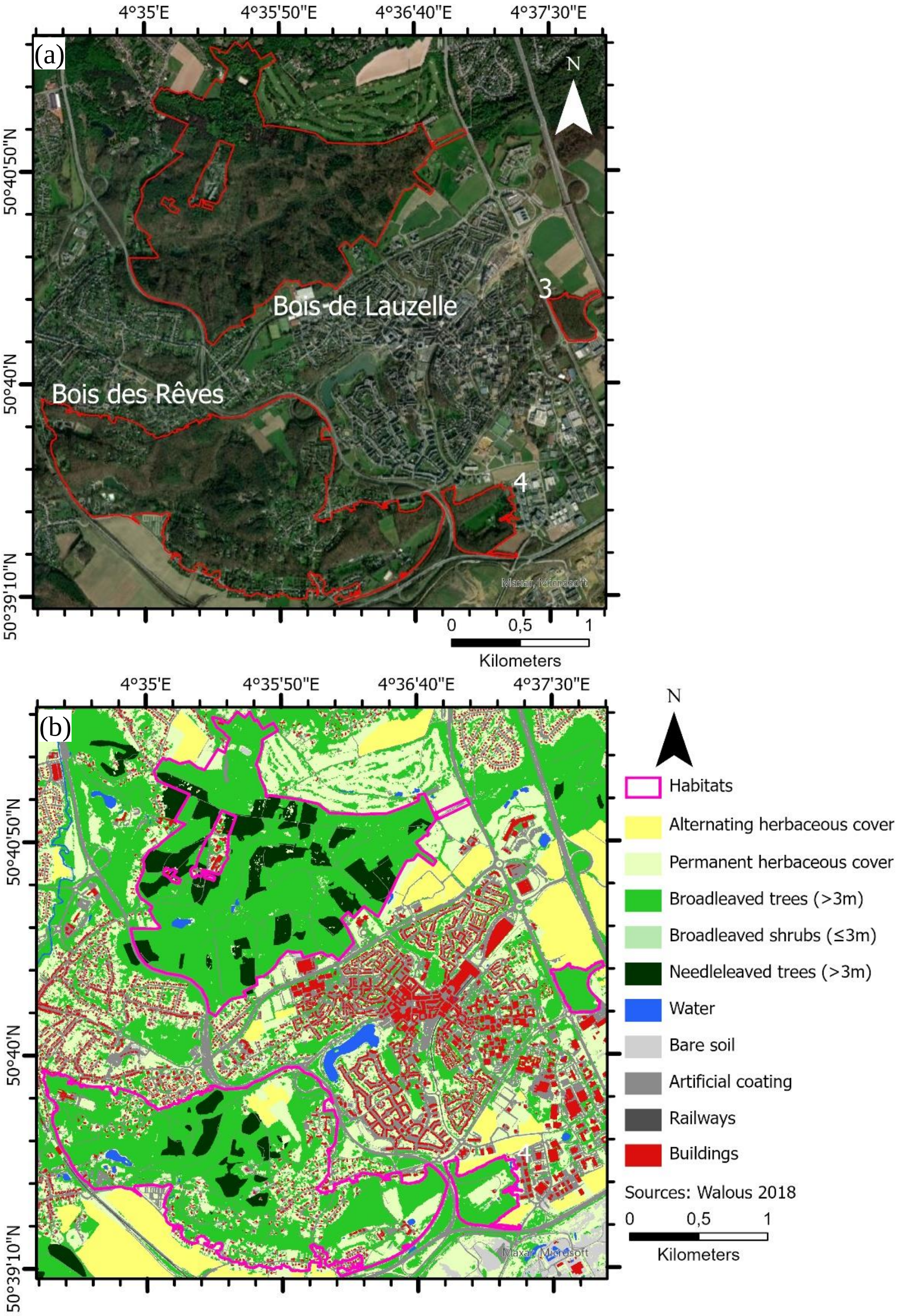

Figure 10: True color image (a) and land cover (b) of the study area and selected habitats

The broadleaved trees visible on the top right corner of the map, whose connection to other habitats is cut-off by the E411 Highway (120 km/h speed limit) or a portion of the N4 (90 km/h) were not selected as habitats to connect.

5. Materials and methods

5.1. Input preparation

5.1.1. Landscape map and resistance surface

The Graphab software only requires a landscape map as input, while Circuitscape and Omniscape require a resistance surface raster file. The WALOUS 2018 land cover map includes data at a 1 m resolution for the 16 902 km^2 of the Walloon region, and is used to prepare both inputs (Occupation du sol en Wallonie, 2020). The land cover raster is clipped to the study area and resampled to a 2 m resolution using ArcGIS Pro, to improve computation time. The resistance surface is created by assigning a resistance value for each WALOUS 2018 land cover class found in the study area, using the Reclassify tool in ArcGIS Pro.

The resistance values for each land cover class (Table 1) are derived from a study conducted on the white-footed mouse, a small mammal native to North America (Marrotte, Gonzalez, & Millien, 2014). Values were estimated for broadleaved and needleleaved trees and shrubs, alternating herbaceous cover, artificial coating, water, and buildings. The mean resistance values of all 975 models produced in the study for the above classes were rounded for simplification. However, most of the artificial coating in the study area i.e., the roads and other paved surfaces, either allow animal movement beneath them (this is especially the case for the N238 which allows several passages along its route) or are not busy enough to oppose small mammals' movement. In contrast, the obtained resistance value for artificial coating in the study aforementioned was calculated for Highway 116 in Quebec, which is highly resistant to animal movement. For this reason, the resistance associated with artificial coating was lowered to 50, except for the E411 and N4, mentioned in section 3, which were given a resistance value of 1000 due to the high traffic and mean car speed on these roads.

The resistance values assigned to the other classes were estimated relative to the values obtained in the study. For example, a permanent herbaceous cover is likely a more suitable habitat (and thus has a lower resistance) for the white-footed mouse than alternating herbaceous cover, but is less suitable than broadleaved or needleleaved trees, resulting in a resistance value of 2. As the main goal of this thesis is to compare different connectivity assessment methods, the accuracy in the assignment of resistance values is of little importance, as the same values will be used for each method.

Table 1: Land cover classes and associated resistance values

Land cover	Resistance value
Broadleaved shrubs (≤3m)	1
Broadleaved trees (>3m)	1
Needleleaved trees (>3m)	1
Permanent herbaceous cover	2
Alternating herbaceous cover	3
Bare soil	10
Railways	30
Artificial coating	50
Water	1000
E411 and N4	1000
Buildings	10000
Greenhouses	10000

The resistance surface (Figure 11) is also used as the landscape map for Graphab, as its only aim is to organize the pixels into different classes, which are used to identify costs for animals crossing these pixels. The travel costs in Graphab are identical to the resistance values in Table 1.

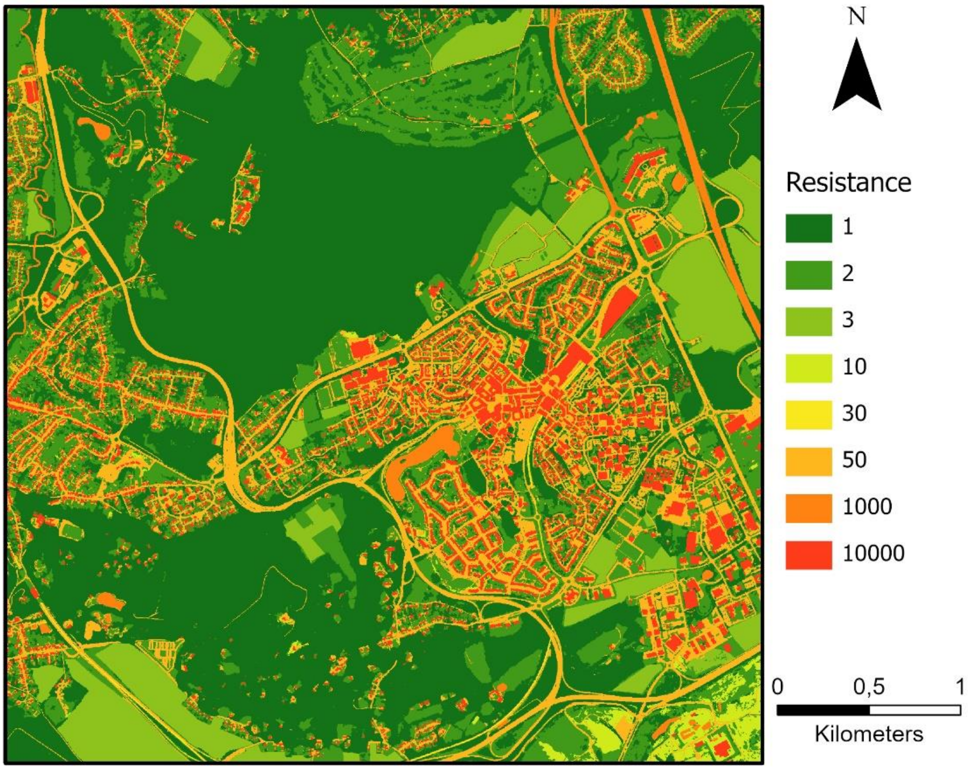

Figure 11: Resistance surface of the study area

5.1.2. Suitability map

The Planning tab from the Habitat and Biodiversity Modeler in TerrSet involves the use of a habitat suitability map. The habitat suitability of a species is usually the inverse of the resistance, where least resistant areas possess high suitability to habitat, and highly resistant pixels are the least suitable. As TerrSet requires suitability values on a 0.0-1.0 scale, the habitat suitability map is created by calculating the inverse of the resistance surface raster using the Raster Calculator in ArcGIS Pro (Table 2).

Table 2: Land cover classes and associated habitat suitability

Land cover	Habitat suitability
Broadleaved shrubs (≤3m)	1
Broadleaved trees (>3m)	1
Needleleaved trees (>3m)	1
Permanent herbaceous cover	0,5
Alternating herbaceous cover	0,33
Bare soil	0,1
Railways	0,033
Artificial coating	0,02
Water	0,001
E411 and N4	0,001
Buildings	0,0001
Greenhouses	0,0001

5.1.3. Terminal regions

All the pixels in the Needleleaved or Broadleaved classes in the land cover file, that therefore have a resistance value = 1, which are overlapping with the selected habitats are to be considered as a terminal region by the different software.

To create these regions, raster files for each of the four habitats were formed by selecting every pixel with a resistance value of 1 within their drawn boundaries. However, the *Bois des Rêves* and habitat 4 did not form a continuous habitat patch due to cells with a resistance higher than 1 cutting through the habitats. To ensure that the tools consider each habitat as a single patch and that there are no high resistance barriers between the different parts of a habitat, the resistance surface file was modified by aggregating every element of the habitats that are within a 20 m distance of one another, to form a continuous patch (Figure 12). To do so, the resistance values of the neighboring pixels were modified to 1, which does not perfectly reflect the reality of the landscape. However, as stated before, the main goal of this work is to compare different methods, while the practical use of the results of connectivity models is of less importance.

TerrSet uses Boolean maps of the two terminal regions to connect. Each habitat file was therefore assigned a value of 1 for the habitat pixels and 0 for all the other elements within the suitability map extent.

As Circuitscape requires a single raster file containing every habitat with a unique ID, the four habitat files were merged into one (Figure 12).

To identify the habitats on the landscape map required by Graphab, all of the pixels overlapped by the selected habitats were assigned a value of 0 to differentiate them from the other pixels with a resistance value of 1 that are not included in the habitats to connect. As the landscape map is the only input file used by Graphab, this indicates to the software which pixels belong to the habitats to be connected, and which are related to the landscape that allows animal movement. In other words, the Graphab landscape map is the same as the one above (Figure 11), but the habitat pixels (Figure 12) have a value of 0[1].

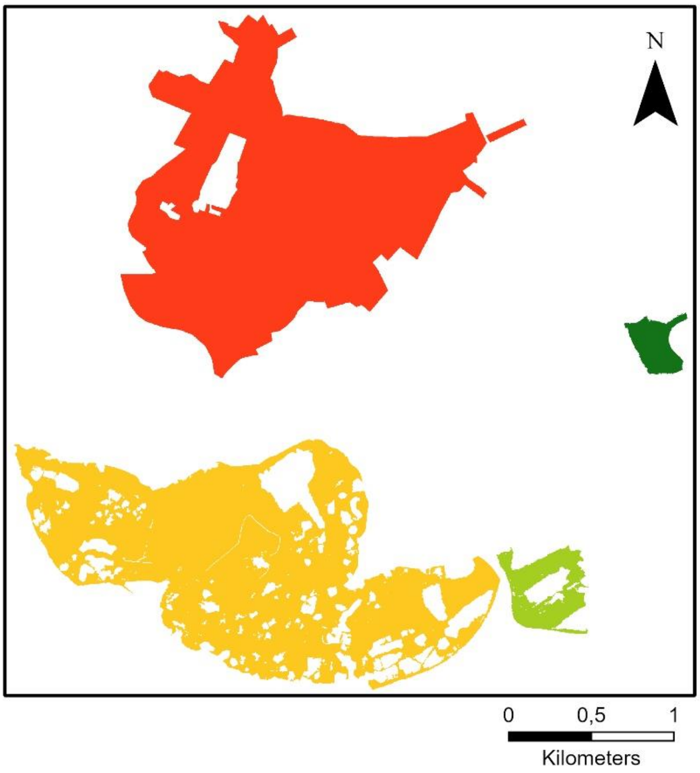

Figure 12: Full area of the four habitats to connect

As stated before, due to its operating process, Omniscape does not necessitate a separate habitat file. The habitats are identified by the software using the specified maximum resistance, which is in this case 1, and the block size whose value was modified for the different computations.

5.2. Outputs analysis

The comparison between the different tools and their outputs was done following several steps.

5.2.1. Step 1: Creation of simple landscapes to understand the functioning of each tool

Two small extent landscapes were created in order to understand how each software operates. This allows running the models rapidly to observe the influence that landscape elements have on the outputs produced by the software. One of the differences spotted between the different tools is that both Circuitscape and Omniscape seem to allow four or eight

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[1] See Appendix 1

neighbors for connectivity modeling, while Graphab only uses the chosen neighborhood to identify the habitat patches, and TerrSet makes no mention of it. The influence that this option has on the outputs was assessed by creating two fictional landscapes where the path between two habitats is separated by a high resistance barrier, but not completely cut off by it, i.e., a longer path is still possible near the edges of the barrier (Figure 13). In the first landscape (Figure 13 (a)), movement across the barrier can only be done by either of its edges. In the second one (Figure 13 (b)), the barrier can be crossed in its center by moving diagonally. This allows observing if, when choosing four-neighbors connectivity, the circuit theory software model animal flow through that diagonal path. To ensure that the observed flow is due to diagonal connectivity and not caused by the fact that the barrier is one pixel narrower in case (b), a third landscape was created (Figure 13 (c)).

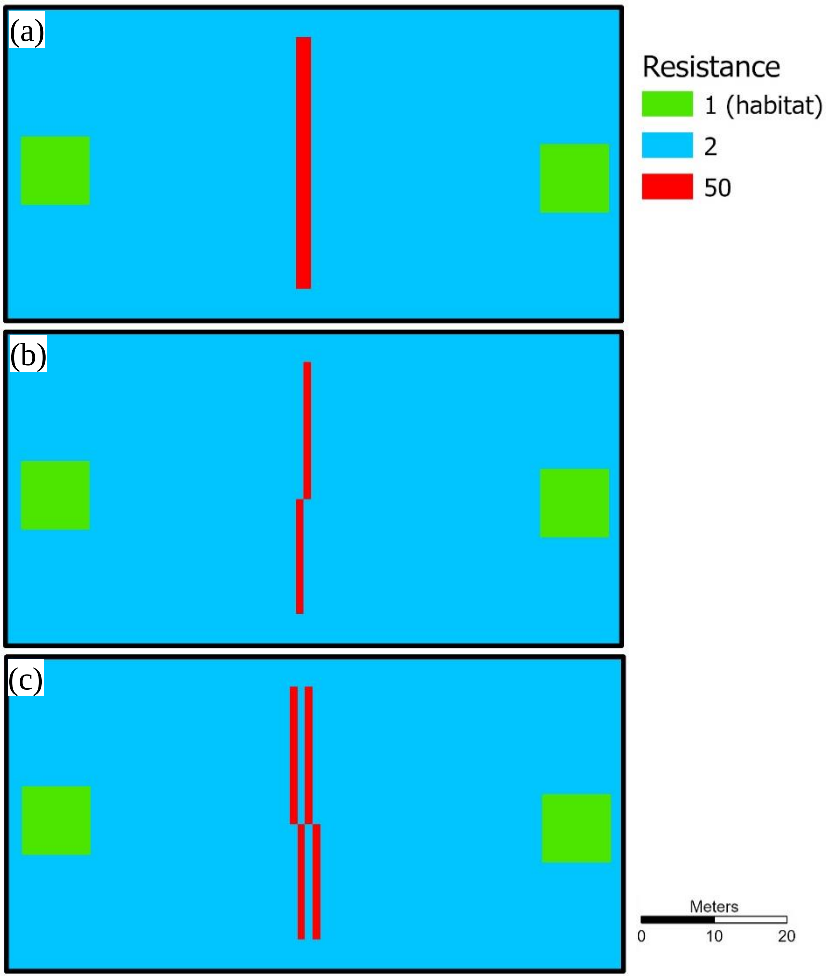


Figure 13: Resistance surface of the three fictional landscapes. Following the shortest path in the first one (a) necessitates crossing the barrier. The second landscape (b) allows following that path by crossing the barrier diagonally, as does the third (c), but the barrier is two cells wide.

Additionally, the exact maps were replicated changing the resistance of the barrier from 50 to 10 000, and the current maps with the higher barrier resistance were subtracted from the ones with the resistance of 50 for better visualization. This allows detecting if the barrier influences flow when having a higher resistance. Note that these changes do not modify the least-cost path outputs as the two software apply eight-neighbor connectivity.

5.2.2. Step 2: Results analysis and comparison of software using similar algorithms

The four studied software rely on two algorithms for their models: least-cost for Graphab and TerrSet, and circuit theory for Circuitscape and Omniscape. As the algorithms that these tools use should be similar, one could assume that results from two different software will be likewise. Therefore, results from tools with similar algorithms will first be analyzed by pair, to identify their similarities and differences.

5.2.2.1. Graphab and TerrSet

Both these software use least-cost algorithms to model connectivity. While TerrSet details in its manual how it calculates least-cost path based on cost values, Graphab makes no mention of how the link is modelized.

The main difference between the two is that Graphab calculates the least-cost link between two habitats, while TerrSet computes the least-cost corridor, whose width is at least four times larger than pixel resolution.

The first analysis to make is to verify if each output overlaps, i.e., if both software identified the same least-cost path. This is done simply by adding Graphab's links and TerrSet's corridors in ArcGIS, and visually identifying at a small scale if they both take the same path in the landscape. If there are differences in their pathways, the paths are compared with the resistance map and their costs are compared to check if one tool produces links with a lesser cost than the other. While Graphab provides the cost of each link between the habitats, TerrSet does not. To calculate the cost of a corridor between two habitats computed by TerrSet, a line overlapping the corridor and least resistant cells, with the smallest length, is drawn in ArcGIS Pro. In other words, a line is drawn to follow the least cost path overlapping the corridor. The cost of the path is then acquired by summing the resistance value of each pixel that this line crosses.

Comparing the paths produced by both tools and their costs raised concerns about the reliability of TerrSet for corridor planning. Three out of four of the produced corridors have a much higher cost than their Graphab counterparts. The fourth corridor's costs were the same for both as it links habitat 4 and the *Bois des Rêves* which are almost contiguous, meaning that there are not many path possibilities (Table 3).

Table 3: Extracted costs from Graphab and TerrSet

Link	Graphab	TerrSet
Bois de Lauzelle - Bois des Rêves	1051	2412
Bois de Lauzelle – Habitat 3	1955	65121
Bois des Rêves – Habitat 4	389	389
Habitat 3 – Habitat 4	1807	3784

Note that the "*Bois de Lauzelle* – Habitat 4" and "*Bois des Rêves* – Habitat 3" linkages are not included as they are respectively the sum of "*Bois de Lauzelle - Bois des Rêves*" and "*Bois des Rêves* – Habitat 4", and "*Bois des Rêves* – Habitat 4" and "Habitat 3 – Habitat 4" links.

While analyzing the TerrSet corridors, additional odd results were observed. The software requests a corridor width to be specified, which is the width desired by the user, meaning that the created corridor can be wider or narrower than the request. The software created 2 m wide corridors when the path is constrained by high resistance surroundings, but much larger ones when the resistance was that of a suitable habitat. TerrSet seems to limit the maximum corridor width to around 10 times more than the specified width but makes no mention of that in its manual.

Moreover, the minimum corridor width when constrained by neighboring high resistance cells depends on the requested width, but the relationship between the two is unclear. Corridors for widths of 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 36, 44, and 50 m were calculated between *Bois de Lauzelle* and *Bois des Rêves* to observe the influence that specified width has on the corridors (Figure 14).

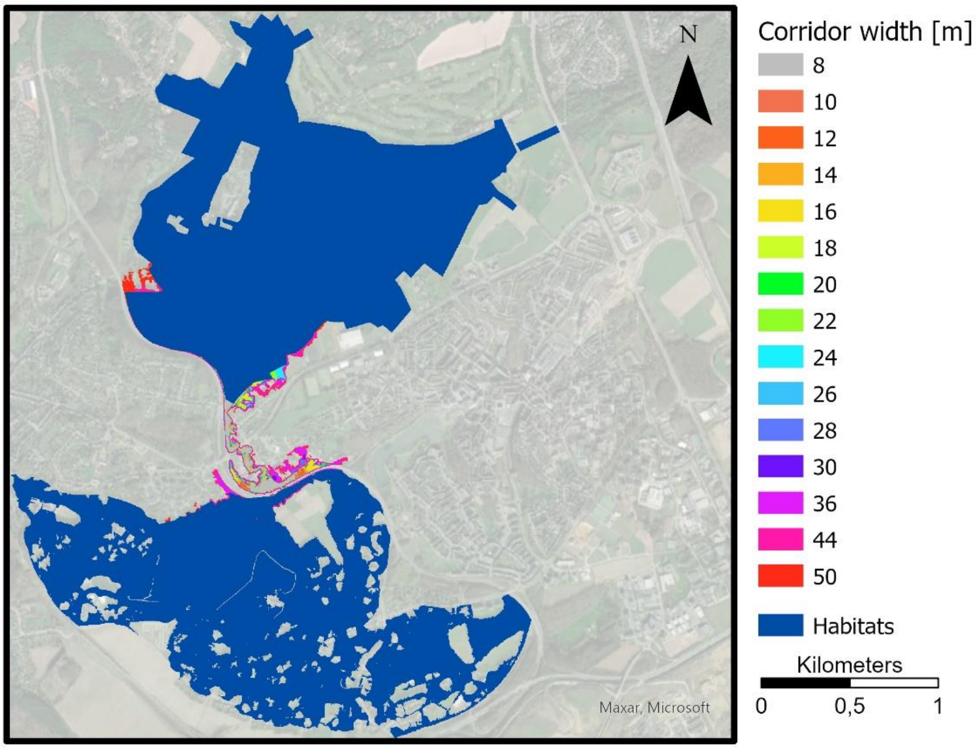


Figure 14: TerrSet *Bois de Lauzelle - Bois des Rêves* corridors from 8 to 50 m wide

When having a closer look at the areas where the corridor crosses a road, i.e., high resistance cells, it appears that the corridor is one cell wide for widths from 8 to 14 m, two cells wide for 16 and 18 m, three cells from 20 to 26 m, four cells wide for 28 and 30 m, five cells for 36 m and seven cells wide for 44 and 50 m (Figure 15). There does not seem to be a clear relationship between the user-specified and the minimum width, which questions the trustworthiness of the software.

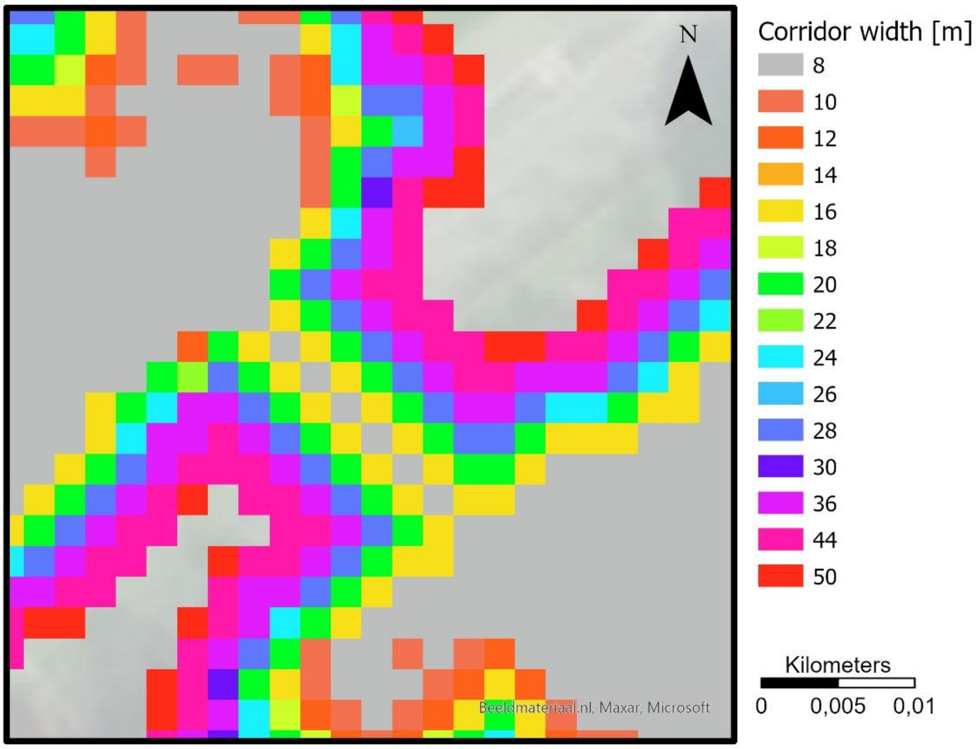


Figure 15: Close-up of the 8-50 m wide TerrSet corridors crossing a high resistance barrier

In addition, it happened on several occasions that the corridors' edges overlapped high resistance pixels (Figure 16). Although this is probably due to TerrSet trying to comply with the specified width, this questions the reliability of the software since it computes corridors in areas that were defined as extremely costly to encounter.

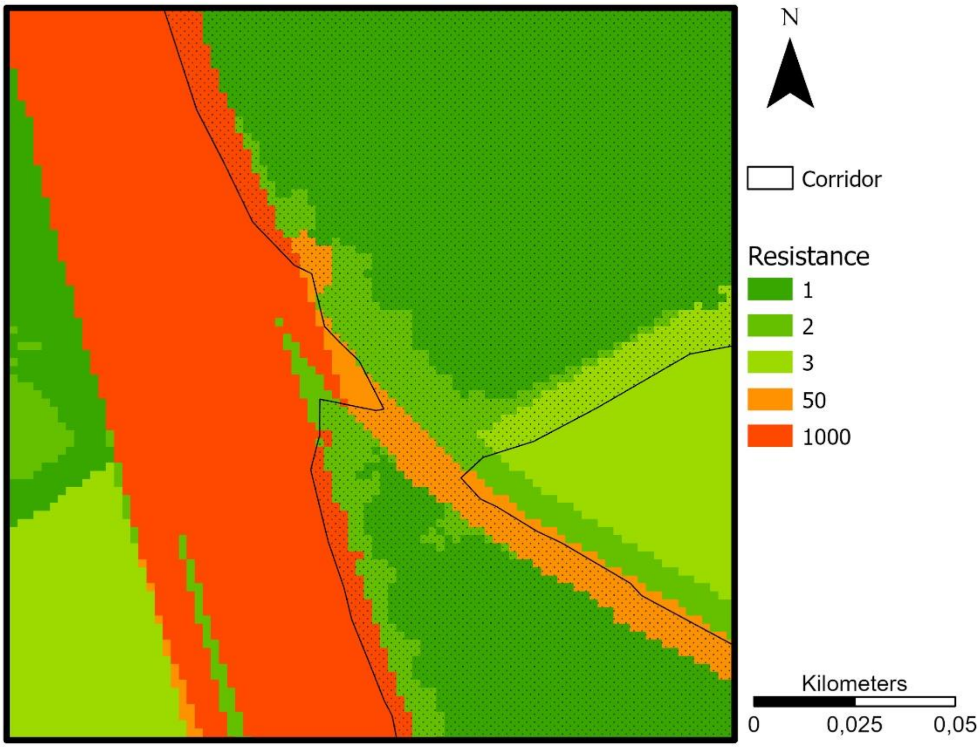


Figure 16: Close-up of the 50 m *Bois de Lauzelle* – Habitat 3 TerrSet corridor overlapping the E411 highway

Furthermore, the computation between *Bois de Lauzelle* – Habitat 3 produced an absurd result as the software always modeled a corridor to the right of the E411 highway, causing the path to cross the E411 and N4 (which have a resistance of 1000) in three spots (Figure 17). As seen in Table 3, an alternative path produced by Graphab that does not cross these two roads possesses a much lower cost.

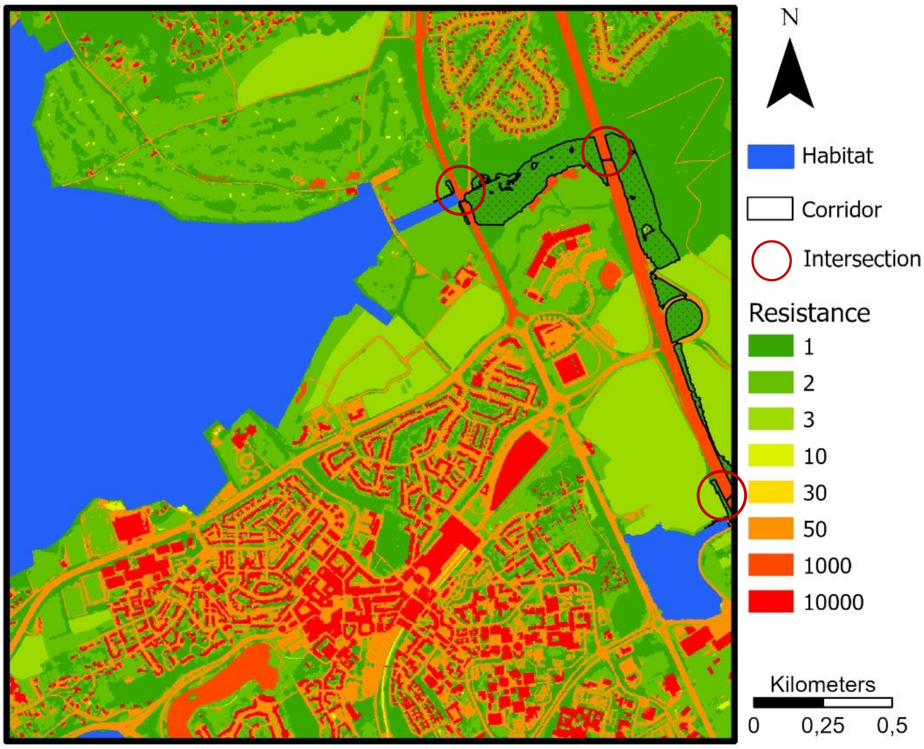


Figure 17: 8 m wide TerrSet *Bois de Lauzelle* – Habitat 3 corridor

Additionally, it happened on several occasions that TerrSet failed to compute a corridor due to an optimization problem likely caused by the high resistance of the roads, which did not happen while using Graphab, even when testing much higher road resistances.

Lastly, the fact that each model in TerrSet requires picking two habitat files and that the computation time was around 1 h long for each corridor in this work makes corridor planning via this software very time-consuming, especially when the number of habitats to connect in the landscape is high.

For all the reasons listed above, the Corridor Planning tool of the Habitat and Biodiversity Modeler in TerrSet does not seem reliable and therefore was not further analyzed.

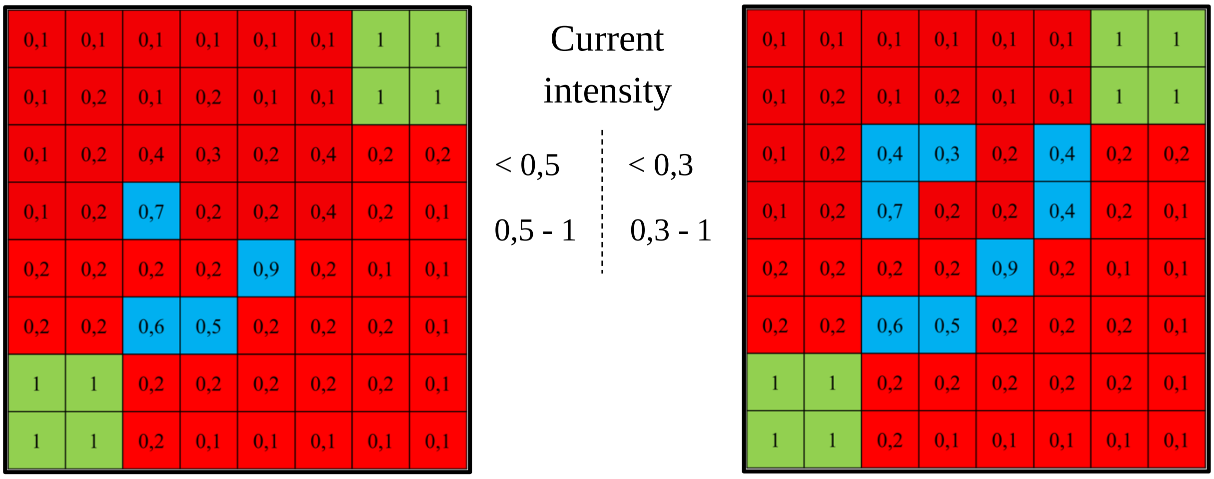
5.2.2.2. Circuitscape and Omniscape

Since Omniscape applies the Circuitscape algorithm in a moving window, it should technically be possible to have identical or very similar outputs by tweaking the parameters in Omniscape. For this reason, the goal is to analyze the influence of changes in Omniscape parameters on the produced outputs. To achieve this, several computations are made by varying the radius and block size, which will also help understand for which applications one software would be preferred over the other.

5.2.3. Step 3: Comparison of software using different algorithms

Although circuit theory and least-cost path produce different outputs, there should be similarities in the results. In some way, circuit theory computes all possible pathways between habitats, where high current flow means that relatively to the other cells in the landscape, movement along this one is least costly than another. Consequently, it can be expected that the least-cost paths computed by Graphab take routes that have the highest current flow in Circuitscape and Omniscape maps.

The Graphab links will be compared with the current maps of habitats pairs in Circuitscape (and not with the cumulative current map that compiles results of all habitats pairs) to make sure that the compared connectivity only depends on the two wanted habitats and is not influenced by current flow between other habitats. Nevertheless, comparing such results is rather complicated as current maps usually offer a variety of paths that seem to have the same current intensity. As a consequence, Graphab links were also compared to maps produced by using thresholds applied to the four Circuitscape habitats pair current maps whose links were also computed by Graphab. The symbology of these maps is modified to classify all the values into two groups. Varying the upper threshold of the class containing the lower values would allow for visually identifying the first complete path to be formed, which has current intensity values greater than the other possible paths (Figure 18).



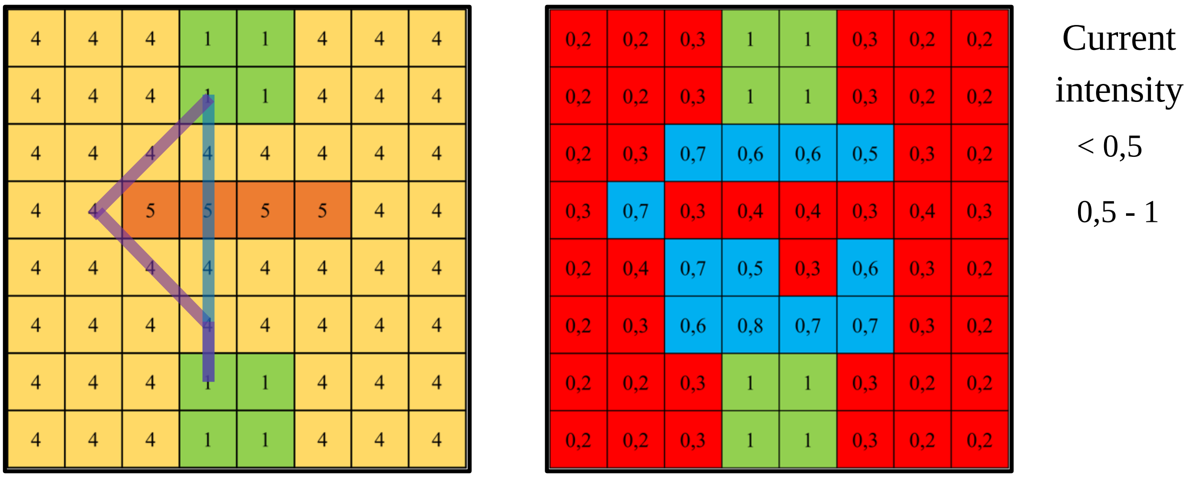
0,1	0,1	0,1	0,1	0,1	0,1	1	1
0,1	0,2	0,1	0,2	0,1	0,1	1	1
0,1	0,2	0,4	0,3	0,2	0,4	0,2	0,2
0,1	0,2	0,7	0,2	0,2	0,4	0,2	0,1
0,2	0,2	0,2	0,2	0,9	0,2	0,1	0,1
0,2	0,2	0,6	0,5	0,2	0,2	0,2	0,1
1	1	0,2	0,2	0,2	0,2	0,2	0,1
1	1	0,2	0,1	0,1	0,1	0,1	0,1

0,1	0,1	0,1	0,1	0,1	0,1	1	1
0,1	0,2	0,1	0,2	0,1	0,1	1	1
0,1	0,2	0,4	0,3	0,2	0,4	0,2	0,2
0,1	0,2	0,7	0,2	0,2	0,4	0,2	0,1
0,2	0,2	0,2	0,2	0,9	0,2	0,1	0,1
0,2	0,2	0,6	0,5	0,2	0,2	0,2	0,1
1	1	0,2	0,2	0,2	0,2	0,2	0,1
1	1	0,2	0,1	0,1	0,1	0,1	0,1

Figure 18: Current intensity of a fictional landscape, with two different classifications. Red values represent the lower class, while blue values represent the upper one and indicate the path between two habitats. Habitat cells, in green, are included in the upper class but are not the same color as path cells for a better understanding.

However, this method does not take into consideration that a pathway could not be complete between two habitats due to a barrier with higher resistance, which therefore has a low current flow. The cost of a path through that barrier could however be lower than another path that avoids crossing that barrier, but whose cost is greater (Figure 19). Consequently, the few paths that first appear were compared with the resistance surface to analyze if the landscape barriers that impede animal movement cause one path to be more costly than another one that is completely formed.

These paths are then overlapped with the least-cost paths produced by Graphab to see whether the results of the different tools are concordant or not.



4	4	4	1	1	4	4	4
4	4	4	1	1	4	4	4
4	4	4	4	4	4	4	4
4	4	5	5	5	5	4	4
4	4	4	4	4	4	4	4
4	4	4	4	4	4	4	4
4	4	4	1	1	4	4	4
4	4	4	1	1	4	4	4

0,2	0,2	0,3	1	1	0,3	0,2	0,2
0,2	0,2	0,3	1	1	0,3	0,2	0,2
0,2	0,3	0,7	0,6	0,6	0,5	0,3	0,2
0,3	0,7	0,3	0,4	0,4	0,3	0,4	0,3
0,2	0,4	0,7	0,5	0,3	0,6	0,3	0,2
0,2	0,3	0,6	0,8	0,7	0,7	0,3	0,2
0,2	0,2	0,3	1	1	0,3	0,2	0,2
0,2	0,2	0,3	1	1	0,3	0,2	0,2

Figure 19: Resistance surface (left) and current intensity (right) of a fictional landscape. The symbology for the current map is the same as Figure 18. The cost of the purple link is higher than the blue one (left), but the visible path (right) does not follow the same route due to a lower current flow for the barrier cells.

5.3. Software usage

The different computations made with each software are detailed in the following sections.

5.3.1. Circuitscape

5.3.1.1. Simple landscapes

The important steps followed to build the INI file used for connectivity modeling in the created landscapes using Circuitscape are described below:

1. Data type – Raster
2. Modelling mode – Pairwise
3. Habitat file – Resistance surface file (Figure 13)
4. Focal nodes – File of the two habitats in Figure 13, each having a unique ID
5. Outputs – Current map

Computations were made for the six created landscapes (the three visible in Figure 13 and the three same with barrier resistance modified to 10 000) for eight and four-neighbors connectivity by changing *connect_four_neighbors_only = false* to *connect_four_neighbors_only = true* in the INI file.

5.3.1.2. Connectivity in LLN

The steps followed to model connectivity in LLN using Circuitscape are described below:

1. Data type – Raster
2. Modelling mode – Pairwise
3. Habitat file – Resistance surface file (Figure 11)
4. Focal nodes – File of the four habitats, each having a unique ID (Figure 12)
5. Outputs – Current map

For an unknown reason, the computation in Julia stops after solving point 1 out of 4 while using the all-to-one and one-to-all methods. For this reason, these two methods were not included in this analysis. The advanced mode is useful when having a good knowledge of the animal population and movement dynamics in the territory and was thus not relevant for this thesis.

Two computations were made on Circuitscape. The first run was made without modifying the INI file created previously. For the second run, cells were connected to their four neighbors rather than the eight neighbors default option.

5.3.2. Omniscape

5.3.2.1. Simple landscapes

Omniscape only uses the resistance surface as input (Figure 13). The option to derive sources from the resistance file was checked with a cutoff value of 1, i.e., the maximum resistance allowed to be considered as a source is 1.

The search radius was set so that it was greater than the maximum extent of the landscape, i.e., the length of the diagonal. The block size was set to 1. Computations were made for eight and four-neighbors connectivity.

5.3.2.2. Connectivity in LLN

The LLN resistance surface was used as input (Figure 10). The option to derive sources from the resistance file was checked with a cutoff value of 1. By doing so, the software considers pixels belonging to needleleaved or broadleaved shrubs or trees as habitats to connect.

The search radius of the moving window, the block size to identify sources, and four or eight neighbors connexity were varied between computations to analyze changes that would occur by doing so.

The parameters used for each run are:

- Run 1 – Radius = 100 (200 m); Block size = 15 (900 m^2); 8 neighbors
- Run 2 – Radius = 100 (200 m); Block size = 15 (900 m^2); 4 neighbors
- Run 3 – Radius = 100 (400 m); Block size = 71 (20 164 m^2); 8 neighbors
- Run 4 – Radius = 100 (400 m); Block size = 71 (20 164 m^2); 4 neighbors

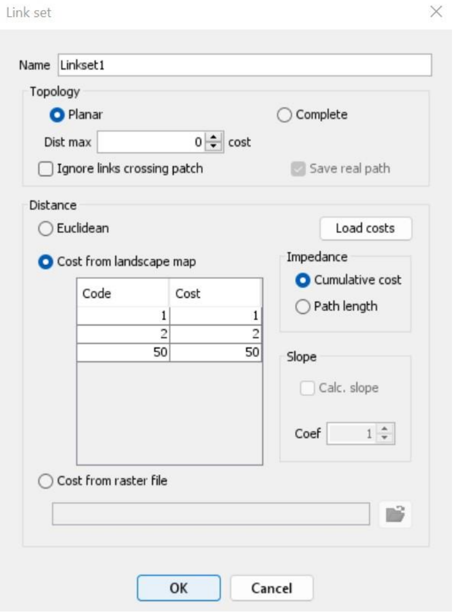
5.3.3. Graphab

5.3.3.1. Simple landscapes

As for the two software above, Graphab was run for each of the created habitats. However, there is no option for eight or four-neighbors connectivity, and assigning a higher resistance to the barrier had no impact on the created path. Therefore, these Graphab computations only produced three maps. The resistance surfaces (Figure 13) were the only required input, where cells with a resistance of 1 were identified as habitats. A planar link set was computed, the option to ignore links crossing patches was checked, and no maximal cost was specified (Figure 20). Costs are derived from the landscape map, as it contains resistance values. The impedance was calculated by summing the cost of all pixels that the link crosses.

5.3.3.2. Connectivity in LLN

Two projects were created in Graphab: one with 4-connexity (four neighbors), and the other with 8-connexity, which influences the manner in which the software identifies habitat patches but not the created links between these habitats. The landscape map required is described in section 5.1.1. Pixels with a value of 0 are chosen as the habitat patch code. The option to simplify the patch for planar graph was left unchecked, and no minimum patch area was specified for habitats since they were already delineated.


Link set

Name: Linkset1

Topology
● Planar ○ Complete
Dist max 0 cost
☐ Ignore links crossing patch ☑ Save real path

Distance
○ Euclidean
● Cost from landscape map

Code	Cost
1	1
2	2
50	50

Impedance
● Cumulative cost
○ Path length

Slope
☐ Calc. slope
Coef 1

○ Cost from raster file

Figure 20: Creation of a Graphab linkset

Both planar and complete link sets were computed, i.e., links between neighboring patches and links between all patches. The option to ignore links crossing patches was checked, and no maximal cost was specified. Costs were derived from the landscape map, as it contains the values of the resistance surface. The habitat patches (Code 0) have a resistance of 1, hence a cost of 1. The impedance was calculated by summing the cost of all pixels that the link crosses.

5.3.4. TerrSet

The suitability map previously created was imported in TerrSet and converted to the IDRISI Raster format (rst) specific to the software, using a built-in *GDAL raster conversion utility*. The *Fuzzy* function was used to eliminate the NoData values outside of the 0.0-1.0 range, required by TerrSet. The four Boolean maps were also converted into the right format.

Computations for every six possible pairs of habitats were made in the Planning tab of the Habitat and Biodiversity Modeler. Computations for corridor width set to 8 and 50 m were made, and two least-cost branches were built for each pair, where the first built corridor is the least costly of the two.

To have a better understanding of the modeling process, a single branch corridor between the *Bois de Lauzelle* and *Bois des Rêves* was calculated for widths of 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 36, 44 and 50 m. These outputs were then compiled in a single raster file using ArcGIS Pro.

As explained in section 5.2.2.1, TerrSet seems to have flaws in its Corridor Planning tab and the results were discarded but the first branch of the corridors are compiled in a single map in Appendix 2 for information purposes.

6. Results

6.1. Simple landscapes

As explained in section 5.2.1, three small extent landscapes with a physical barrier to animal movement were created to be run in Graphab, Omniscape, and Circuitscape.

6.1.1. Graphab least-cost paths

The least-cost paths were computed by Graphab for the three landscapes (Figure 21).

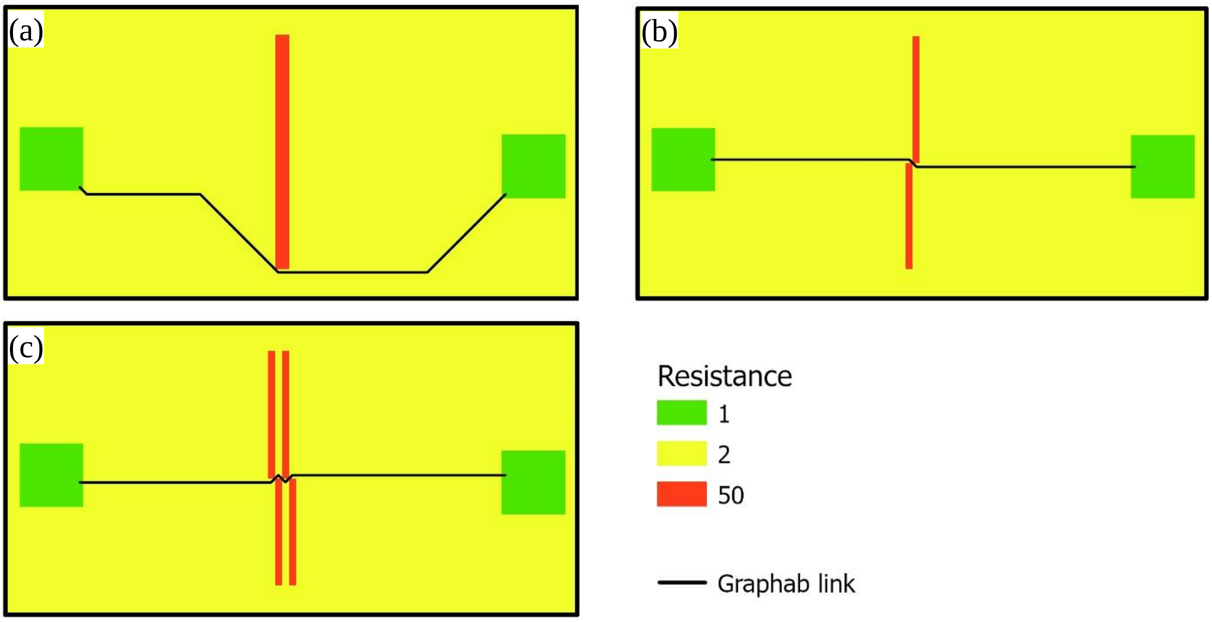


Figure 21: Graphab least-cost paths of landscapes *a*, *b*, and *c*.

6.1.2. Circuitscape and Omniscape current maps

Due to the simplicity of the landscape, it can be expected for both tools, which use a similar algorithm, to produce nearly identical results.

Two maps with eight-neighbors connectivity were created for each tool to illustrate the difference between the two outputs (Figure 22).

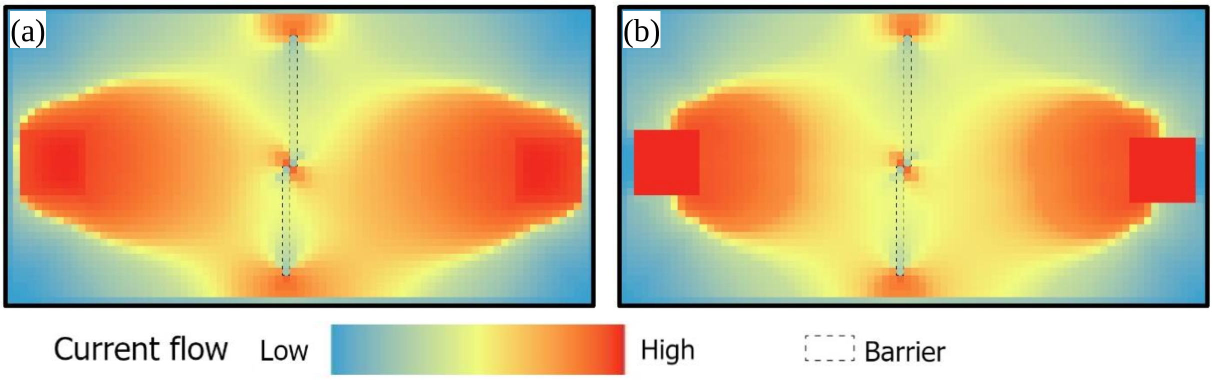


Figure 22: Eight-neighbors connectivity current maps of landscape *b* produced by Omniscape (a) and Circuitscape (b).

It is important to note that, due to the wide range of intensity values for current maps (from 0 to 1 with values of 10^{-3} or 10^{-4}) with most of them being concentrated around two values, a histogram equalization had to be established in the ArcGIS Pro symbology to increase contrast between the landscape cells' color. This was done for every current map unless specified otherwise. This means that two pixels from the same image can have very close values, e.g., 0.002913 and 0.003059, but have a tone difference on the color scale. This also implies that, when comparing two images, two pixels can have the same value but a different color and vice versa. However, current maps are generally analyzed by looking at the color intensity of areas rather than at their current intensity values.

The current maps for landscape *a* using four and eight-neighbors connectivity provides an insight into the influence that this option has on the output (Figure 23).

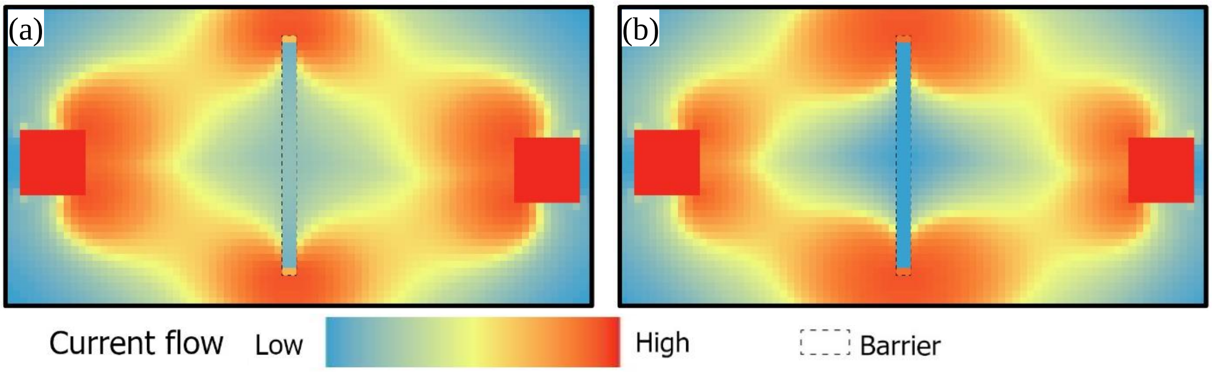


Figure 23: Circuitscape current map of landscape *a* using four (a) and eight-neighbors connectivity (b), with barrier resistance of 50.

The same current maps were also produced for landscapes *b* (Figure 24), and *c* (Figure 25). This allows to ensure that the intensity observed in landscape *b* is not related to its barrier being one cell narrower than in landscape *a* (it is possible to cross the barrier in landscape *b* by overlapping only one cell, while landscapes *a* and *c* require crossing two barrier cells).

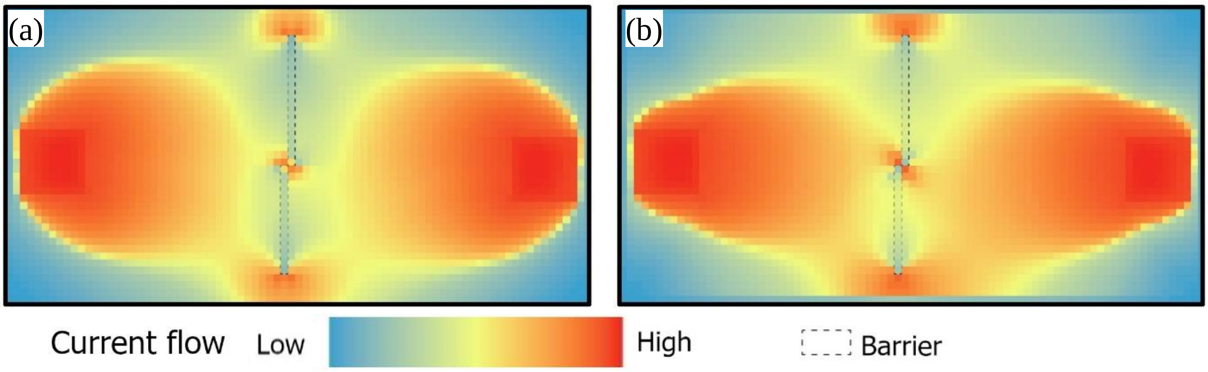


Figure 24: Circuitscape current map of landscape *b* using four (a) and eight-neighbors connectivity (b), with barrier resistance of 50.

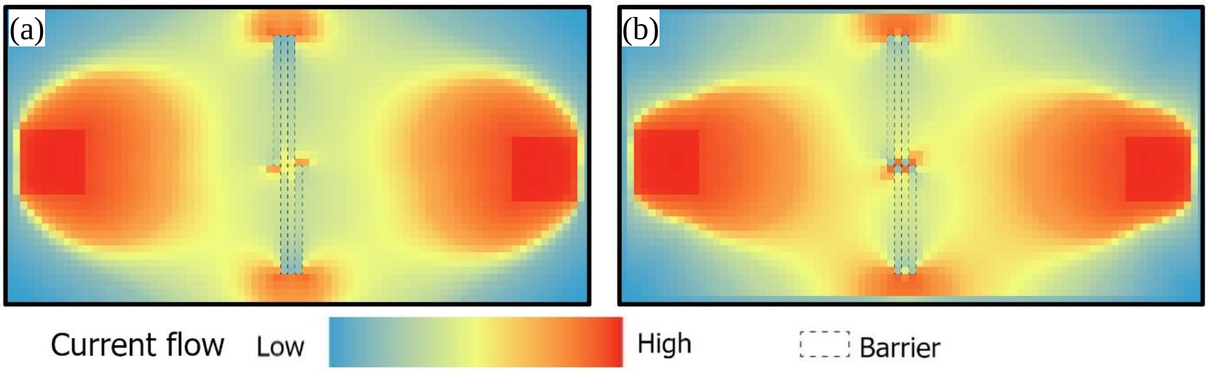


Figure 25: Circuitscape current map of landscape *c* using four (a) and eight-neighbors connectivity (b), with barrier resistance of 50.

The current intensity values of the bright red cells that connect diagonally in the center of Figures 24 and 25 are provided in Table 4, numbered starting from the first cell on the left, to the last cell on the right. The difference between Figure 24 (a) and Figure 25 (a) equivalent cells (in green) included in Table 4 was also calculated.

Table 4: Current intensity for bright red cells in the center of Figures 24 and 25.

	Cell 1	**Cell 2**	**Cell 3**	**Cell 4**
Landscape *b* (a)	0.030575	0.030618	/	/
Landscape *b* (b)	0.033455	0.033481	/	/
Landscape *c* (a)	0.029678	0.026346	0.26308	0.029612
Landscape *c (b)*	0.032384	0.032277	0.032261	0.032326
Landscape *b* (a) − Landscape *c* (a)	0.000897	0.001006	/	/

To analyze the impact that the barrier resistance has on the output current, barrier resistance for landscapes *b* and *c* was set to 10 000 rather than 50, and current maps were produced using four-neighbors connectivity. For better visualization, both maps with the higher resistance were subtracted to their landscape equivalent that has a barrier resistance of 50 (current_50 – current_10000), and are displayed with a classify (Figure 26) and stretch symbology (Figure 27).

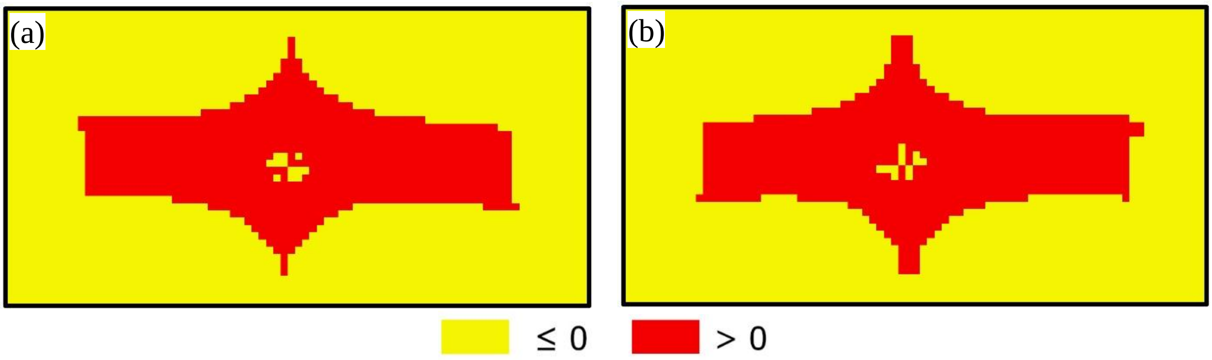


Figure 26: Differential current flow of landscapes *b* (a) and *c* (b) with classify symbology using four-neighbors connectivity.

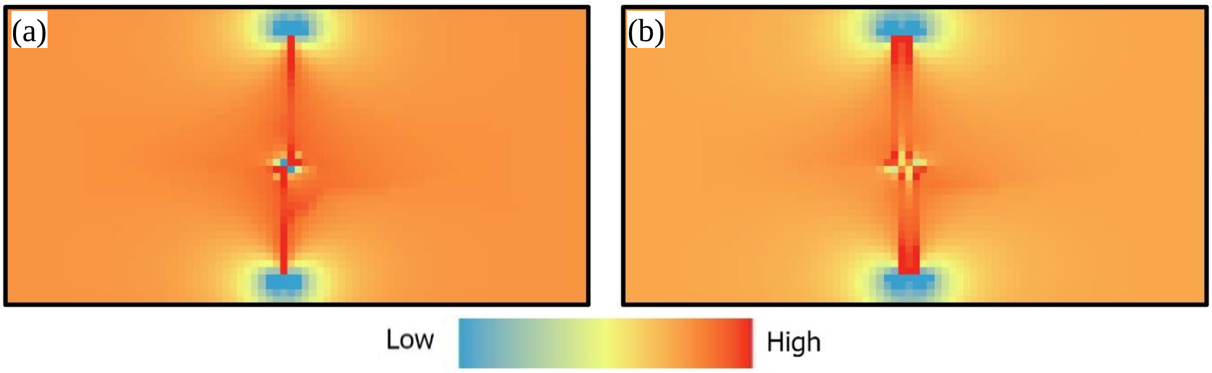


Figure 27: Differential current flow of landscape *b* (a) and *c* (b) with stretch symbology using four-neighbors connectivity.

The values of the cells in Figure 27 (a) and (b) that were mentioned in Table 4 (landscape *b* (a) and landscape *c* (a)) are visible in the table below.

Table 5: Differential current map values of the cells included in Table 4.

	Cell 1	**Cell 2**	**Cell 3**	**Cell 4**
Landscape *b* (a)	− 0.000337	− 0.000335	/	/
Landscape *c* (a)	− 0.000259	− 0.000128	− 0.00128	− 0.000265

The Omniscape outputs are visible in Appendix 3.

6.2. Software using similar algorithms

6.2.1. Graphab

As stated before, TerrSet results will not be analyzed, meaning that only Graphab outputs are available in this section. The four created links between the habitats are visible in Figure 28.

The graph with complete topology was also created and is not included as the links are the exact same as the ones visible below, because the option to ignore links crossing patches was checked. This means that the least-cost path going from, say habitat 4 (bottom right) to the *Bois de Lauzelle* (top of the map) follows the link to one of the other two habitats, passes through that habitat, and then follows the link from that habitat to the *Bois de Lauzelle*.

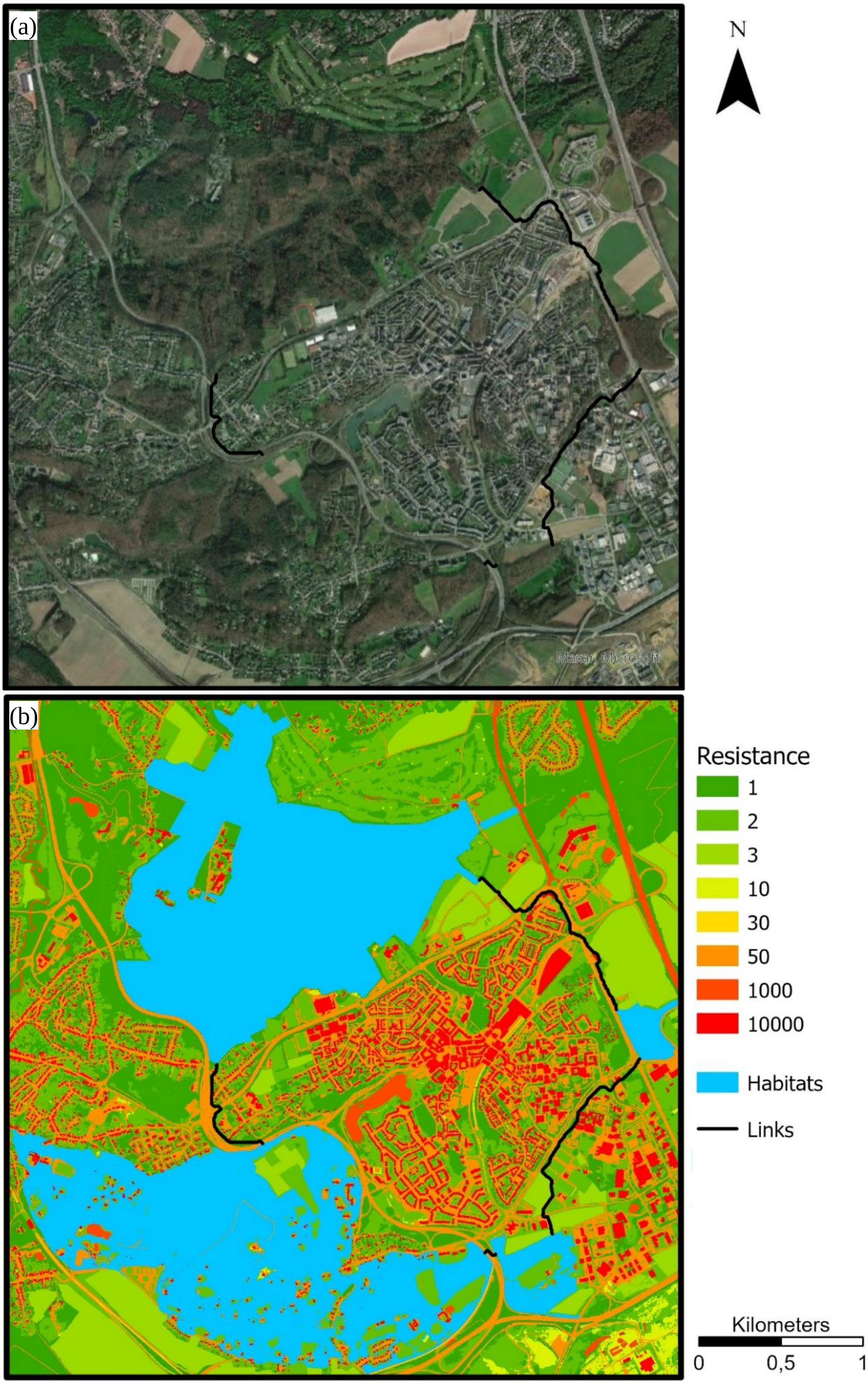


Figure 28: Graphab least-cost paths with planar graph and 8-connexity options and an orthophoto (a) or the resistance surface (b) as basemap.

6.2.2. Circuitscape and Omniscape

6.2.2.1. Circuitscape

The cumulative current map produced by Circuitscape displays possible pathways between habitats (Figure 29).

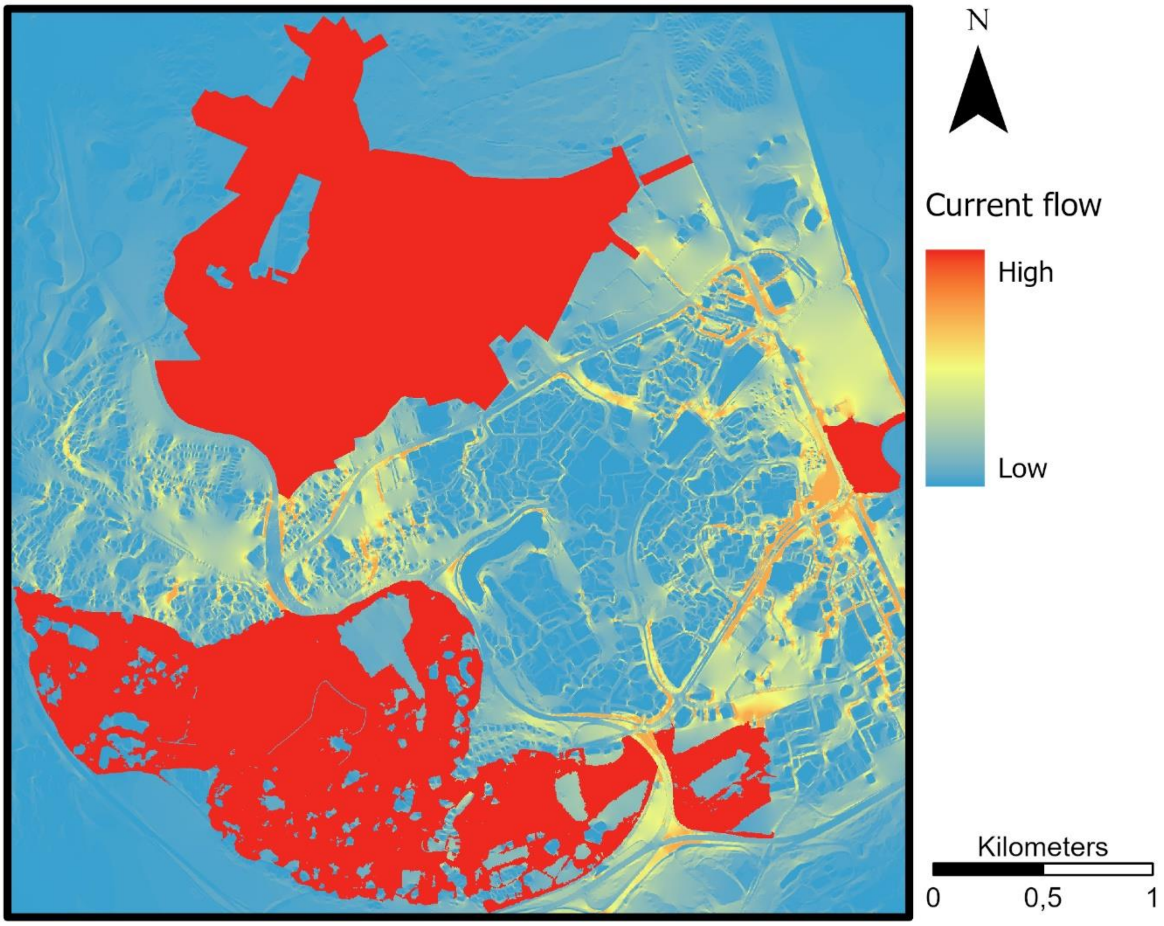


Figure 29: Circuitscape cumulative current map using pairwise mode and eight-neighbors connectivity.

The current map obtained when using four-neighbors connectivity is almost identical to the one above, analyzing it is therefore not relevant.

6.2.2.2. Omniscape

Two computations were made on Omniscape, varying the block size from 15 (Figure 30) to 71 (Figure 31).

As for Circuitscape, four-neighbors connectivity maps do not provide useful information and are thus not included.

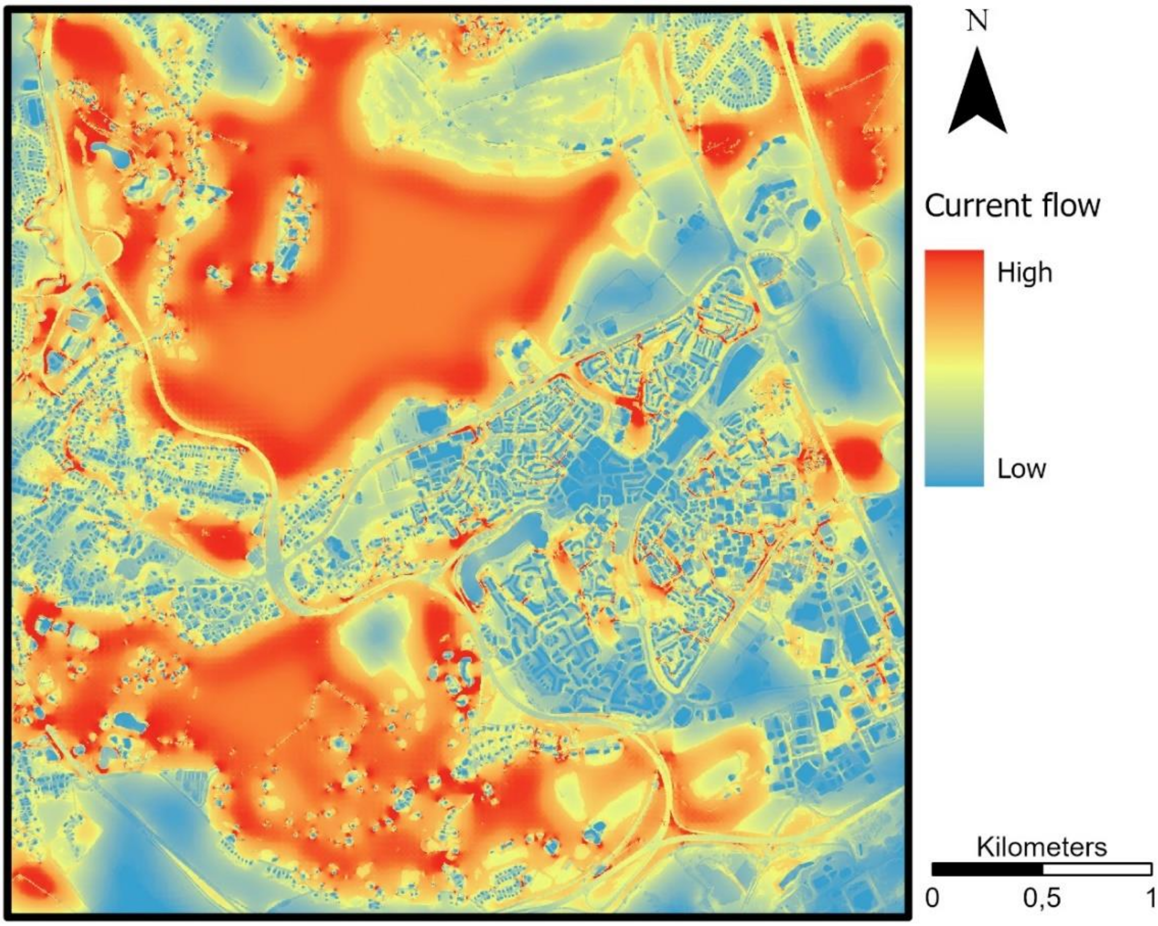


Figure 30: Omniscape cumulative current map using eight-neighbors connectivity, a block size of 15 (900 m^2) and a search radius of 100 (200 m).

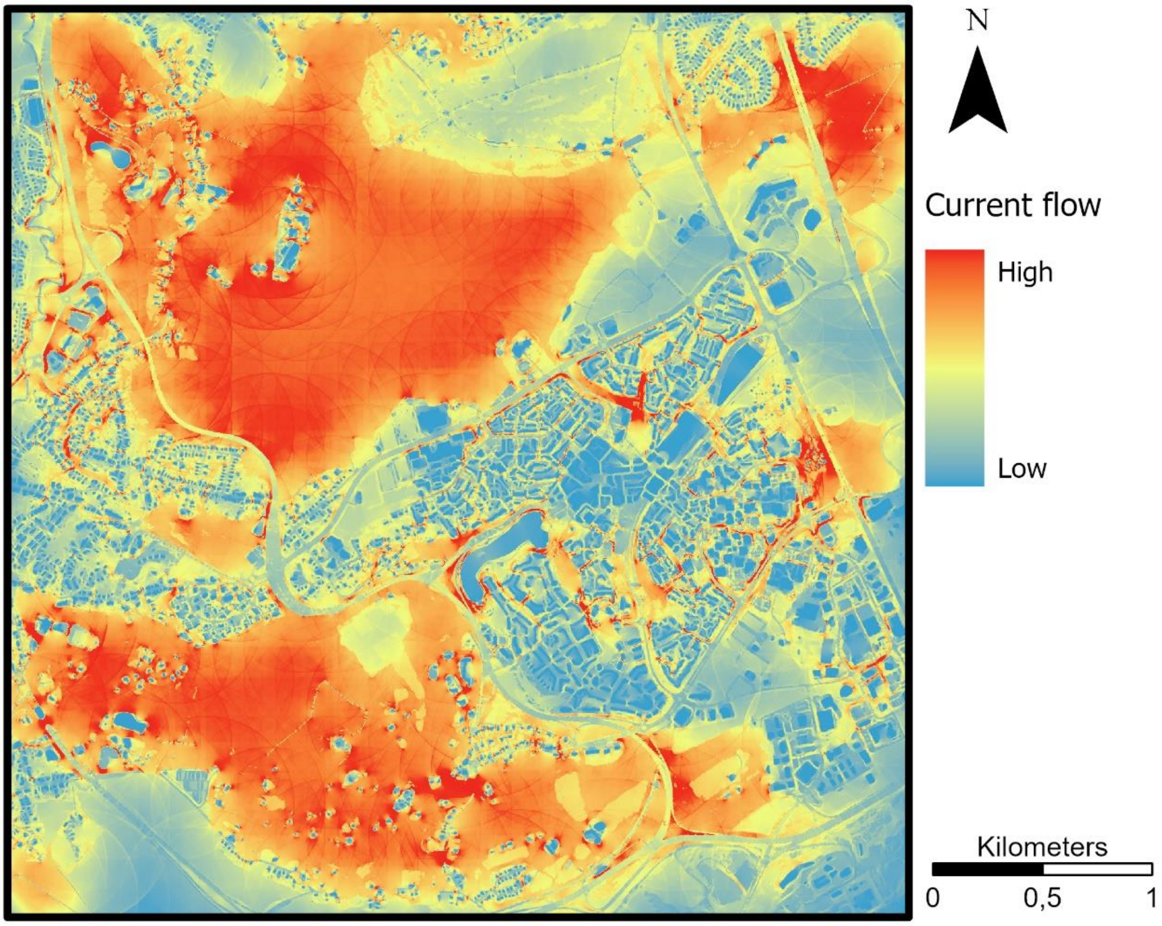


Figure 31: Omniscape cumulative current map using eight-neighbors connectivity, a block size of 71 (2,0164 ha) and a search radius of 100 (200 m).

6.3. Software using different algorithms

As the results produced by TerrSet were rejected and Omniscape's current map did not depict connectivity between habitats effectively (see section 7.2.2.2), only Graphab and Circuitscape results are visible in this section.

The Circuitscape cumulative current map and the Graphab least-cost links were combined in a single map to compare the two outputs (Figure 32).

Since the cumulative current map combines the current maps for all six possible pairs of habitats, comparison between the Graphab links and Circuitscape current flow was done by combining each Graphab least-cost path and its equivalent habitats pair current map (Figures 33, 35, 37, and 39)

To better identify the Circuitscape paths, each current map of the pairs of habitats was applied a threshold, and the resulting Circuitscape paths between a pair of habitats were compared to the Graphab links between these two same habitats (Figures 34, 36, 38, and 40).

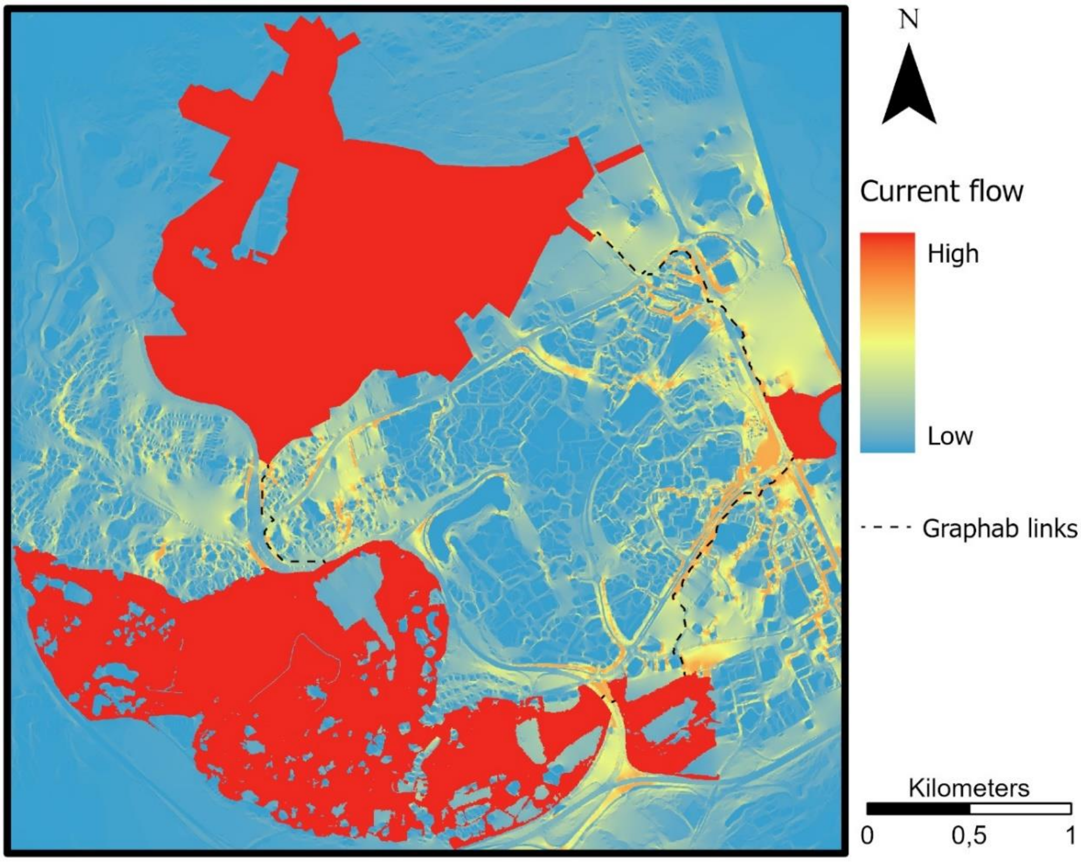


Figure 32: Overlapping of Graphab links and Circuitscape cumulative current map.

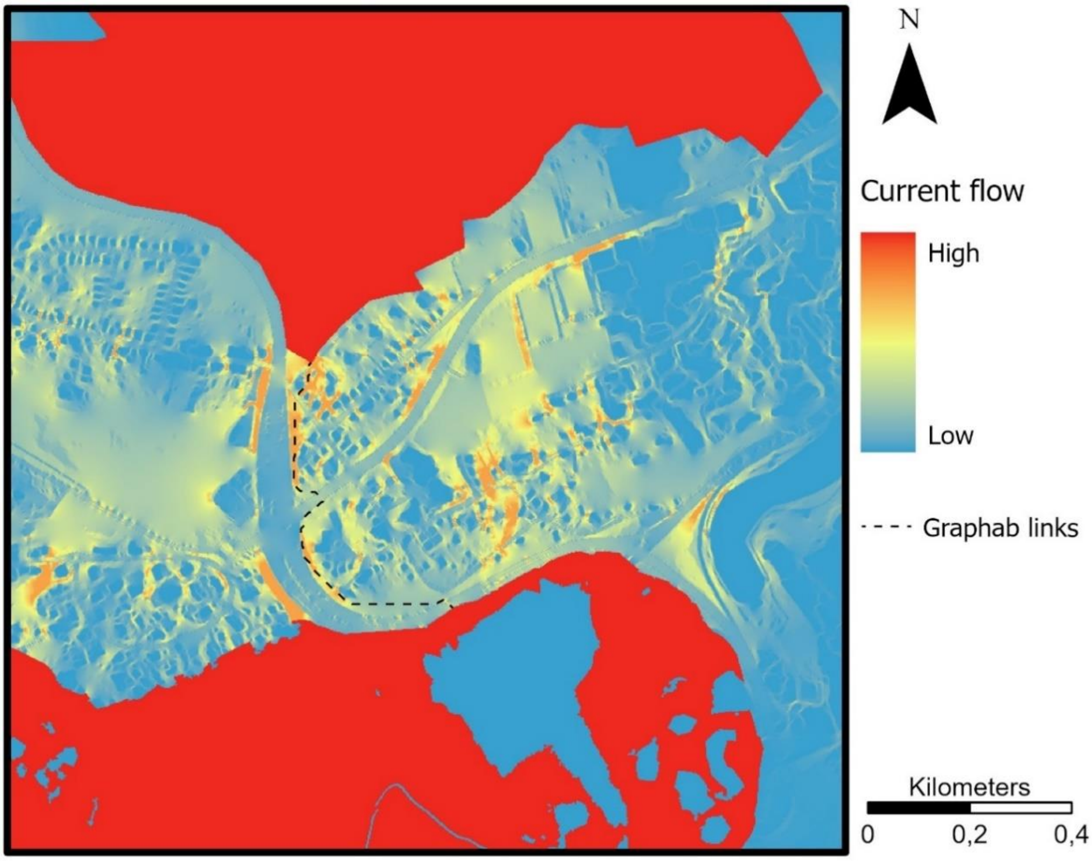


Figure 33: Circuitscape current map and Graphab least-cost link between *Bois de Lauzelle* and *Bois des Rêves.*

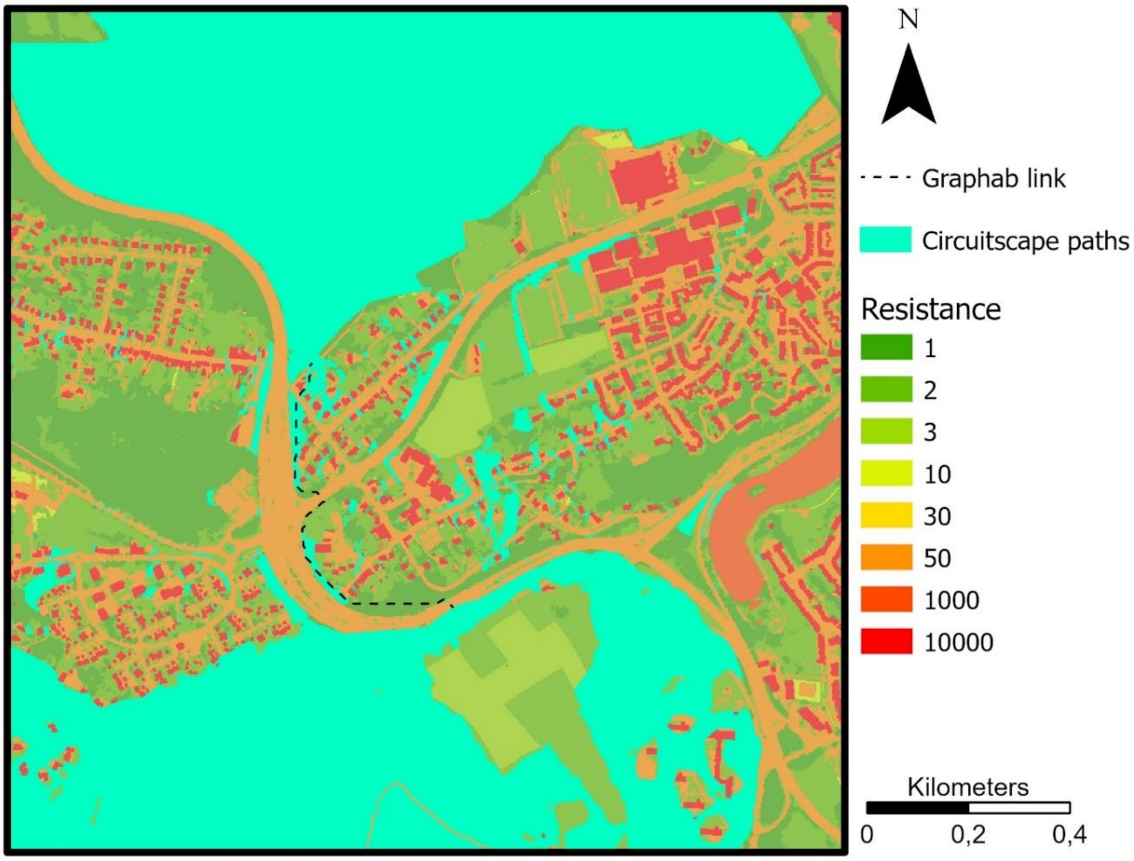


Figure 34: Circuitscape paths and Graphab least-cost link between *Bois de Lauzelle* and *Bois des Rêves* with the resistance surface as basemap.

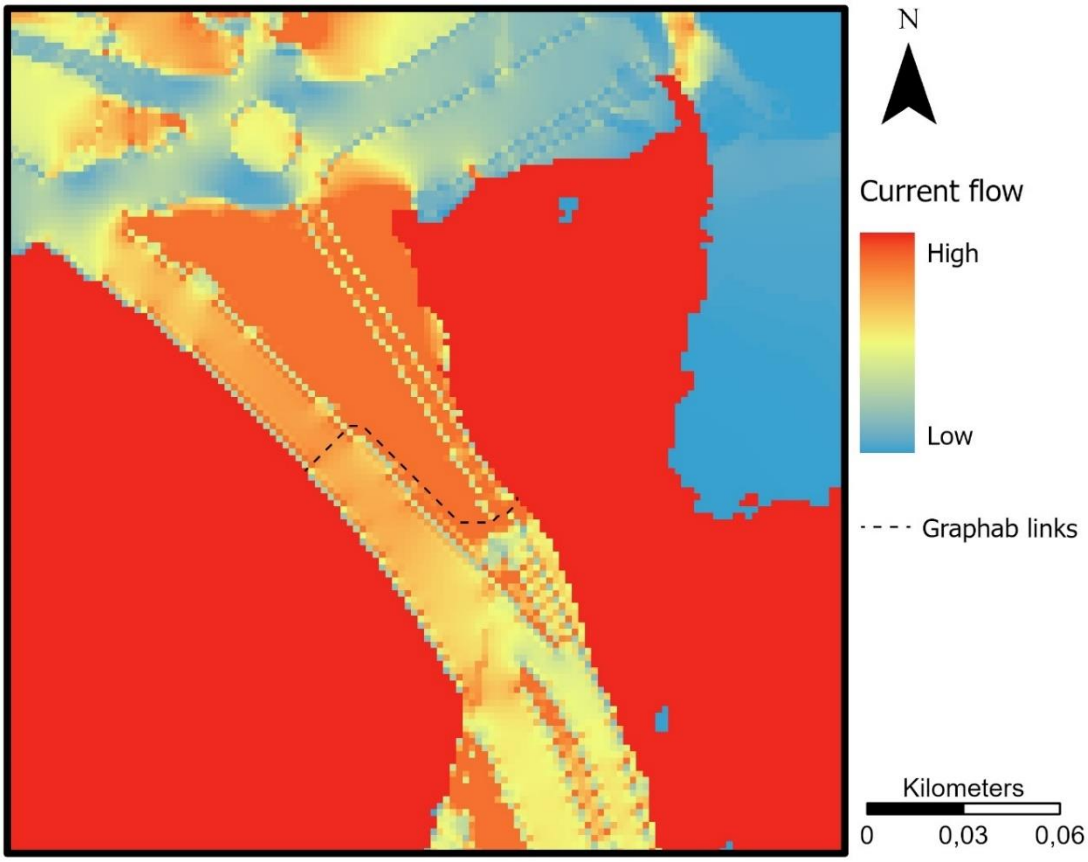


Figure 35: Circuitscape current map and Graphab least-cost link between *Bois des Rêves* and habitat 4.

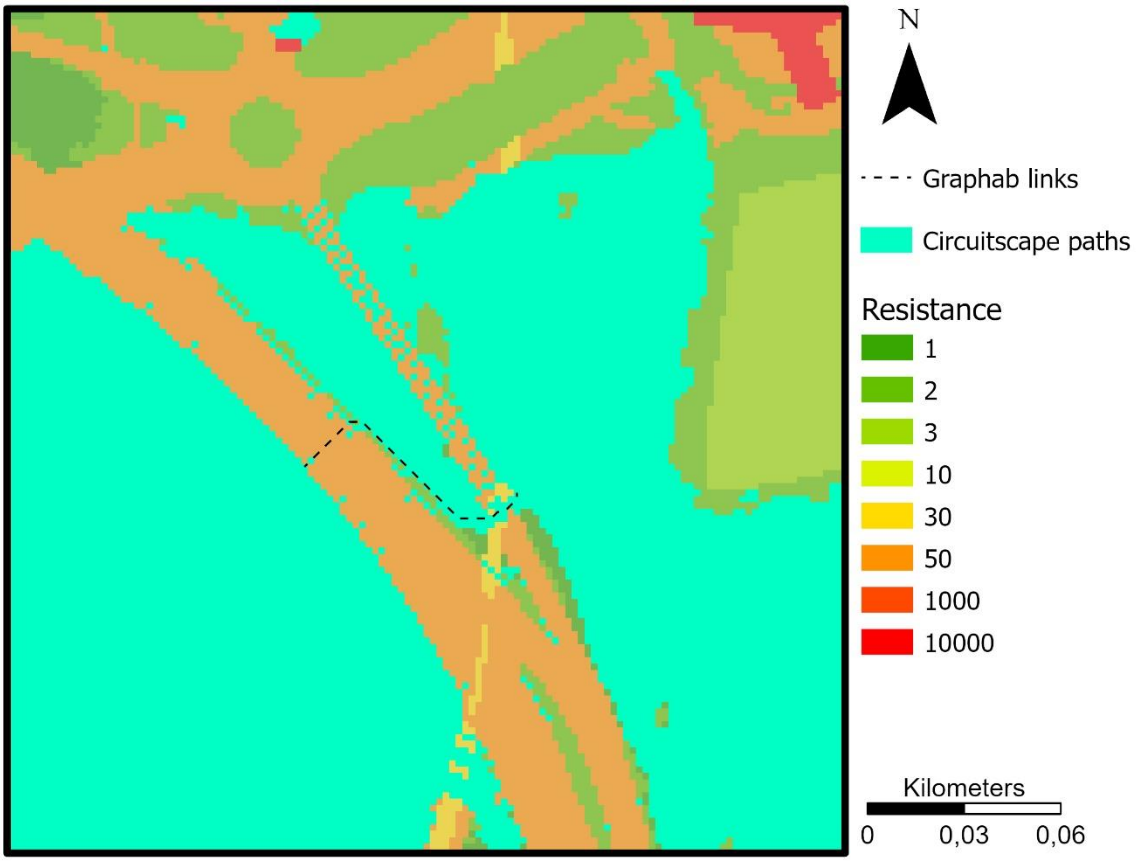


Figure 36: Circuitscape paths and Graphab least-cost link between *Bois des Rêves* and habitat 4 with the resistance surface as basemap.

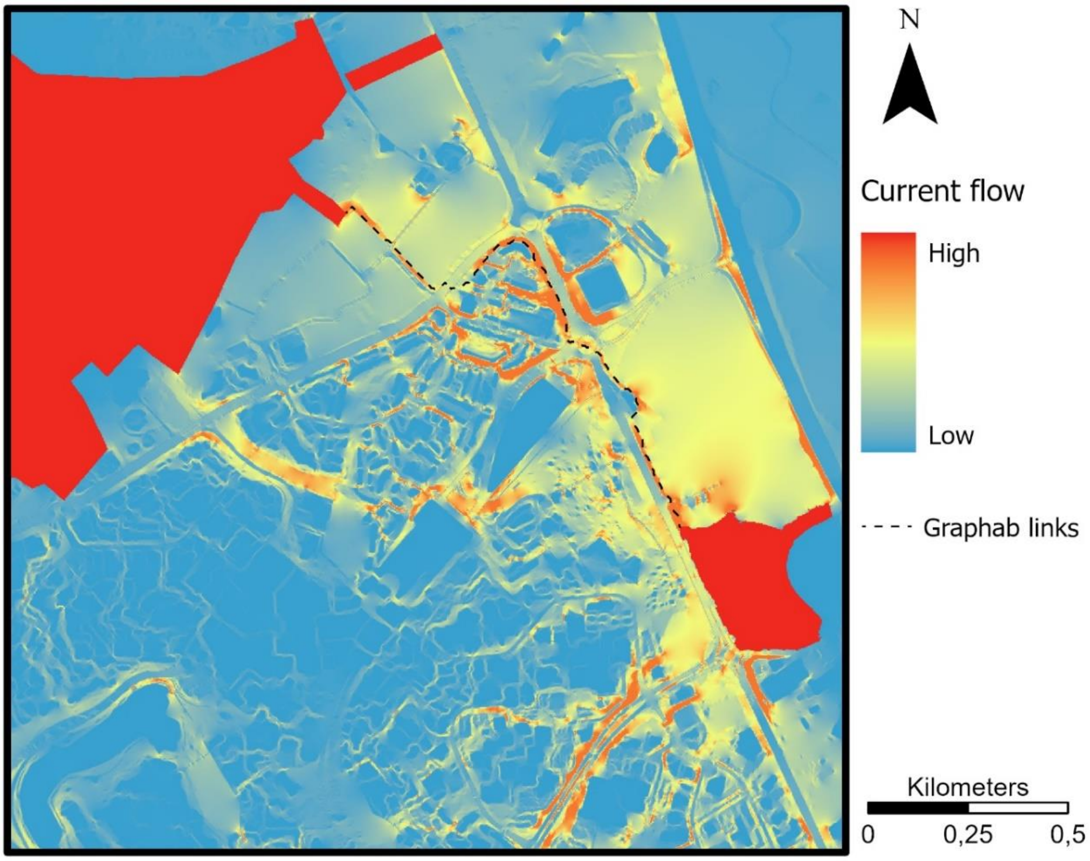


Figure 37: Circuitscape current map and Graphab least-cost link between *Bois de Lauzelle* and habitat 3.

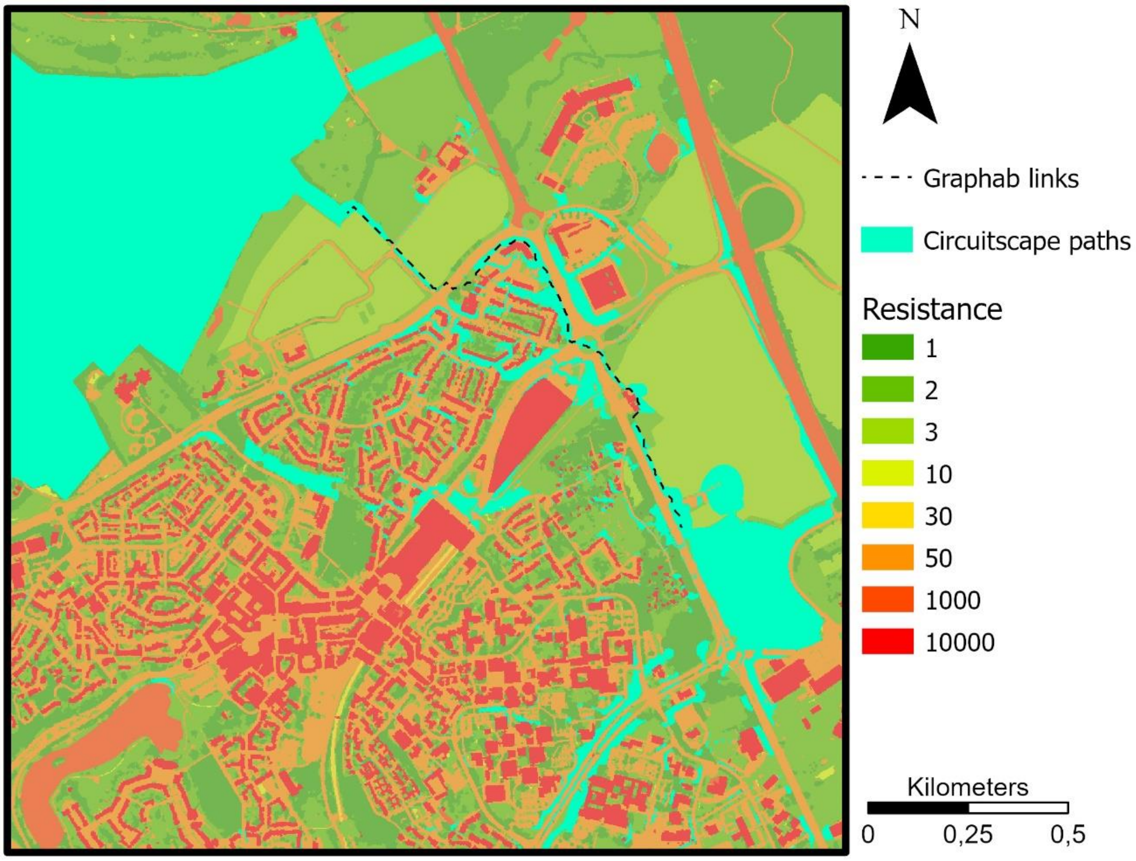


Figure 38: Circuitscape paths and Graphab least-cost link between *Bois de Lauzelle* and habitat 3 with the resistance surface as basemap.

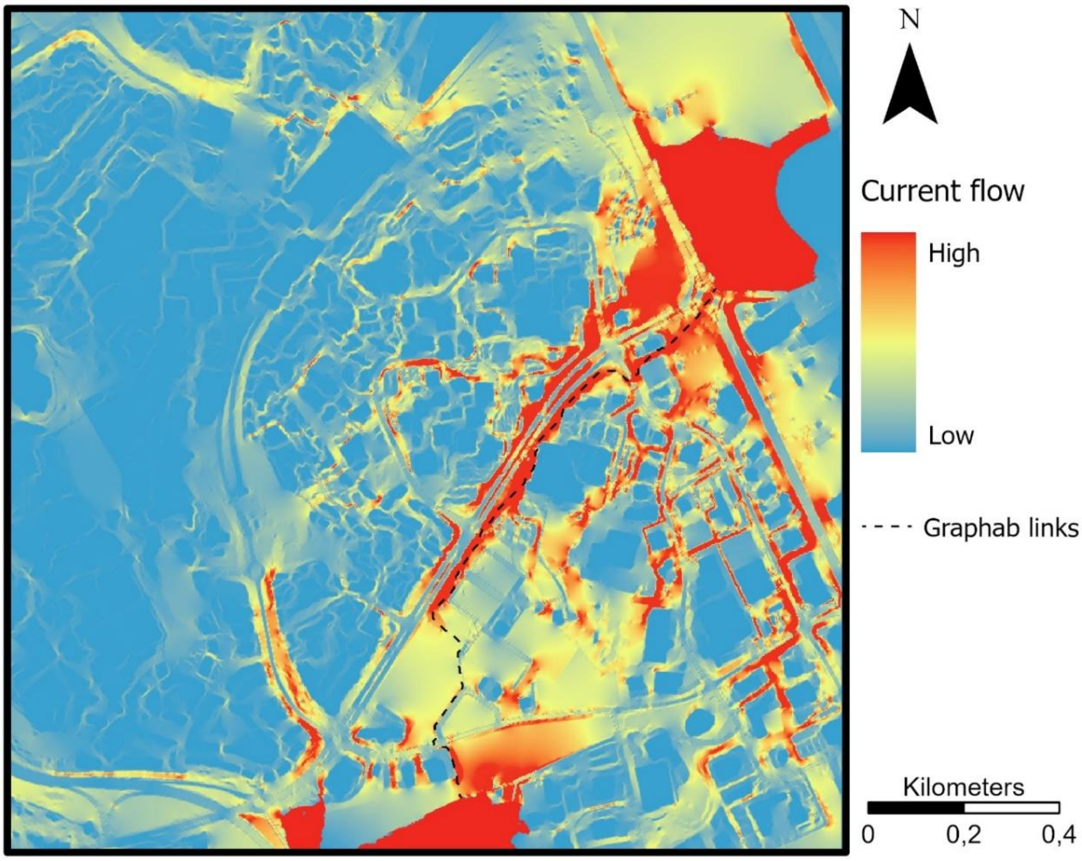


Figure 39: Circuitscape current map and Graphab least-cost link between habitat 3 and habitat 4.

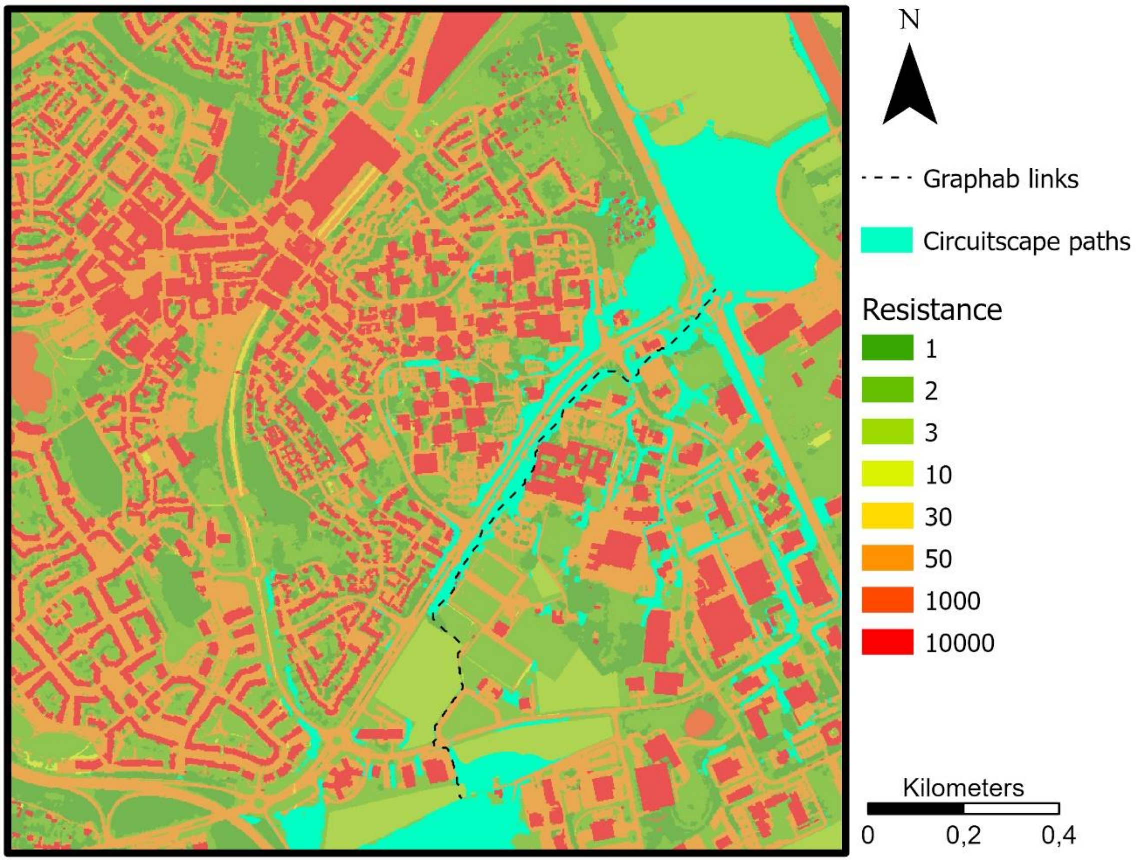


Figure 40: Circuitscape paths and Graphab least-cost link between habitat 3 and habitat 4 with the resistance surface as basemap.

7. Discussion

7.1. Simple landscapes

These simple landscapes were created, and their connectivity analyzed to have a better understanding of the functioning of each tool.

7.1.1. Graphab least-cost paths

The least-cost paths created by Graphab for the three landscapes follow the expected route, i.e., the shortest one without overlapping the cells with a resistance of 50 (Figure 21). Given that the software uses eight-neighborhood connectivity, the (b) and (c) paths cross the barrier by connecting diagonally to low resistance cells, thus having the shortest length possible (as it minimizes the path cost).

7.1.2. Circuitscape and Omniscape current maps

Since Omniscape applies Circuitscape in a moving window, it is relevant to compare the current maps produced by the two software to fully grasp their specificities.

When comparing two maps from the tools with eight-neighbors connectivity, the main visible difference is that Omniscape seems to model a more scattered flow (Figure 22 (a)), while Circuitscape produces more dense paths between the two habitats (Figure 22 (b)).

This is likely because, during an Omniscape iteration, a target pixel in the landscape is selected with account of the resistance cutoff (resistance = 1), and current flow is measured between this pixel and every other pixel with a resistance of 1. This implies that pixels within the same habitat are linked during each iteration, hence the high current intensity values at the rear of the habitats and slightly larger “paths”. On the other hand, Circuitscape only models connectivity between the two habitats thanks to a node location file, causing the current to be oriented towards the other node.

Apart from this variation, there are no major differences in the outputs produced by both software for these fictional landscapes. For this reason, only the Circuitscape outputs will be analyzed in this section, as modeling connectivity only between the two habitats and not within them seems more relevant, since this work aims to assess connectivity between the habitats surrounding LLN, and not inside them.

The high current paths with four-neighbors connectivity (Figure 23 (a)) seem to take up a wider area than with eight-neighbors (Figure 23 (b)). This is due to the current not being injected diagonally, which causes the current flow to be more spread out when connecting the habitats.

The comparison of current maps of landscape *b* with four and eight-neighbors connectivity reveals a rather surprising result (Figure 24). When Circuitscape applies connectivity for four neighbors only, it is not expected that high intensity values be present where the barrier can be crossed diagonally (in its center), as it would necessitate passing through a barrier cell (due to four-neighbors connectivity) which is not the case as seen in Figure 23. In this case (Figure 24), aside from the slightly larger width of paths in map (a), the two maps in the figure are similar and show a possible path in the center of the barrier. The flow directed towards that passage is however greater in map (b), as seen in Table 4. Although the current intensity values are greater for eight-neighbors (b) than four-neighbors connectivity (a) (Table 4), the flow with four-neighbors is higher than what could have been expected.

To ensure that this high intensity flow in the center of the barrier isn't because the obstacle can be crossed by only passing through one cell in landscape *b*, rather than two in landscape *a*, the same current maps were produced for landscape *c* (Figure 25).

There are still high current intensity cells near the center of the barrier, meaning that animal movement in that spot isn't exclusively linked to the barrier being narrower for landscape *b* than *a*. However, it can be observed when comparing Figure 24 (a) and Figure 25 (a), and by checking the values in Table 4, that there is a higher flow directed towards the center in the first than in the latter. The same observation can be made for Figure 24 (b) and Figure 25 (b) but the difference in the current flow towards the center is surprisingly bigger for eight-neighbors connectivity, as seen in Table 4. However, when visually analyzing Figure 24 (a), (b) and Figure 25 (a), (b), there seems to be a bigger difference between the maps where four-neighbors connectivity was applied than the ones with eight-neighbors, which means we would expect current values to be closer for the latter than the first. This mismatch is due to histogram equalization being applied to the map symbology and means that, relatively to the other current intensity values in the map, the distribution of flow in Figure 24 (b) and Figure 25 (b) is more similar than in Figure 24 (a) and Figure 25 (a), even though the differences in intensity might be greater at times.

Nevertheless, the observations made above imply two things: four-neighbors connectivity is indeed applied when that option is picked in Circuitscape even though the high flow values were misleading, and increasing barrier width also reduces current intensity in the center of the barrier for eight-neighbors connectivity.

The most likely explanation for the first observation is that, when crossing the barrier in landscape *a* with four-neighbors connectivity, a random walker will have four possible directions, three of which being barrier cells with a high resistance, and the last one being a cell with low resistance (Figure 41 (a)). As each movement in circuit theory is independent, the walker can retrace its steps, and the most probable direction it picks only depends on the resistance of the destination cell. For landscapes *b* and *c*, when crossing the barrier in the middle where it is connected diagonally, the four options are different (Figure 41 (b)); three of them are low resistance cells, and only one is a barrier cell. For this reason, although the probability of arriving on a barrier cell is relatively low, two out of the three equiprobable options result in crossing the barrier. Cells 3 and 4 (Figure 41 (b)) being probable directions due to their location (adjacent to barrier edges), this causes them to have higher current intensity, hence the high flow where barriers touch diagonally in Figure 24 (a) and Figure 25 (a).

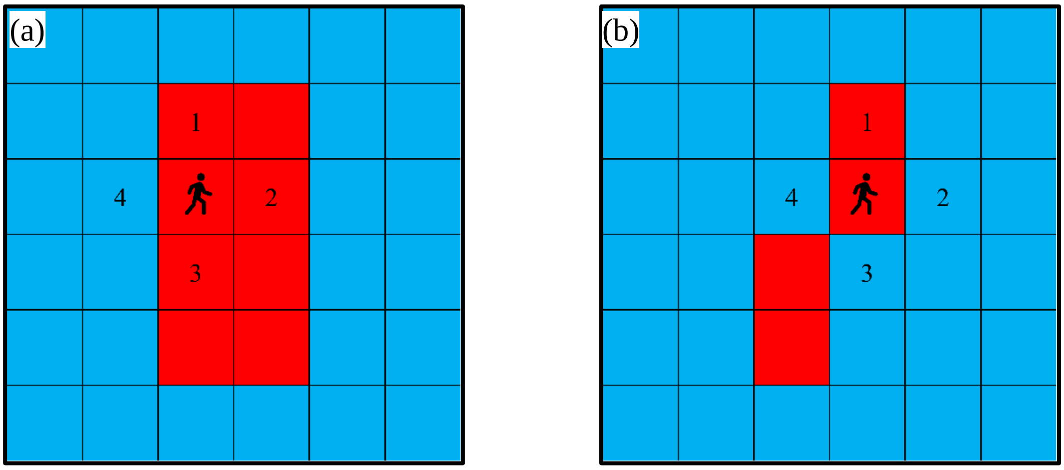


Figure 41: Possible directions when being on a barrier cell for landscapes *a* (a) and *b* (b). Red cells represent barrier resistance, blue cells have a lower resistance.

As these cells with high intensity current in the center of the barrier (Figures 24 and 25) are due to movement across the barrier, it would be expected that assigning a higher resistance to the barrier would reduce passage in its center. To verify this hypothesis, Figures 26 and 27 were produced.

As seen for both landscapes (Figures 26 and 27), the current intensity seems to be greater near the edges when using a resistance of 10 000 (hence the negative values), but also increases in the center of the barrier. The difference between the maps with the two different barrier resistances (Table 5) is smaller than the difference when increasing the width of the barrier (Table 4), since increasing barrier resistance increases current intensity by 0.000337 and 0.000335 units, while increasing barrier width decreases the flow of 0.000897 and 0.001006 for the cells in the center. It is however tough to analyze the significance that such changes have on animal movement.

It is difficult to establish a link between higher barrier resistance and current flow in areas that the software seems to have identified as easier to cross. Due to the higher resistance of the barrier, movements of animals that used to go through the barrier before are being reorientated to areas where the current flow was already higher, i.e., near the edges and the center of the barrier. Although increasing the resistance probably reduces animal flow in the center at first, it is counterbalanced by the higher current coming from other spots that are more difficult to cross than before, which ultimately increases the current intensity in the center.

Finally, it should be pointed out that the current maps for the barrier resistance of 10 000 were almost identical to the ones with the resistance of 50. As measures of current intensity have little interpretative value on their own, it is probably safer to analyze a current map by looking at the color variation, which does not provide a universal metric of connectivity but indicates relevant information regarding the analyzed landscape.

7.2. Results analysis and comparison with software using similar algorithms

7.2.1. Graphab

Using 4-connexity instead of 8-connexity only influenced the habitat patches, which is not relevant in this case as the precise extent of the four habitats was already delineated. Habitat cells that were connected to other habitats only by their diagonal were identified as another habitat patch, but the link back to the other habitat is one cell wide and connects the two patches by their diagonal. It would have been interesting for Graphab to allow choosing four-neighbors connectivity for the link modeling, as it is rather odd that two habitats contiguous by their diagonal can be identified as separate patches but movement between the two can be done without stepping foot outside of any.

For the reasons mentioned above, only the links with planar topology and 8-connexity are illustrated in this work (Figure 28).

The created links pass through the outskirts of LLN, where the resistance is usually lower. It can also be observed that the paths follow major roads and only cross over them when necessary. This is due to these roads often connecting areas so that travel time is fastest, which generally results in the shortest possible route. Trees are also frequently present along the roads and have the lowest resistance value. From an ecological standpoint, these trees are certainly not as suitable habitats as the *Bois de Lauzelle* or *Bois des Rêves*, which are SGIBs, and it would have been relevant to assign higher resistance values to trees bordering roads, especially if they present high traffic.

7.2.2. Circuitscape and Omniscape

7.2.2.1. Circuitscape

The display of possible pathways on the Circuitscape map (Figure 29) is useful for showing different corridors between habitats that could be taken advantage of and gives great flexibility in corridor planning. Not only does it show a variety of possible routes, but the fact also that these paths are sometimes not complete allows for designing several possibilities that could be implemented for the missing parts (areas between high current intensity cells that have a lower current flow), and for pinpointing areas where animal movement is less likely. On the other hand, having a path that is not complete does not show which route it would be best to follow and could lead to less appropriate corridors. Although these cells with lower current flow might have, for example, higher resistance values, the cost of the path that goes through these cells could be lower than that of an alternative path that seems suitable only by looking at the current map.

Another thing to keep in mind is that high current intensity in a cell might be caused by highly resistant areas neighboring that cell. As seen in section 7.1.2, a high current flow could be due to adjacent cells with high resistance, leading to a higher probability of movement in that least resistant cell. However, this does not necessarily mean that the pixel is more suitable for the species than another cell. For example, a 15 pixels wide area with resistance values of 1 could have a lower current flow than a one-cell wide strip with a resistance of 3, but adjacent to high resistance pixels which therefore channel the animal flow. The total flow for the 15 pixels width would however be similar to the cumulative flow of the 3 pixels width, the difference in color tone (thus in current intensity) being due to the amount of current being distributed among a different number of pixels (e.g., a total flow of 15 distributed equally among 15 pixels would equal to an intensity of 1 for each, while the same flow distributed across 3 pixels sets a value of 5 for each cell).

These details help identify pinch points in the landscape, which are usually areas very important to preserve as they form the only route in the surroundings where animal movement is not impeded, and which must be followed to move from one habitat to another.

7.2.2.2. Omniscape

The main advantage of Omniscape is that it can identify potential habitats that may have been omitted when building the node file used in Circuitscape. As seen in Figure 30, there are many more areas with high current flow than in Figure 29. However, the main flaw of Omniscape lies in the fact that no minimum habitat size can be specified, resulting in high intensity values for every pixel with a resistance of 1. This causes some bias when trying to analyze connectivity between two habitats, as cells where land cover is broadleaved or needleleaved trees are also identified as a habitat by the software. This leads to great current flow in the landscape in areas whose extents are not sufficient to be considered by the animals as suitable habitats but which the software does. This is problematic when the user broadly identified areas of interest (or habitats) prior to the use of Omniscape, as the software will not model connectivity solely between these areas.

This feature, however, constitutes the advantage of Omniscape and is the main purpose of using this tool rather than another. Moreover, it also helps identify areas of higher flow within the habitats, as can be seen for the four habitats (Figures 30 and 31), whereas Circuitscape automatically assigns a current value of 1 for all the habitat cells.

Although the software is useful to detect other potential habitats, it applies the same processes to a cell in a 36 m^2 patch as it does to another included in a 200 ha habitat. This problem could be avoided by changing the resistance surface (e.g., habitat cells have a resistance of 1, and values for all other classes are raised by one unit), but the main interest of the software would then be lost since the advantage of using Omniscape is to not be obligated to identify the node locations.

Changing the block size in Omniscape slightly influences the produced output, but the same patterns can still be observed from one map to the other (Figures 30 and 31). Using too large block sizes does however produce esthetically unpleasant maps and influences the current flow values due to the low number of iterations having to be made in the landscape, causing the outline of the circle window to be visible. Nevertheless, reducing the block size did have a major impact on computation time, and is, therefore, an appropriate option when used correctly, i.e., the block size should not be set too high when dealing with a relatively small extent but could be increased as the size of the study area increases. This also depends on the resolution of the data, as a lower resolution would diminish the number of iterations being made, once again showing the outline of the moving window.

The specified radius for the moving window is particularly useful when dealing with a large extent landscape and animal species that have a dispersal distance smaller than the extent. This allows for a more realistic modeling of connectivity and is not available in Circuitscape. However, in this case, the extent of the landscape is small enough so that this option is not relevant. In addition, computations with a radius greater than 100 cells failed at each attempt for an unknown reason.

Due to the reasons mentioned above, i.e., not being able to model connectivity between the wanted habitats nor picking their minimal size, further analyses of Omniscape do not seem relevant in this work. Therefore, only Graphab and Circuitscape will be compared in the following section.

7.3. Comparison of software using different algorithms

At first sight, when comparing the cumulative current map from Circuitscape with the least-cost paths created by Graphab, both outputs seem to overlap (Figure 32).

To ensure that both software do indeed produce concordant results, the Graphab links were also compared to the habitats pair current maps and the current maps with thresholds applied.

When comparing the Graphab output with the current map between *Bois de Lauzelle* and *Bois des Rêves* (Figure 33) it is rather difficult to determine if the least-cost path overlaps the paths formed by high current intensity. Although the Graphab link follows a route where there are high flow values, there are other high intensity cells on the left of the road (left of the link) and the right of the link. The path to the left of the road seems to be the shortest out of the three, but also has several spots with low current along its route. Nevertheless, it is always safer to analyze the current map while taking account of the surrounding landscape, either with an orthophoto or the resistance surface.

The current map where the thresholds were applied (Figure 34) allows doing that, as the high intensity cells from the current map are still visible but the blank areas between them show the resistance values which facilitates identifying the most appropriate path.

The path on the left of the wide road forces animals following that path to cross a road in four places to reach the other habitat. Apart from that, it seems to pass through needleleaved or broadleaved trees with low resistance, or permanent herbaceous cover. The path that overlaps with the Graphab link requires animals to cross a road on three occasions and only goes through cells with a resistance of 1 mostly, and 2 on a few occasions. The other pathways on the right-hand side of the map require going over artificial coating at least three times and no distinct path appears.

By analyzing the *Bois des* Rêves-habitat 4 link, it is difficult to determine if both software outputs follow the same route due to very narrow gap between the two habitats (Figures 35 and 36). The Graphab path crosses the high resistance road where it is overlapped by least resistant cells (sand color), thus having a less costly path. The Circuitscape pathways cross the road diagonally in several areas, but the wider path is the one crossing at the same spot as Graphab.

The results in Figure 37 seem to show one clear Circuitscape path between the two habitats, taking the same route as the Graphab link. By applying a threshold on the current map, a path almost complete appears between the two habitats, overlapping with the Graphab output (Figure 38). Although there are other potential corridors to the left, they are more discontinuous and lengthier. The Graphab links follow once again the low resistance cells bordering the roads and cross high resistant barriers at their narrowest spots. This causes however the path to go through the center of the roundabout rather than crossing the adjoining roads, which is probably not the most favorable path for animal movement since there is unquestionably more car traffic on the roundabout than on its entrance roads. This proves once again that the outputs produced by corridor planning must be extensively analyzed, and their path not strictly followed.

Finally, it is difficult to establish the most suitable path between habitats 3 and 4 as Circuitscape displays several routes between them (Figure 39). However, with the threshold, a more apparent Circuitscape path appears, although not uninterrupted, following the same route as the Graphab link (Figure 40).

In a general manner, both outputs follow the same path approximately, although it is difficult to say with certainty. Circuitscape and Graphab do however seem to be reliable tools to model connectivity as they both produce consistent and coherent results regarding the landscape and its resistance surface.

7.4. Software purpose of use and shortcomings

As the different tools and their outputs have been analyzed and discussed extensively, the strengths and shortcomings of each tool can be synthesized, and their possible applications reported accordingly.

7.4.1. TerrSet

The purpose of corridor planning in TerrSet was to model a least-cost corridor between a pair of habitats with more flexibility than a standard least-cost link (as the Graphab links), as an ideal corridor width could be specified, and several paths could be computed. However, the software failed to produce rational results, since the paths were of much higher cost than what was achievable, the width of the corridor seemed random at times, and computations were cumbersome and time-consuming. The Planning Tab of the Habitat and Biodiversity Modeler is therefore not reliable and should not be used for corridor modeling.

7.4.2. Graphab

The other tool using least-cost algorithms, Graphab, produces easily readable maps and links coherent with the resistance surface. The computations take little time and do not necessitate high performance hardware, making it easily accessible. The graphical user interface (GUI) and detailed user manual make the software user-friendly and allow exploration of the numerous functionalities of the software. In addition, a minimal habitat patch size can be specified, meaning that habitats don’t need to be identified prior to software usage (unless only connectivity between certain habitats must be assessed), and a maximal path cost can be set so that only realistically accessible paths be produced (although it is difficult to determine what is the maximum path cost that the animal can follow). A wide variety of metrics are also computable in Graphab but were not assessed in this thesis.

However, the software displays several weaknesses. As stated above, a maximal path cost can be specified, but a maximal path length would also be useful to take account of dispersal distance for the species. This option is available when computing links between habitats based on Euclidean distance, but not for cost distance. Furthermore, the four or eight-neighbors connectivity option only applies for the delineation of habitat patches but not for connectivity modeling between them. This detail is odd and incoherent, as two cells can belong to two separate patches but be connected diagonally, thus without leaving any of the habitats. Additionally, there is no possibility to compute multiple paths of increasing cost, which would give interesting alternative routes. For example, a second path between habitats a and b could merge with another existing link between habitats c and b. It would then be interesting to allocate resources for preserving this path rather than the least-costly one, depending on the means available for land use planning.

The features in the software make it operable for most animal species and landscapes extent. Users should however be cautious when studying a species with a dispersal distance greater than the landscape extent, as the created links could exceed the maximum distance that an animal could travel. Apart from this detail, connectivity modeling using this software should be possible for any animal species, whether terrestrial, aerial, or marine, using a resistance surface accordingly.

In terms of land use planning, Graphab paths show the path that would be best to follow but do not provide its approximate width nor allow for certain flexibility in its use. As Graphab shows the path with the least cost, it allows for identifying the areas that are critical to preserve for animal connectivity.

7.4.3. Omniscape

As stated before, the advantage of Omniscape is that it does not necessitate a file where node locations are specified, thus facilitating the connectivity modeling and removing some sort of bias that can happen when identifying habitats. The defined radius allows to pick a dispersal distance for the studied species, and the block size makes smaller computation times achievable. In addition, four or eight-neighbors connectivity options are available.

Nevertheless, there are a few points to keep in mind when using the software. The block size must be defined with consideration for image resolution and extent of the landscape, but the acceptable limit can only be defined through trial and error. Although not having to specify habitat locations is advantageous, the lack of minimal size is a major setback. One way of resolving this issue would be to coarsen the resolution of the used images, thus having habitat cells of greater area, but sacrificing a higher level of detail. Using a different resistance surface, where values representing habitats are much scarcer across the landscape for example, could also partly solve this problem since there would be less influence of individual habitat cells.

Regarding the use of Omniscape, several things could be improved. The software runs on Julia, meaning that it does not have its own GUI. Additionally, there is no built-in INI file builder necessary to run Omniscape, which also deteriorates the user-friendliness of the software. Furthermore, the number of parallel threads to use is an environment variable and must be defined outside of Julia. It is difficult to establish the computation times to produce the current maps, as an issue with parallel threads (probably not related to the software) made it impossible to set the variable to a higher number than one, greatly increasing the computation times. Moreover, the software crashed several times when using a radius higher than 100. Finally, the use of Omniscape requires a computer with high RAM, as computations failed on computers with 8 and 16 Go of RAM due to memory errors.

Although the dispersal distance can be defined, the fact that the user cannot define a minimum habitat area means that the software should be used with caution, depending on the species under consideration and the created resistance surface. The best use of Omniscape is probably for large extent study areas since a dispersal limit can be set and the block size can greatly reduce computation times, in addition to not having to identify the habitats in such a wide area. Since studies to regional scale or higher do not always require a high level of details, less precision in the delineation of habitats would not be as important as in a small landscape.

7.4.4. Circuitscape

One of the main flaws of Circuitscape is that no dispersal distance can be specified, meaning that the size of the study area must be defined according to the species under consideration. The all-to-one and one-to-all modes failed for each attempt, but it is unknown whether that error is linked to the files used or to a software malfunction. In addition, Circuitscape also requires a high computer RAM or memory errors will occur.

As for the software usage, Circuitscape also runs on Julia but has a built-in user interface to build Circuitscape jobs (build INI files). The number of parallel processes to use can be set directly in the builder, which allowed to compute results in approximately one hour.

Apart from the dispersal distance, there is no evident limitation in Circuitscape use. Connectivity could be assessed for any species, as long the extent of the study area does not exceed the species’ distance of dispersal. Working on too large landscapes might however greatly increase computation times and demand high performance hardware.

The current maps display a variety of pathways and a somewhat precise delineation but do not necessarily show the path with the least cost. Circuitscape displays all areas where connectivity is or could be important, and provides information on the landscape elements that could or should be more developed to improve connectivity between habitats in a landscape. It also shows pinch points in the landscape, which are critical to preserve for animal movement.

7.4.5. Combining current maps and least-cost paths

Because both outputs provide different information, they could in fact be used jointly; the Graphab least-cost path gives the best route to follow, and Circuitscape's current map is used to delineate the extent of the path and to allow for different routes to be followed if the user finds some areas more interesting, from an ecological point of view for example. Moreover, the user could be interested in developing or preserving all possible paths that Circuitscape displays, and not be limited by a single route. When dealing with larger study areas, Graphab, which is much faster to run but also provides less detailed results, could be run to identify areas of interest in the study area. Circuitscape could then be used for these interesting areas to model connectivity with more conservation planning possibilities.

Finally, it is important to note that least-cost path and circuit theory algorithms are both based on theories that do not necessarily depict the reality of animal behavior. Least-cost paths assume that the individuals are omniscient, meaning that they have full knowledge of the landscape and thus identify the best path to follow. Circuit theory considers that each movement is independent of the previous one and that current flow is only determined by the probability of moving from one cell to another. Although both these assumptions are not technically correct, current maps and least-cost paths have proven in the past to efficiently model animal connectivity.

8. Conclusion

In the context of global increasing pressure on natural areas leading to habitat loss and fragmentation, and their consequences on biodiversity, computer tools for assessing landscapes' ecological networks were compared. The objective of analyzing corridor planning tools, their purpose of use, and characterizing the connectivity in LLN was achieved by running least-cost path and circuit theory software and analyzing their outputs.

The connectivity analyses were conducted on four habitats surrounding LLN for which animal movement between one another could necessitate navigating through the town.

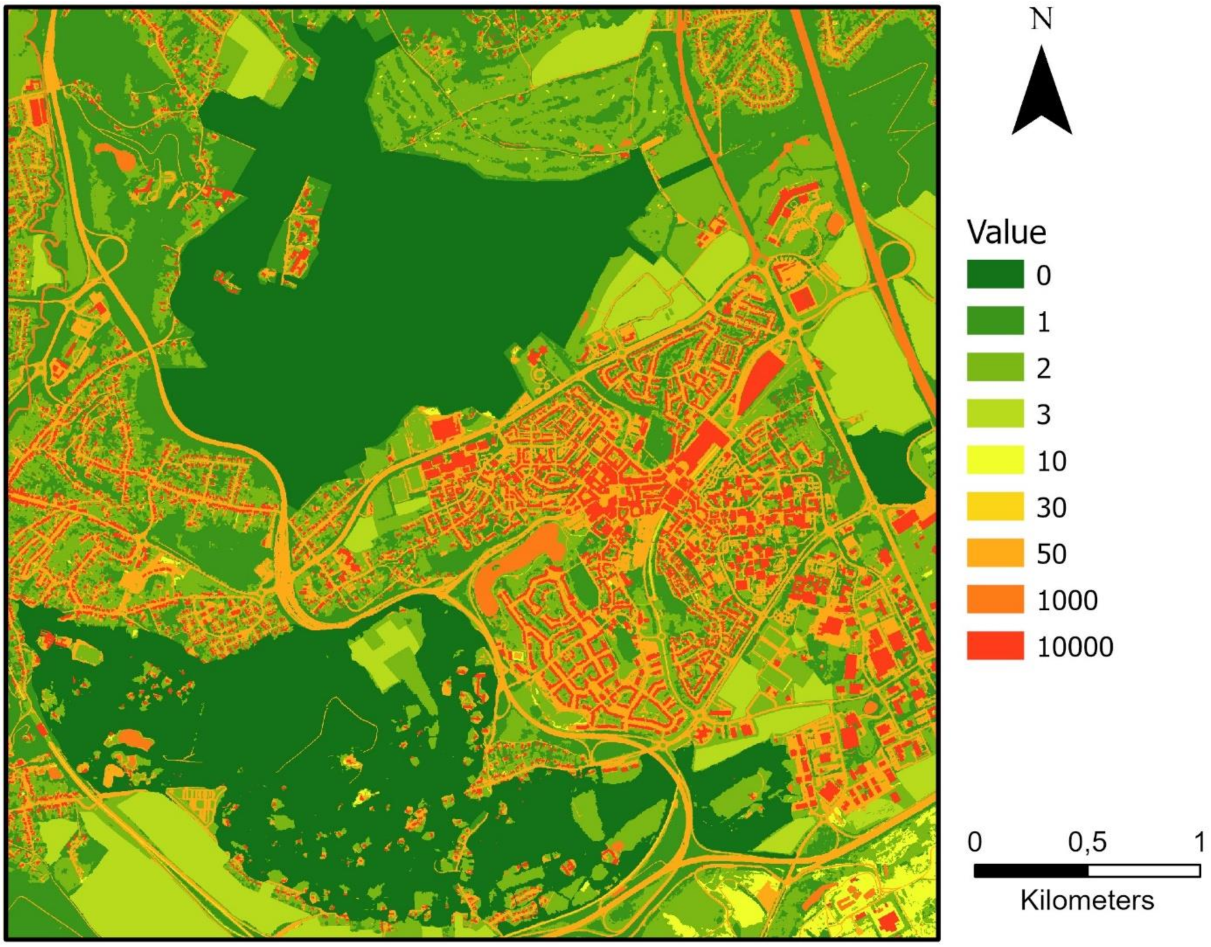
The corridor planning feature in TerrSet was deemed unreliable and should not be used for connectivity modeling. Graphab least-cost paths can be obtained rapidly and do not necessitate high computation power. The outputs are easily readable but also do not provide many details on their own and a dispersal distance limit would be valuable. Current maps from Circuitscape provide detailed analyses of the landscape and the connectivity between habitats but necessitate higher computation time and power, and cannot apply a dispersal distance limit either. Omniscape offers circuit theory features without requiring the user to identify the habitats before its use and allows applying a maximum dispersal distance, but does not provide an option to specify a minimal habitat size which causes bias as the software can identify ecologically unsuitable areas as potential habitats. It necessitates high computation time and power as well.

Since the information they provide is not identical, current maps and least-cost paths could be used jointly in the same study for more comprehensive results and possibly less time-consuming methods. Additionally, it is important to remind that connectivity planning tools only provide an indication of important areas for connectivity, but their results must be critically analyzed and confronted with terrain analyses and their applicability must be reviewed. Moreover, landscapes are ever changing environments and the utilized data must be as recent as possible.

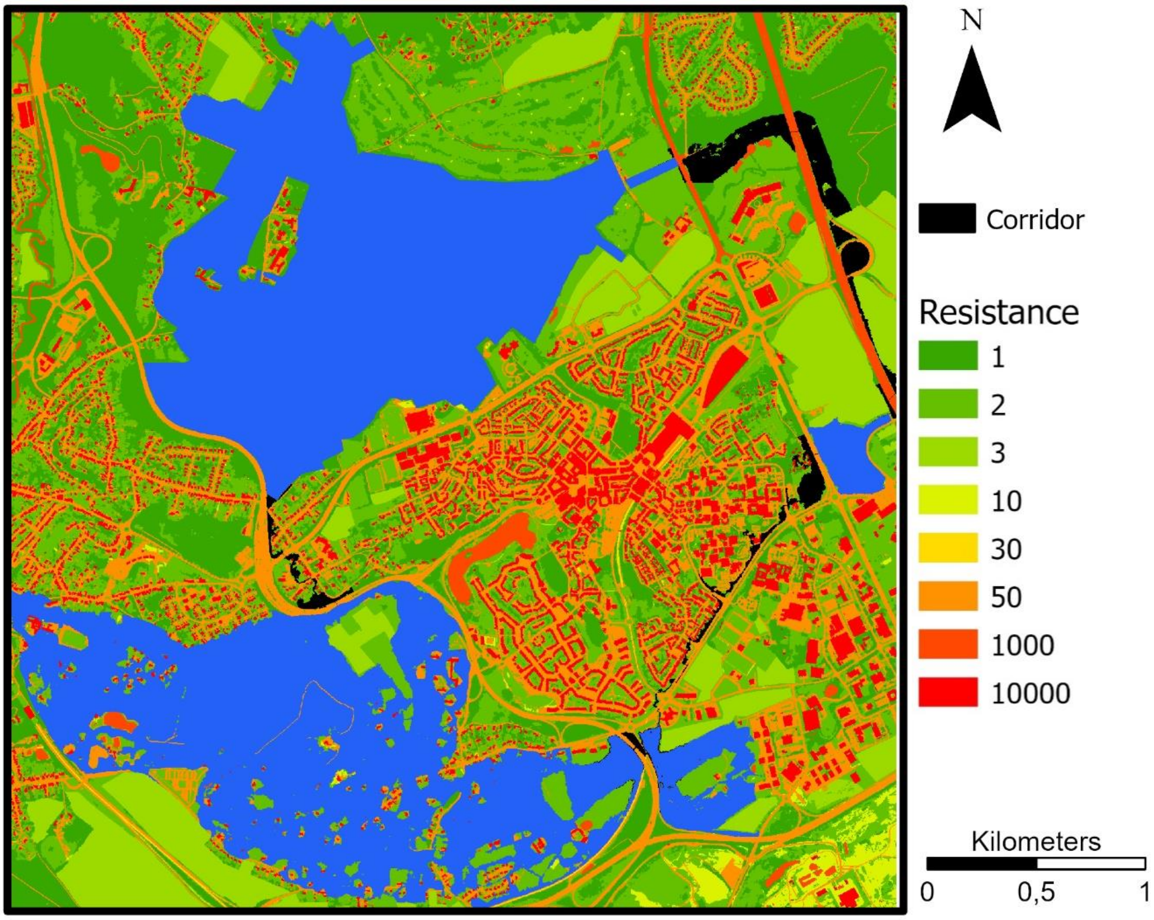
Further work on this subject using landscapes of larger extent with an increased number of habitats would be relevant to fully assess the different tools and their computation capabilities when dealing with larger data volumes. Moreover, more reliable methods to compare Circuitscape high current paths and Graphab least-cost links could be found than the thresholding used in this thesis, since it was difficult to determine with certainty that both outputs overlapped.

To acquire more realistic assessments of the ecological network around LLN, it would be appropriate to construct the resistance surface differently, by assigning different values to the land cover classes based on the ecological value of the landscape cell regarding the monitored species. For example, clusters of cells with needleleaved trees should be assigned a lower resistance than single needleleaved trees, or trees bordering roads. A buffer could also be applied to the roads to increase the resistance of the cells in the surroundings. Furthermore, the resistance values were derived from a study conducted on the white-footed mouse using other land cover classes than in this thesis. Expert knowledge on a small mammal species that is present in LLN would be valuable for determining resistance values for the WALOUS land cover. The topography of the landscape could have been taken into account by using digital elevation models and modifying the resistance values in consequence. Lastly, the land cover file used in this study contains multi-layered land cover classes to account for the overlap of cells from different classes, and could have been used in this work since it offers a better representation of the reality (e.g., safe passages under a bridge).

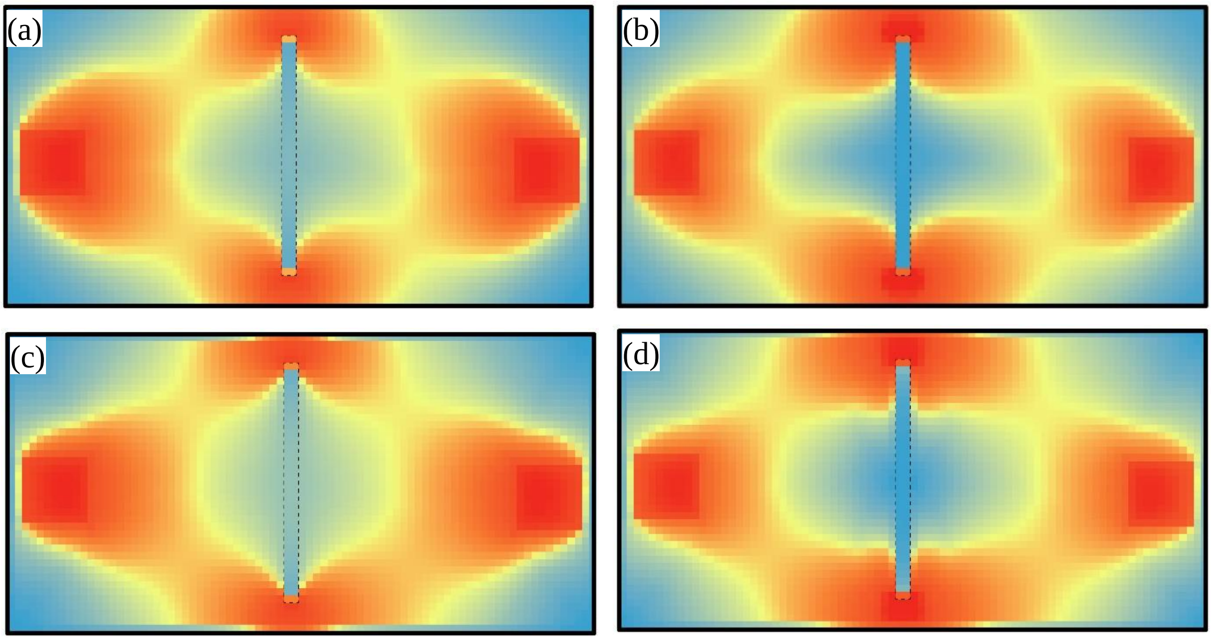
Appendices

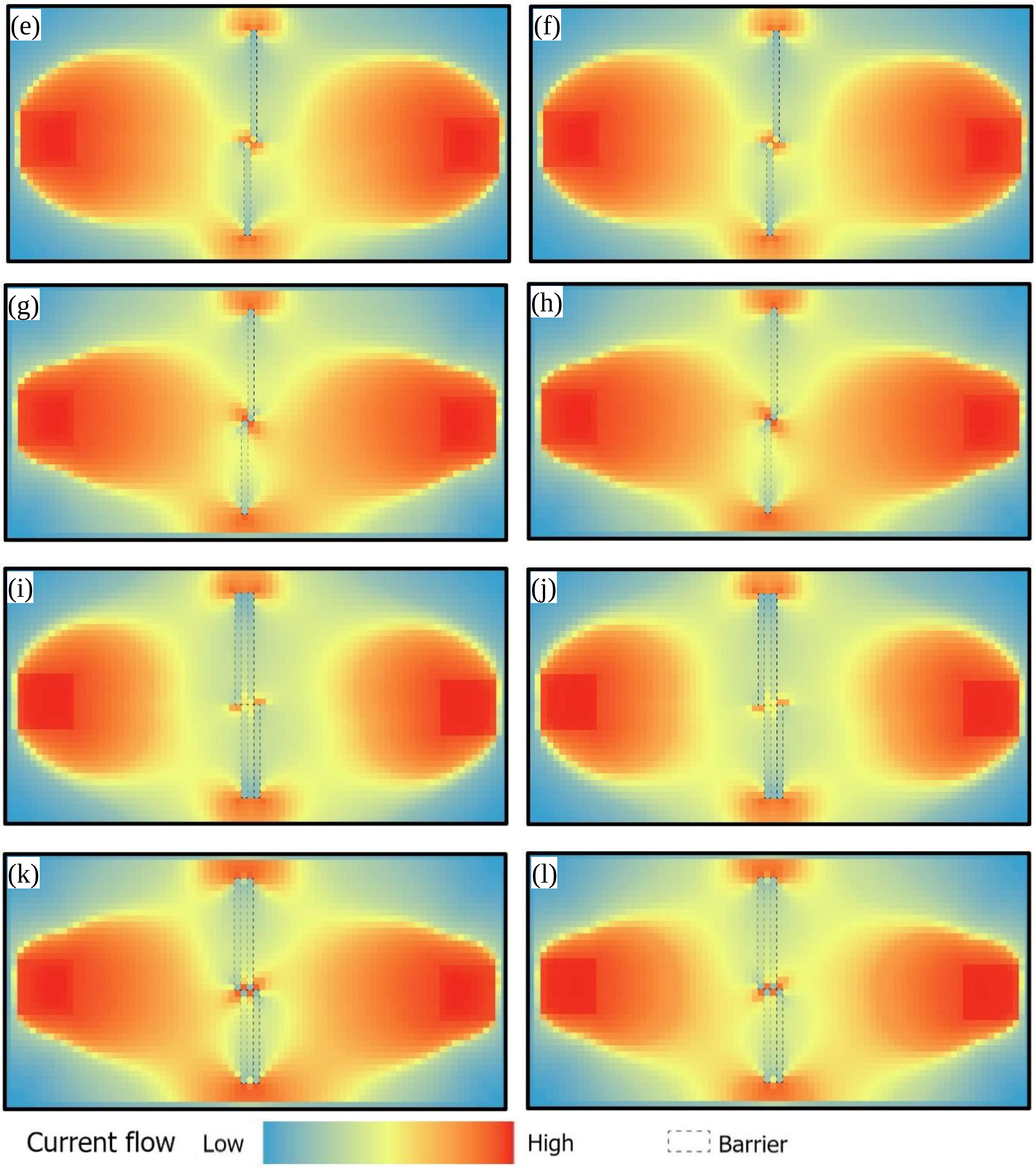


Appendix 1: Landscape map used by Graphab. The values indicate the resistance, where cells with a value of 0 have a resistance of 1.



Appendix 2: 8 m wide TerrSet least-cost corridors





Appendix 3: Omniscape current maps using four-neighbors in landscape *a* with barrier resistance of 50 (a) and 10 000 (b), eight-neighbors in landscape *a* with barrier resistance of 50 (c) and 10 000 (d), four-neighbors in landscape *b* with barrier resistance of 50 (e) and 10 000 (f), eight-neighbors in landscape *b* with barrier resistance of 50 (g) and 10 000 (h), four-neighbors in landscape *c* with barrier resistance of 50 (i) and 10 000 (j), eight-neighbors in landscape *c* with barrier resistance of 50 (k) and 10 000 (l).

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Study of spatial analysis methods for characterizing the green infrastructure of Louvain-la-Neuve

Présenté par Robin Marlier

Biodiversity at the global scale is endangered by human activities, causing habitat loss and fragmentation among others. These processes apply pressure to animal populations, affecting their dispersion, reproduction, and movement between their habitats. In order to preserve these habitats, ecological networks must first be assessed, which is possible by using connectivity analysis tools to characterize the green infrastructure of landscapes.

In this context, this work offers a comparison between four landscape connectivity analysis software relying on least-cost path and circuit theory algorithms: Graphab, TerrSet, Omniscape, and Circuitscape.

The study is conducted on habitats surrounding Louvain-la-Neuve for which movement of small mammals is impeded by the town and its infrastructures.

Small fictional landscapes are also created to extensively understand the functioning of each tool.

To compare the software, input files are created so that every tool uses the same data despite diverse requirements in format and parameters. These files are obtained by precisely delineating the habitats and creating a resistance surface of the landscape through the assignment of resistance values to the WALOUS 2018 land cover classes.

The computations of Circuitscape and Omniscape produce results in the form of current maps displaying the probability of movement for every cell across a landscape, while Graphab computes habitat linkages whose cost to follow is the least among all possible paths, and TerrSet models least-cost corridors of defined width.

Results analysis demonstrate that TerrSet is unreliable to model least-cost corridors. Omniscape produces coherent current maps but is flawed by the lack of minimal habitat size to specify, which biases connectivity across the landscape, and is therefore not an appropriate tool for this thesis. Graphab and Circuitscape both compute consistent outputs and the comparison of their results reveals useful elements. The Graphab least-cost paths provide easily readable results but also lack details as they do not display alternative pathways. The Circuitscape current maps allow identifying all possible paths across a landscape to connect habitats but do not indicate the least costly one and demand more computation power which limits its use for large extent areas.

The choice of software depends on the conducted study; if dealing with a large extent landscape and not needing an extensively detailed result, Graphab is appropriate; if the assessment of connectivity between habitats must be thorough and the volume of data is not too important, Circuitscape might be more relevant. Both tools can also be used jointly in the same study.

Lastly, this thesis could be improved by analyzing larger landscapes containing more habitats, and the connectivity assessment of Louvain-la-Neuve can be enhanced by fine-tuning the resistance surface and taking better account of the landscape layout.

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