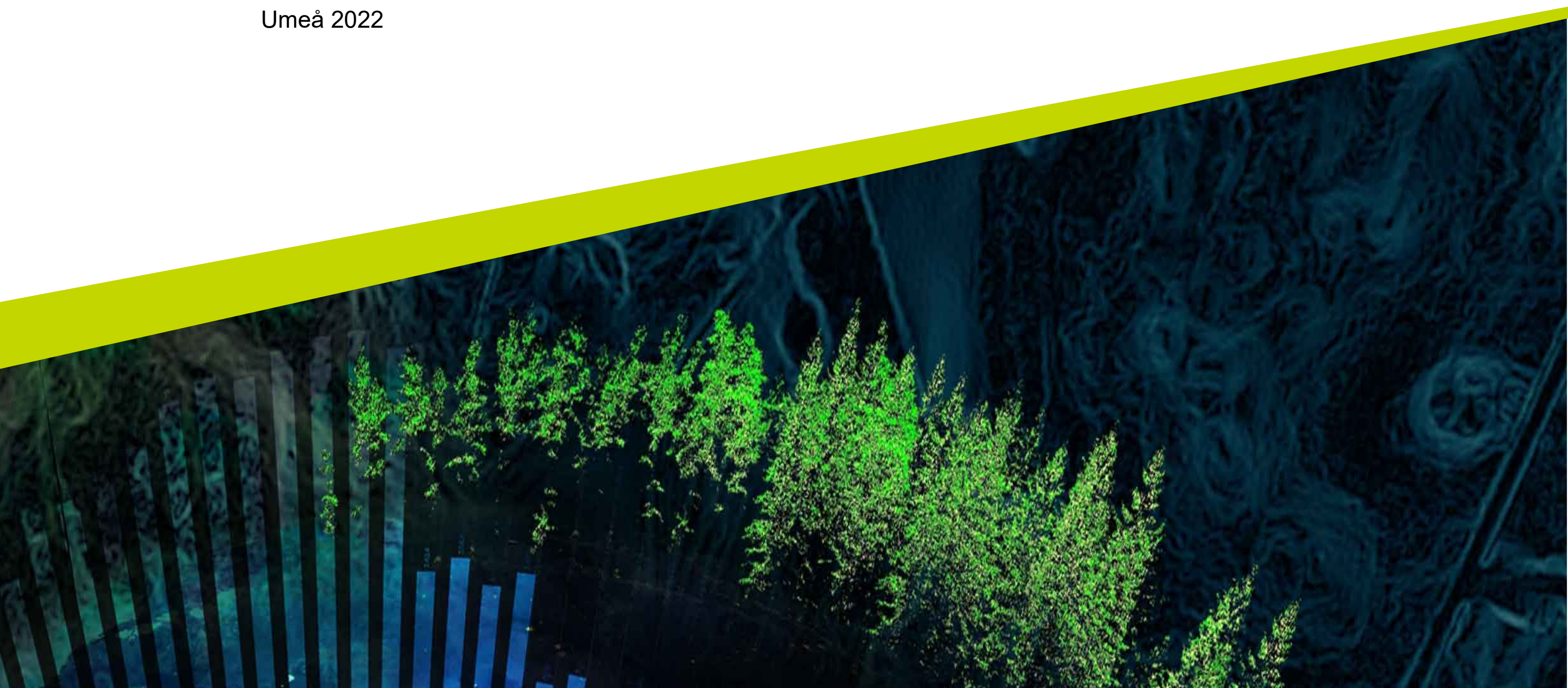
Strengthening green infrastructure

Modelling connectivity between continuity forests with high nature conservation values at the Sveaskog forest holding in northern Sweden

Simon Mattsson

Master thesis • 30 credits
Swedish University of Agricultural Sciences, SLU
Department of Wildlife, Fish and Environmental Studies
Master of Science in Forestry, 2022:25
Umeå 2022



Strengthening green infrastructure – Modelling connectivity between continuity forests with high nature conservation values at the Sveaskog forest holding in northern Sweden

Stärkande av grön infrastruktur – Modellering av konnektivitet mellan kontinuitetsskogar med höga naturvärden på Sveaskogs skogsmark i norra Sverige

Simon Mattsson

Supervisor:	**Johan Svensson, Swedish University of Agricultural Science, Department of Wildlife, Fish and Environmental Studies**
Assistant supervisor:	Wiebke Neumann, Swedish University of Agricultural Science, Department of Wildlife, Fish and Environmental Studies
Assistant supervisor:	Bengt-Gunnar Jonsson, Mid Sweden University, Department of Natural Science
Examiner:	Magnus Magnusson, The Swedish Forest Agency

Credits:	30 credits
Level:	Second cycle, A2E
Course title:	Master’s thesis in Forest Science, A2E – Wildlife, Fish and Environmental Studies
Course code:	EX0968
Programme/education:	Master of Science in Forestry
Course coordinating dept:	Department of Wildlife, Fish, and Environmental Studies
Place of publication:	Umeå
Year of publication:	2022
Serietitel	Examensarbete / Maste´s Thesis
Part number	2022:25

Keywords:	proxy continuity forest, high conservation value forest, connectivity, forest biodiversity, QGIS, Graphab, graph modelling, betweenness centrality

Swedish University of Agricultural Sciences
Faculty of Forest Sciences (S)
Department of Wildlife, Fish, and Environmental Studies

Publishing and archiving

Abstract

The continuity forests of the Swedish boreal landscape have become very sparse due to intensive rotation forestry and human land-use, and the remaining forests are very fragmented. These forests have a high conservational importance as they hold nature values that relies on a long forest continuity. Continuity forests are recognized as essential for biodiversity, both worldwide and in Sweden, and to conserve and strengthen biodiversity it is crucial to map the remaining continuity forests and appoint the appropriate management. In 2017, Metria delivered a dataset that mapped proxy continuity forests (pCF) and provided information about forests that had not been clearcut since the first orthophotos in the 1960s. As they did not have sufficient data, the mapping included large overestimates in some areas, but it is still the best source of data to find continuity forests. I used the pCF-dataset to find core areas (patches) of pCF and combined it with information about high conservation value forest (HCVF) from Metria and Sveaskog. I investigated the share and distribution for different combinations of pCF and HCVF on Sveaskog holdings in 11 regions in northern Sweden. I then investigated how connectivity could be strengthened by developing areas between patches in two selected connectivity study areas. This was done by applying graph theory combined with matrix resistance values. I gave non proxy continuity forests (pCF) categories of forest in this study a higher resistance while prioritized categories such as pCF and HCVF combined were given lower resistance values. I then computed least-cost paths and multiple paths (corridors) between all patches in three different scenarios of land coverage. I repeated this for four different distances in two connectivity study areas and then assessed the importance of paths and patches by applying the connectivity metric index *betweenness centrality* (BC). The results highlight the Sveaskog ecoparks as connectivity hotspots, with the BC-index revealing the connectivity value of both least-cost paths and patches. In addition, the results also show patches currently isolated and how different dispersal distances affect patch isolation. Most importantly, my results show the relative contribution of patches and identify areas that can be further developed to increase the functional connectivity between patches within a larger landscape. The results are thus relevant both for Sveaskog and for other forest owners.

Keywords: betweenness centrality, connectivity, forest biodiversity, Graphab, graph modelling, high conservation value forest, proxy continuity forest, QGIS

Table of contents

List of tables

List of figures

Abbreviations

pCF	Proxy Continuity Forest
HCVF	High Conservation Value Forest
NMD	National land cover Data
SFH	Sveaskog Forest Holding
BC	Betweenness centrality

1. Introduction

1.1 Land use and threats to biodiversity

The anthropogenic expansion with increasing land use demands and an environmental crisis has led to an increased pressure on ecosystems (Shukla et al. 2019). The decrease of functioning ecosystems pose an increasing threat to ecosystem services regarded as critical for both humans and other species (IPBES 2019). Overexploitation of resources, climate change, and land use changes lead to habitat loss and fragmentation resulting in grave negative consequences for biodiversity worldwide (Cousins et al. 2015).

The transformation of the Swedish boreal landscape during the 20th century has been dramatic (Linder & Östlund 1998) with changes leading to more homogeneous and on average younger forest (Ericsson et al. 2000) that do not provide habitat qualities to many old-growth dependent or in other way demanding species (Angelstam et al. 2020). The losses of boreal forests, that are entirely caused by the dominating clear-cut rotation forestry system (Kuuluvainen et al. 2012) are only exceeded by the loss of tropical forest (Hansen et al. 2013).

The loss and degradation of habitats affects all species depending on functional forest ecosystems as it leads to loss of biodiversity (Hanski 2005, 2011). At the same time, habitats remaining become too fragmented to enable species movement between habitat patches which further worsen the situation and enhance an already high risk of species loss (Lindenmayer et al. 2006). Ongoing pressure from rotation forestry also lead to less important elements and structures such as coarse dead wood, when compared to the amounts found in natural forests (Jonsson et al. 2016), which might take a long time to re-establish and are important for many forest species (Nordén et al. 2014). The need for improvement is urgent. The latest report of red listed species in Sweden (SLU Artdatabanken 2020) stated that clear-cutting has a large negative impact on 1400 forest dependent species and that rotation forestry is one of the largest threats to biodiversity in Sweden. Despite the large and intense pressure on the forest, Sweden holds some of the last intact boreal forest landscapes (Potapov et al. 2008, 2017). The intact forest ecosystems with long continuity in the foothills zone of the Scandinavian Mountain Range have been recognized as vital for ecosystem functionality (Haddad et al. 2015; Wilson et al.

2016; Watson et al. 2018) as they often hold high nature conservation values and are important for supporting a high biodiversity (Potapov et al. 2017; Svensson et al. 2020).

Since 2011, the Swedish Forest Agency define continuity forests as forests with nature values that can only be explained by a long continuity of suitable forest environment and substrates within the particular forest or in close proximity to this forest (Skogsstyrelsen 2011). On initiative by the Swedish Environmental Protection Agency, a mapping of continuity forests was conducted for northern Sweden (Ahlkrona et al. 2017); i.e. the boreal biome. They used satellite and laser scanning data to map land coverage that consisted of forests that not had been clearcut since the middle of the 20th century. The nature values of these forests have not been validated by field data and the forests mapped are therefore termed proxy continuity forests (pCF; (Svensson et al. 2019). Deriving from this study of pCF, the study by Svensson et al. (2019) showed that these forests are declining and that the decline is most evident in the inland region below the mountain forest border. A study by Ecke et al. (2013) also revealed large scale fragmentation and decrease of patch size for non-clearcut conifer forests in the Swedish inland.

As the boreal forests have suffered a rapid decline of continuity forest and severe fragmentation, different measures have been taken the last decades to mitigate the loss caused by rotation forestry, such as setting aside forests with conservation values, leaving retention trees, buffers and dead wood (Lindenmayer et al. 2006; Simonsson et al. 2015; Angelstam et al. 2020; Koivula & Vanha-Majamaa 2020). Although these measures reduce the loss of important forest values, they do not enable the forests to sustain the same properties as intact old forests with high continuity (Gustafsson et al. 2010).

A recent approach is the concept of green infrastructure to support functional connectivity between natural forests or forests with a long forest continuity as a mean to strengthen biodiversity (European Commission 2021). Such a strategy is important as long-term conservation is greatly affected by a species ability to disperse and move across the landscape (Fahrig 2007). However, Mikusinski et al. (2021) emphasized that conservation restoration should not be targeted towards continuity forests solely, but also should be distributed throughout the landscape with targeted measures towards specific biotope attributes, such as trees species, in areas where improvements have the greatest impact on connectivity. In addition to targeted tree species measures, Angelstam et al. (2020) pointed out that simply setting forest areas aside for nature conservation does not mean that they will be well functioning in a landscape context as they need to connect to other forests with high conservation values to be well functioning.

The need for protection of continuity forests and improved connectivity within the boreal forest landscape is well-known and targeted in the Swedish environmental goals. However, it leads to questions about how to successfully target protection and conservation restoration (Andersson et al. 2019; Svensson et al. 2022). Research targeting such questions is important as it can help forest owners implement suitable management while preserving naturally occurring ecosystem services, biodiversity and ecosystem resilience. For this reason, areas with long forest continuity and high nature conservation values needs to be carefully mapped, and opportunities to strengthen their network functionality in the surrounding forest landscape matrix need to be investigated

1.2 Modeling landscape connectivity

One method more commonly used to model and assess ecological networks is graph theory. Once core areas (often referred to as patches) of importance are defined and found, these patches can be transformed into nodes with links representing potential connectivity between all pairs of nodes (Bunn et al. 2000; Urban & Keitt 2001; Foltête et al. 2012). To account for landscape heterogeneity the approach of resistance surfaces with values representing possible movement barriers through different landscape types is often used (Minor & Urban 2007; Kool et al. 2013; Clauzel et al. 2015; Sahraoui et al. 2021). This approach makes it possible to find core areas and the probable movement routes (connecting corridors) based upon the assumptions that a landscape is more or less likely to support movement for specific species (Zeller et al. 2012). Adding resistance values to the landscape matrix also makes it possible to find least-cost paths by cumulatively counting all pixel resistance values between two patches (Keitt et al. 1997; Adriaensen et al. 2003; Minor & Urban 2008). In addition to graph theory and least-cost path models, connectivity metrics are often applied to include relative connectivity importance of patches and links and help management prioritization (Bodin & Norberg 2007; Estrada & Bodin 2008; Saura & Torné 2009; Saura & Rubio 2010; Watts et al. 2010).

1.3 Aim

The aim of this study was to assess the connectivity between continuity forest patches with high nature conservation values within the Sveaskog forest holding in northern Sweden. By including connectivity metrics and applying these on patches and links between patches, areas critical for strengthening the connectivity can be detected and management both targeted and prioritized. Such knowledge is critical for Sveaskog as it can support decision-making and improve conservation within their forest holding.

To find the areas of continuity forest with high nature conservation values, and then assess their importance for connectivity, I set up a few research questions. These research questions guided the analyses:

1. *What is the share and spatial distribution of continuity forests and non-continuity forests within the batch of Sveaskog forestland in the Metria proxy continuity-forest mapping?*

2. *Following from continuity forests in (1), what share holds nature conservation values already, and what share would need nature conservation restoration or other directed management actions to develop such values to support the connectivity of continuity forests?*

3. *Following from non-continuity forests with management impact in (1), what share could be subject to initiated nature conservation restoration to develop values that support the connectivity of continuity forests?*

4. *Following from (2) and (3), what spatial arrangement of continuity forests and connectivity forests within the Sveaskog forest holding can contribute to increased functionality of existing valuable forest areas such as Sveaskog Ecoparks?*

1.4 Delimitations

Studying large-scale landscape configuration demands a lot of computer power and time. To limit the study, I have chosen not to add new patches to the study but assess the patches found and the least-cost paths and corridors surrounding these patches. For the same reason, this study will not be able to rank targeted areas but rather point out priority areas in the landscape suitable for further assessment where connectivity metrics for newly added patches can be computed. Besides focusing only on the two main boreal trees, pine and spruce, limitations were made to not include specific management methods such as creation of dead wood but rather find areas with high values and areas suitable for improvements.

It is important to emphasize that this study presents a generalized and simplified model which take forest continuity with known high conservation value forests under consideration and does not focus on one specific forest living species. It rather takes on a general multi-species approach for three large general forest types, “all forest species”, “pine forest” and “spruce forest” as the three forest types analysed. The provided results should thus be taken with this in mind.

Because of time limitation I only had time to make two case studies on the Sveaskog forest holding, one on the border between Dalarna/Gävleborg, and another one in Norrbotten/Västerbotten. If this method is to be adapted, this could be done for all Sveaskog forest holding.

Further, I analysed the Sveaskog forest holding in relation to all other forest land as this study focused on Sveaskog to give them a basis to support decision-making regarding connectivity. However, I only divided pCF in age-classes within the Sveaskog forest holding, meaning that overestimations of pCF were only found within their forests. This might have affected the results. Still, the result from this study is relevant to all forest owners within the study area and not only Sveaskog.

2. Method

2.1 Study area

The study area chosen includes the six northern counties of Norrbotten, Västerbotten, Västernorrland, Jämtland, Dalarna and Gävleborg. These counties have been covered by Metria in their mapping of proxy continuity forests in boreal Sweden (Ahlkrona et al. 2017) which makes them suitable as a target area for this study. The forest landscape consists mainly of either pine forest, spruce forest or mixed conifer forests. In the two northern counties pine forests dominate the productive forests with about 60% in Norrbotten, 46% in Västerbotten, 58% in Dalarna and 46% in Gävleborg. In Västernorrland and Jämtland both spruce and pine forest cover about 29-37% each of the productive forest areas. The percentage of spruce forest covers about 18% of the productive forest in Dalarna and increases with a northwestern angle to a maximum coverage of 37% in Jämtland. Broadleaf forest covers about 5% in all of the counties. The amount of old forest is about 0-5% (with patches of higher amounts) in the coastal areas and increases with a western gradient to more than 20% above the mountain forest border for all study areas. In Norrbotten the amount of spruce forest covers about 9%. Reasons such as latitude, precipitation and natural disturbances promote conifer species over broadleaf species in the northern counties (Bradshaw 1993; Swedish NFI 2022). However, broadleaf forests are less interesting for forest companies and conifer forests are commonly planted on new forest stands. Also, the low interest in broadleaf forest culminated in the usage of herbicides during the mid 20th century to kill broadleaf tree species (Östlund et al. 2022).

Out of the 23 million ha of productive forest in Sweden, Sveaskog owns about 3 million ha (Sveaskog 2022). The largest part (81%) of their forest holding is within the six northern counties. Their forest holding consists mainly of pine forest (64%) and spruce forest (27%). About 76% of forest within SFH is below 60 years old and about 1,3% is forest older than 140 years (Sveaskog, 2022). The study includes forests both above and below the mountain forest border.

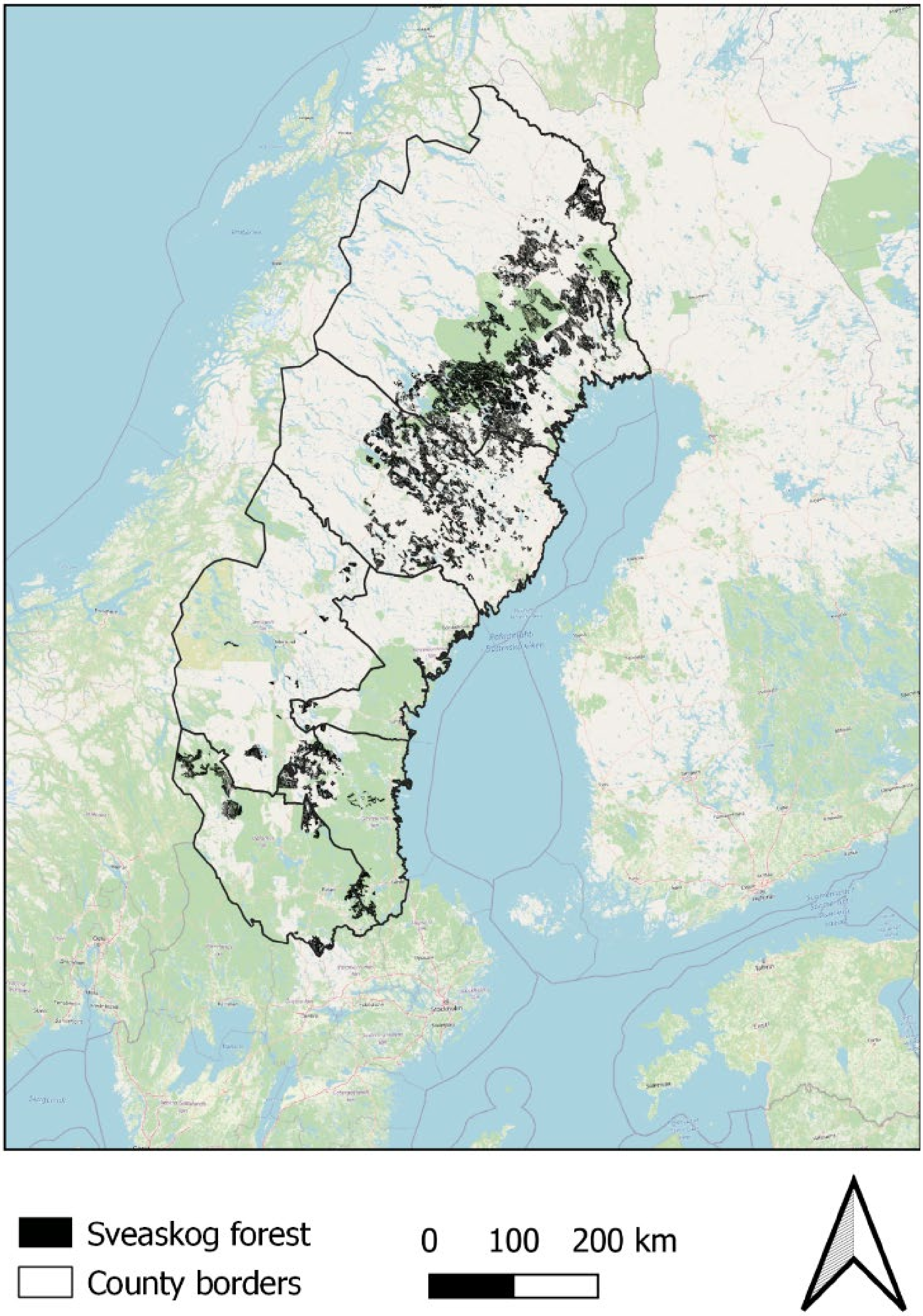


Figure 1. Study area defined by black outline of the six northern counties. The Sveaskog forest holding within the study area is represented by black polygons.

2.2 Input data

2.2.1 Proxy continuity forests

To find continuity forests in the landscape I use a dataset with mapped proxy continuity forest (Ahlkrona et al. 2017). The dataset covering proxy Continuity Forest (pCF) in Sweden was delivered to the Swedish Environmental Protection Agency (Swedish EPA) in 2017. It is targeted towards counties that mainly consists of boreal forests meaning the counties of Norrbotten, Västerbotten, Jämtland, Västernorrland, Dalarna, Gävleborg and Värmland. Metria uses orthophotos available since the 1960s and satellite-data available from the 1970s to search for changes in tree cover. The analysis covers 20 million hectares (ha) of forest land and 16 million of these consist of productive forest. The pCF-dataset has a 10x10m pixel size but is generalized with the smallest size of pCF-patches being 0,5 ha and wider than 20m to exclude edge effects from images. They use the Swedish Forest Agency's definition of continuity forest which states that forest that has never been clearcut can be considered continuity forest as it holds nature conservation values explained by long forest continuity. The definition includes forests that have not been clearcut since they were first registered in an orthophoto or a satellite image, meaning that most forests established before industrial rotation forestry in the 1950s can be considered continuity forests as long as they were large enough to be considered forests in the first analyzed orthophotos. This would result in that the youngest forests considered pCF could be about 70 years old if no changes in tree cover are detected since.

Using land survey data for verification they conclude that their model includes about 90% of forest older than 70 years in Norrbotten, Västerbotten, Jämtland and Västernorrland, while 80% of forest in Dalarna and Gävleborg is included. About 5,5 million ha is mapped as pCF on productive forest land and another 2,3 million ha is pCF on non-productive forest land. Most of the forests mapped as pCF on productive forest land is below the mountain forest border (4,6 million ha). One issue is that their model does not include if nature conservation values are established in areas mapped as pCF, but simply detects forest with forest continuity if there are no changes in tree coverage between the first and the second round of orthophoto analyzation. A second issue with relevance for this study is that forest aged between 50-70 years occasionally has been included in the mapping as pCF as it might have grown old enough to be visible on the first historical orthophotos in the 1960s, resulting in an overestimation of pCF. A similar issue is that images are lacking in some periods for different areas, meaning that a forest could have been clearcut and then be fully grown again in the next period where images are accessible, also resulting in overestimations of pCF.

As the pCF-dataset is one of the core inputs in my analysis, I will try to improve the estimate what can be considered as overestimations of pCF within the Sveaskog forest holding. This would then improve the results of my connectivity analysis as the data input are more reliable.

2.2.2 Sveaskog stand data

This study uses information from Sveaskog using stand information regarding nature conservation values, stand age and land classification. The information is in vector format and generalized in polygons according to their stand delineations. All stands classified with any conservation class in Sveaskog stand data is considered to consist of high conservation value forest and included in the category of HCVF throughout this study.

2.2.3 High Conservation Value Forest

One important dataset for this study covers high conservation value forests (HCVF). I used a dataset from the Swedish EPA produced by Bovin et al. (2017) covering known areas with HCVF. This dataset covers the same 7 northern counties as the pCF-dataset and is thus very compatible with the study area analyzed. The dataset covers known areas of HCVF with and without formal protection and includes national parks, nature reserves, nature conservation agreements, biotope santuaries (biotopskyddsområden), nature management areas (naturvårdsområden), Natura-2000 areas, key woodland habitats from both the Swedish Forest Agency (SFA) and large forest companies, proposed and planned nature reserves, the SFAs objects with high conservation values and state-owned natural forests identified by the Swedish EPA (Naturvårdsverket 2004).

2.2.4 National landcover data

To make connectivity analyses targeted on forest and specific tree species I used the information about land coverage in Sweden (NMD) from Naturvårdsverket (2020). They apply the forest definition from FAO (2020) meaning that tree height must be over 5 meter and coverage more than 10 percent in an area spanning over more than 0,5 ha. Using satellite images and laser scanning Sweden is divided into 25 land coverage classes with a raster of 10×10m pixel solution. Out of these, 16 classes are directed at forest and the remaining 9 classes is other types of land coverage such as open wetland, farmland, water, open land or exploited land. The forest cover classes includes if they grow on wetland or not, but for this study I regroup the trees independent of if the trees grow on wetland or not, making 8 forest classes instead of 16.

Table 1. Datasets used in the analysis with data format, coordinate reference system, source, and what date that each dataset has been downloaded.

Description	Format	Coordinate reference system	Date	Source
Proxy continuity forest	**Raster (.tif)**	**SWEREF99 TM**	**2019-04-10**	**Swedish EPA**
Sveaskog stand data	**Vector (.shp)**	**SWEREF99 TM**	**2021-06-15**	**Sveaskog**
High Conservation Value Forest data	**Vector (.shp)**	**SWEREF99 TM**	**2018-11-21**	**Swedish EPA**
Administrative borders	**Vector (.shp)**	**SWEREF99 TM**	**2022-01-28**	**The Swedish Mapping, Cadastral and Land Registration Authority**
National Landcover data	**Raster (.tif)**	**SWEREF99 TM**	**2022-01-28**	**Swedish EPA**

2.3 Analyses

2.3.1 Focus of the analyses

I made two main analyses in this study. The first analysis aimed to find share and distribution of pCF and HCVF within SFH and was also part of the data preparations for the second analysis. Finding shares and distribution of pCF and HCVF was needed to answer study questions 1-3. In the second analysis I studied connectivity at two interesting areas based on the findings of the first analysis. Connectivity metrics were calculated to assess the spatial importance of targeted patches and their contribution to connectivity in the landscape. The second analysis was targeted towards study question 4 to see what areas needs to be protected and what areas can be developed to strengthen current patches of importance and increase connectivity within the selected study areas.

2.3.2 Preparing data for analyzing share and distribution of HCVF and pCF

The analyses were performed in five steps with the first, second and third step being considered as preparatory steps (figure 3).

In the first step I focused on extracting data from the SFH-dataset using the open-source software QGIS (QGIS Development Team 2022) and Microsoft Excel. I used the attribute table of the SFH-dataset and selected stands with *selecting with expression* and created 5 new raster layers. One of the new vector layers consisted of all pixels classified as forest within SFH. This layer was created so that I could separate all Sveaskog forest from all other forests owned by other forest holders. A second layer included all Sveaskog forests with assigned nature value classes, including those already selected by Sveaskog as restoration forests despite that they might not yet be HCVF. Three more raster layers were made with information from Sveaskog based on mean stand age to classify pCF in three age classes. With the first age class I wanted to find overestimations of pCF and made a layer with all forests below a mean stand age of 70 years as these forests are too young to be considered pCF within the pCF-mapping by Metria. The second age class was to find pCF with a mean stand age of 140 years or older as forest of this age within this northern study area is considered old forest in the Swedish environmental goals (Swedish NFI 2022). The third age class was to find all other pCF that are not classified as overestimations or old forest. Therefore, this age class ranges between 70-139 years.

In the second step I wanted to create a 10x10m raster map of the study area with each pixel having binary information about all input layers and additional information about land coverage. For this reason, the first part of the second step was to assign binary codes for the input layers so that all information used from the different layers would remain when rasterizing and merging. For the dataset with pCF I used the tool *Reclassify by table* and gave all pixels mapped with pCF the value of 10000000 while all other pixels missing pCF were assigned the value 0. For the layers deriving from vector datasets (table 1), I made new fields in the attribute tables of each layer and called this field “Binary”. I then assigned a specific value to the new Binary fields of each layer (Appendix 1) which would be used to see what features from my input layers each pixel in the landscape includes. The NMD dataset was already built up in a similar way for land coverage (including tree species) and therefore I kept the NMD-codes for now.

After I had assigned values to all layers, I used the conversion tool *Rasterize (vector to raster)* on all vector layers and selected the Binary field to be used as a burn-in value and a pixel size of 10x10m. This gave all pixels in each raster layer only the assigned value while excess information not used for this study from each vector layer were removed. In this way I created 6 new raster layers with binary numbers in addition to the existing pCF-, and NMD-rasters, making it 8 raster layers in total (Appendix 1). I then used the tool *Merge*, and the pixel values from the 8 overlapping raster input layers were summarized into a new raster with 1131 unique combinations of pixel values (Appendix 2). The large number of combinations were explained by keeping the NMD-dataset which created many different possible combinations.

To only achieve information relevant to this study I created a mask layer from the "administrative borders" layer by first selecting the 6 counties in the study area from the attribute table and then created a new vector layer with the selected counties. I then used the extraction tool *Clip raster by mask layer* with the mask layer. The masked raster layer with summarized pixel values (hereafter called *sum.raster*) were given the same resolution and no data values were set to 0. To see the number of pixels with unique values I used the tool *Raster layer unique values report* which exports the entire layer into an excel-file. From this file I received the number of each unique pixel value and the area in m^2 covered by these as an output.

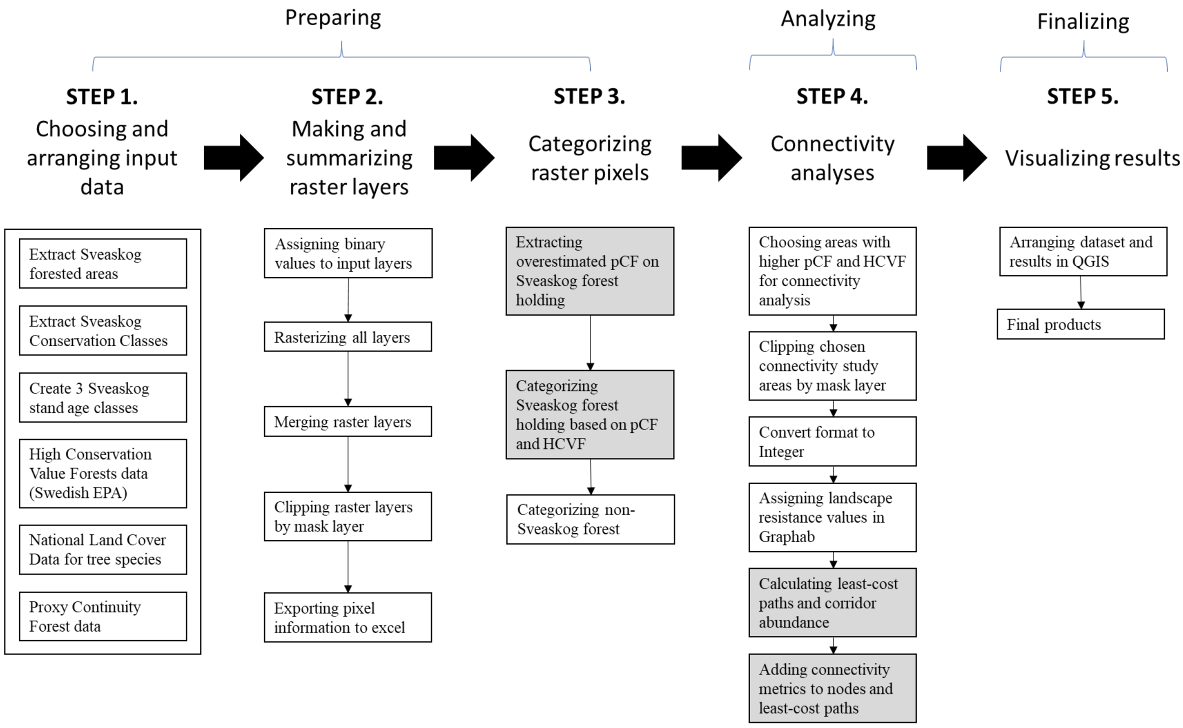


Figure 2. Five steps with brief explanatory boxes for the order of preparations and analyses made within each step. Step 1 and step 2 are preparatory steps. Step 3 represent the first analysis, step 4 the second analysis and step 5 represent a final step taken for arranging datasets and visualizing results of both analyses. The grey boxes in Step 3 are to be considered as results concerning shares and regional distribution of pCF and HCVF within the Sveaskog forest holding. The grey boxes in Step 4 are to be considered as main results from the study regarding connectivity.

2.3.3 Regional shares of pCF and HCVF within SFH

To estimate the share of pCF and HCVF within SFH I worked with *sum.raster* in Microsoft Excel. The first thing I did was to transform the area from square meters to ha for each unique pixel value by dividing the areas of all unique pixel values with 10000.

As the unique pixel values functioned as codes for inherent features, I divided the Sveaskog forest holding into a few different categories (figure 3). I first created three categories *non-pCF*, *pCF 70-139 years* and *pCF 140+ years*. The fourth class was regarded as overestimations of pCF and named "*pCF < 70 years = overestimated pCF"*. Due to issues occurring among edges when transforming vector layers to raster layers (Congalton 1997), some areas gave pixels with values representing interfering data. For this reason, I made the fifth category *QGIS pixel mapping errors*. These pixels were removed from the next steps in the analysis. I included land coverage information from NMD to simplify data preparations in the connectivity analyses.

I excluded eventual QGIS pixel mapping errors, I then further divided the four categories in another step and added information about HCVF which resulted in the categories *non-pCF without HCVF*, *non-pCF with HCVF, pCF 70-139 years without HCVF, pCF 70-139 years with HCVF, pCF 140+ without HCVF* and *pCF 140+ years with HCVF* (figure 3). All pCF with HCVF were eventually grouped into one category as they were considered of equal value for the connectivity analysis. To set SFH in a greater landscape perspective, all other forest not owned by Sveaskog were divided into categories in the same way. However, as I did not use data about mean stand age for forest outside of SFH, all pCF outside of SFH was only divided into two categories, pCF with HCVF or pCF without HCVF. This also meant that no category for overestimations of pCF was made outside of SFH.

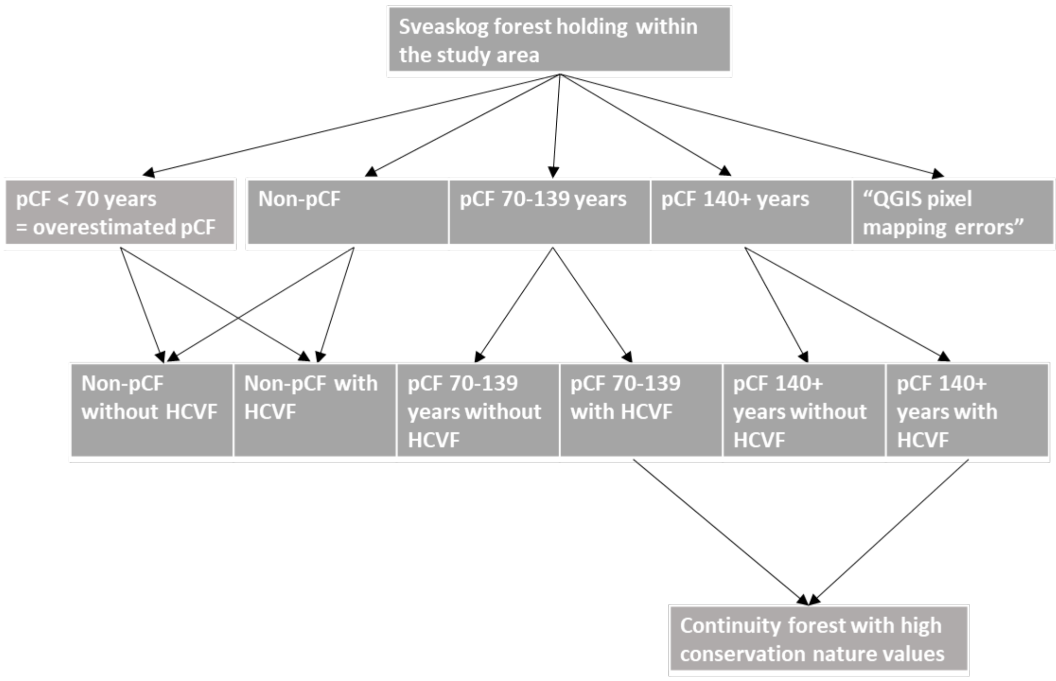


Figure 3. Sveaskog forest holding divided into categories using stand ages provided by Sveaskog and information about HCVF from the Swedish EPA and Sveaskog to find core areas of pCF with HCVF. Overestimated areas of pCF were considered "forestry forest" and further divided depending on presence of HCVF.

2.3.4 Finding the distribution of pCF and HCVF

To investigate the spatial distribution of pCF and HCVF within SFH I divided the entire study area into 11 regions in QGIS based on municipality locations. These 11 regions were either considered mountainous, central inland, or coastal (figure 4) The decision was made together with Sveaskog representatives as this type of division might reveal the spatial distribution of pCF and HCVF in a western-eastern as well as a northern-southern gradient while maintaining administrative borders. The regions were made by selecting chosen municipalities from the attribute table of the *administrative borders* vector layer and then creating new vector layers from the selected municipalities.

Before finding the distribution of pCF and HCVF within SFH, additional preparations were made in QGIS. The previously merged raster layer *sum.raster* with 1131 combinations were reclassified again with *reclassify by table* into the final 6 categories of pCF and HCVF only this time I divided these categories and used the information about land coverage from NMD, resulting in 34 categories for SFH and 21 categories for all areas not owned by SFH (Appendix 3). I gave each category a new simplified value. All pixels not featured in each category were given a no data value of 0. All of the 55 raster layers were then merged into a new layer called *category.raster*. I clipped this merged raster using the raster extraction tool

Clip raster by mask layer for each of the 11 regions and exported the information to excel using *Raster layer unique values report*. The distribution of categories between regions was analyzed and shares of each category within each region were calculated in excel (figure 7, figure 8).

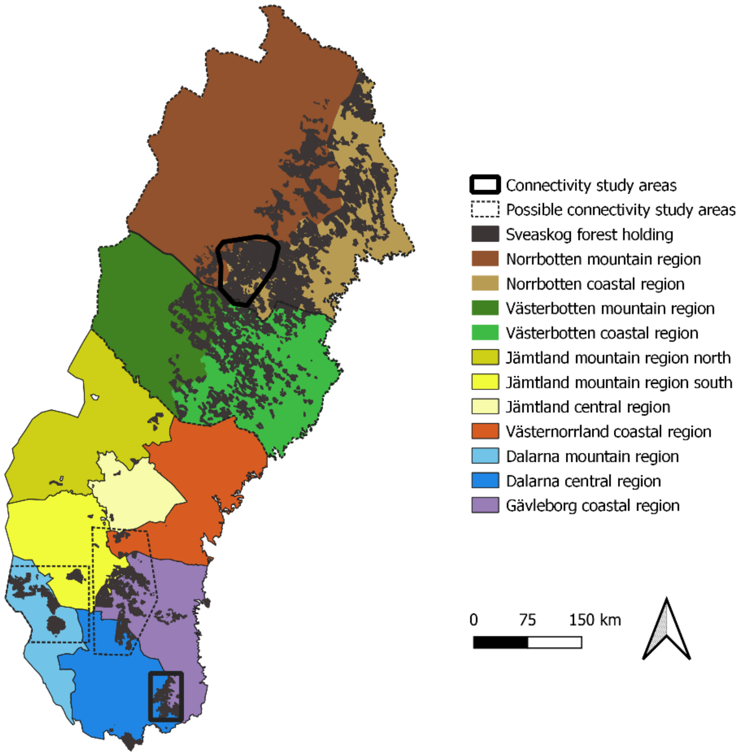


Figure 4. The 11 municipality regions based on nearness to the coast, the mountain region or categorized as central. Two areas (marked with thick black lines) are selected for further connectivity analyses. One is located between the regions in Norrbotten, stretching across the border to Västerbotten. The other connectivity study area is located between Dalarna and Gävleborg. Four additional possible study areas are marked with dotted lines. One possible connectivity study area cover the entire county of Västerbotten and another connectivity study are the county of Norrbotten. The other possible connectivity study areas cover areas with large proportions of SFH in Dalarna and Gävleborg.

2.3.5 Approach for the connectivity analyses

The goal with the connectivity analysis was to find core areas (hereafter *patches*) which consisted of both HCVF and pCF combined. When the patches were found I wanted to assess the connectivity value for each of these patches in relation to all other patches found within each studied network. Another target with the connectivity analysis was to find possible least-cost paths of HCVF or pCF between the patches that can be targeted for further development into HCVF to support the connectivity of the ecological networks. This was done with least-cost paths by assigning resistance values to the different categories of pCF and HCVF.

To investigate connectivity based on categories of pCF and HCVF I defined patches with pCF and HCVF larger than 3 ha as core areas for a “general species”. This approach was applied throughout the connectivity analysis and can be seen as a multispecies approach which was used (Watts et al. 2010; Gurrutxaga et al. 2011) to find features in the landscape with importance for many species, instead of finding features that are important for a single species. I used this approach and set up three scenarios with different land coverage. The first scenario focused on all forest land coverage. As the study areas mainly consist of pine forest, spruce forest or mixed conifer forest this first scenario can be regarded as relevant to find features for groups of species dependent on any conifer forests. The second scenario focused on pine forest and thus focused on features valuable for pine forest species while the third scenario focused on spruce forest and thus features valuable for spruce forest species. Each scenario was repeated four times with different distances to include difference in dispersal abilities of the “general species”. All analyses were repeated for three distances of a) 1000m, b) 3000m, and c) 5000m. For each scenario, I also made an analysis with 20000m dispersal distance to reveal all least-cost paths and BC of nodes if the study area were fully connected, to see if this can assist in assessing future development.

2.3.6 Software – Graphab

The connectivity analyses were made by applying graph theory and least-cost paths using QGIS and the plugin version of the software Graphab v.0.6.1 (Foltête et al. 2012, 2021). Graphab is developed by a French team of researchers and is used in several studies (Foltête et al. 2014; Clauzel et al. 2015; Huang et al. 2021; Tang et al. 2021; Tiang et al. 2021) to investigate connectivity in ecology. It has been developed to integrate construction and visualization of ecological networks into one software. Although other programs such as GuidosToolbox (Vogt & Riitters 2017) or Conefor (Saura & Torné 2009) can be combined to receive similar results and are more commonly used, I decided to use Graphab as it seemed more user friendly due to the possibility to visualize results simultaneously within the program. Besides the standalone version, a plugin version for QGIS was recently developed (Foltête et al. 2021) with all the basic tools of the standalone version. Although the standalone version of Graphab has a wider variety of tools than the QGIS plugin version and can compute larger landscape resistance maps with smaller patch sizes. However, the processing time within the standalone version was very long and all tools needed for this study were available in the plugin version. For this reason, I used the plugin version for the main computations and only used the standalone version for visualizing the distance conversion, which were done automatically within the plugin version of Graphab.

2.3.7 Preparing data for the connectivity analysis

Before making the second analysis, data must be prepared to be compatible with Graphab. First, a few of the 11 regions were excluded while other regions were targeted for further connectivity analyses. Five interesting areas were identified with high shares of pCF and HCVF. These areas had large proportions of SFH (figure 4). Out of these five interesting areas I decided to further investigate two, based on the time available for the study. The first connectivity study area is located between the border of Dalarna and Gävleborg and is dominated by pine and mixed conifer land coverage with high amounts of pCF and HCVF. In the northeastern area a large Sveaskog ecopark is located. The second connectivity study area chosen is in a central part of Norrbotten/Västerbotten with proximity to the mountain forest border. The shares of pCF and HCVF were higher than in the Dalarna/Gävleborg study area. Within this study area are four large Sveaskog ecoparks.

I made new vector layers in QGIS which covered the two areas selected for connectivity analyses, and used these vector layers as extraction masks on the layer "*category.raster*" which consisted of my categories of pCF and HCVF for different land coverage. Finally, I converted the data type of the resistance to Int16 which only allows (and ensures) that numbers range from -32768 to 32768 as required in the Graphab software. This was done using the GDAL raster conversion tool *Translate*.

2.3.8 Selection of patches

The first step when setting up a connectivity analysis with Graphab is to import a prepared landscape map and select patches. I used the maps prepared for the two chosen connectivity study areas. The patches (called habitat patches in Graphab) of pCF with HCVF was set to a minimum size of 3 ha (figure 5a). The minimum patch size of 3 ha was chosen because I studied large areas and had to limit patches to shorten computation times and prevent computation errors in the QGIS-plugin version of Graphab. Due to the large number of patches in the study area of Norrbotten/Västerbotten the minimum patch size had to be increased to 6 ha to keep computation processes reasonable. Still, the distance of 5000m could not be computed correctly due to the large amount of connected nodes and therefore only the distance of 1000m and 3000m area computed in the Norrbotten/Västerbotten connectivity study area.

I repeated the selection of patches for each of the three land coverage scenarios in both connectivity study areas. In the scenario including all land coverage, patches with land cover of "temporarily not forests" were considered unfavorable and pixels with "not forest" were considered as barriers. In the second and third scenario, all non-targeted tree species were considered as unfavorable and excluded as patches. When computations were finished patches and a set of links between all pairs of patches were calculated within the software.

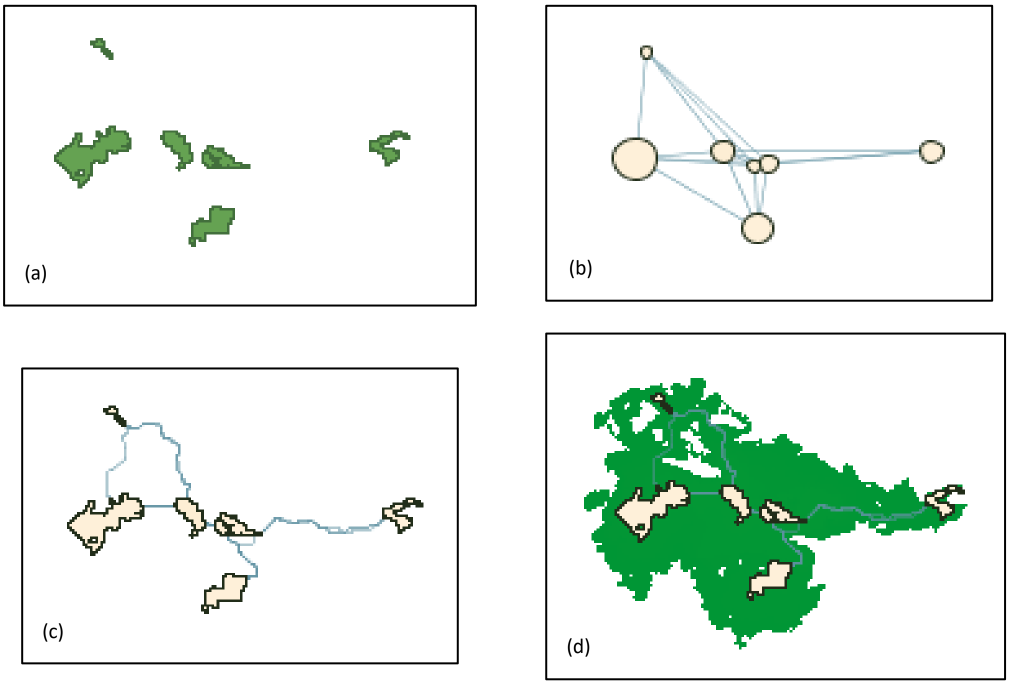


Figure 5. Example of patches, nodes, links, least-cost paths, and corridors. Image a) illustrate patches (green areas). Image b) illustrate transformation of patches to nodes with circle sizes corresponding to the capacity (area) of the patch and links between all the nodes. Based on the heterogeneity of the matrix, c) illustrate least-cost paths between patches. Image d) illustrate patches with least-cost paths and corridors (green area) between patches, representing all cumulative cost-paths below a threshold between patches.

2.3.9 Setting the landscape cost-resistance values

The second preparatory step done in the connectivity analysis was to assign cost-resistance values to each of the categories of pCF and HCVF in the landscape. Assigning resistance values takes builds on the theory that certain species or groups of species prefer to disperse through the landscape at a "cheap" cost. As this is a very theoretical approach, especially when having a multispecies approach, I am using previous literature as guidance for setting the resistance values. However, different studies use alternative approaches when they set resistance values to a landscape matrix. While some studies (Clauzel et al. 2015; Sahraoui et al. 2021) use logarithmic values, others use expert-groups to make species-specific connectivity analyses and assign resistance values relevant for a single species (Driezen et al. 2007; Gonzales & Gergel 2007; Stevenson-Holt et al. 2014; Bourdouxhe et al. 2020; Tiang et al. 2021). I base my settings partly on the findings from these studies to find patches and important areas in this study. Following Clauzel et al. (2013) I decided to set cost-resistance values with quite contrasting values (table 2) to delineate between suitable and unfavorable areas. As this was not a species-specific study but a study investigating development of pCF with HCVF in three scenarios I assigned different categories of pCF and HCVF resistance values between 1-50 which was considered appropriate for finding areas which can develop into pCF with HCVF. I gave pCF with HCVF the lowest resistance of 1, as these areas already have developed continuity and contain high nature conservation values. Areas mapped as “forestry forest with HCVF” was given the second lowest resistance of 10 as these areas have established high nature values but needs time and perhaps further management to be developed into continuity forests. After discussions with Sveaskog about their future managing plans with setting aside old forest in some regions, I assigned pCF older than 140 years without HCVF with the third lowest level of resistance of 25 to prioritize old pCF over younger pCF. The resistance value for younger pCF without HCVF was set to twice the resistance level of old pCF with a resistance value of 50 in order to still prioritize pCF of any age over other forests. Finally, I gave all forests without pCF or HCVF a resistance value of 100. The resistance value for areas temporarily not consisting of forest was set to 500 and everything that is not forest, such as roads, water, and open areas, were given a resistance value of 1000. When making connectivity analyses for only spruce forest or only pine forest all other forest types are considered unfavorable matrix and the resistance value for these areas are set to 500 resulting in very different resistance surfaces in the landscape (figure 6). The final resistance values set are similar to those used by Gurrutxaga et al. (2011) in their study of forest networks.

Table 2. Resistance-cost depending on forest class and forest species as mapped by the national landcover data. Areas classified as temporarily not forest, such as clear cuts, are regarded as unfavorable. For connectivity analyses targeting specific tree species, non-included tree species are also regarded as unfavorable, receiving a high resistance value.

Type of landscape	pCF	High-conservation values	Function	Resistance
All forest or targeted tree species	Yes	Yes	Habitat	1
	No	Yes	Suitable	10
	Yes	No	Suitable- (140+y)	25
	Yes	No	Less suitable (70-139y)	50
	No	No	Not suitable	100
Temporarily not forest	-	-	Unfavorable	500
Not forest	-	-	Barriers	1000
Non-targeted forest tree species in tree species-specific analysis	-	-	Unfavorable	500

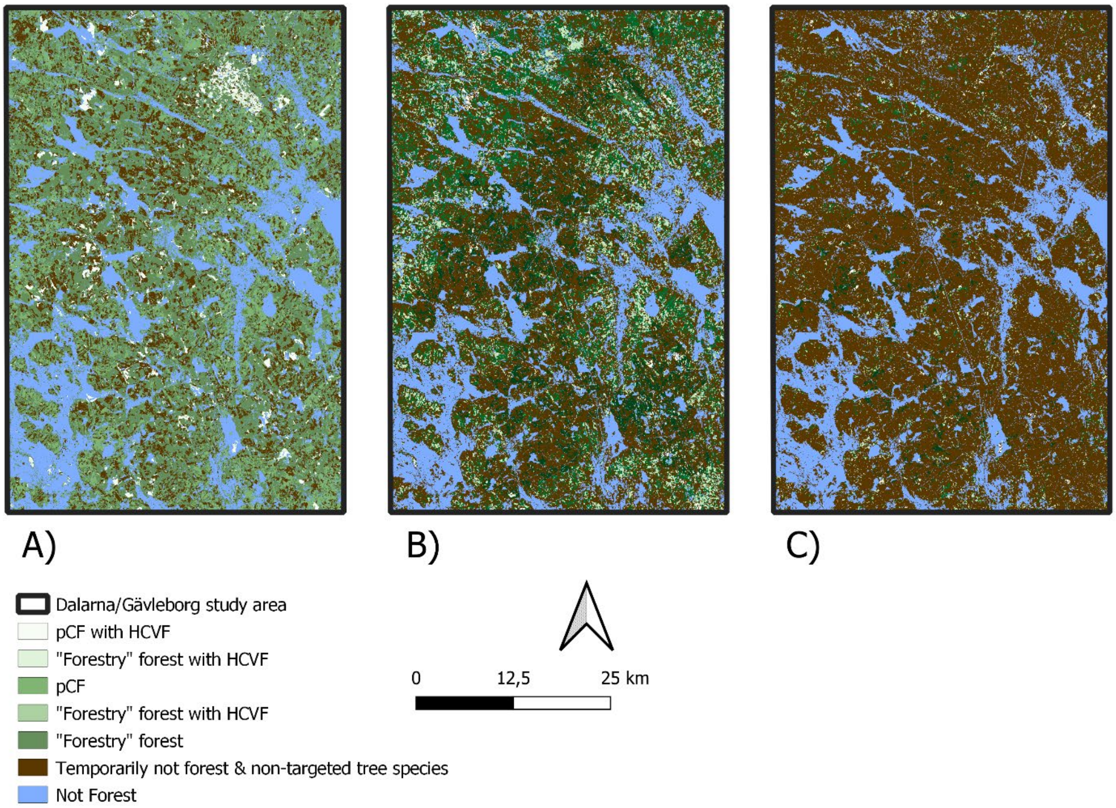


Figure 6. Resistance maps for A) all forest land coverage, B) pine forest land coverage, C) spruce forest land coverage. For B) and C), all non-targeted tree species land coverage is set to the same values as temporarily not forest. Blue areas are considered barriers while brown areas are considered as unfavourable matrix.

2.3.10 Producing a graph with nodes, links, and least-cost paths

The third step was to produce a graph which would be used to transform all patches into *nodes* with *links* between pairs of patches below my set threshold distance (figure 5b). This was done for each scenario where I pruned all links exceeding the set distance. When pruning graphs on a cost-resistance linkset (appendix 4), Graphab automatically convert Euclidean distance in meters to a cost-distance relative for each scenario using the cumulative cost of all pixels between to paths by adding values of each pixel in the resistance map between all pairs of patches. This conversion and calculation of *least-cost paths* (figure 5c) was done in all scenarios for all pairs of patches below my threshold distances.

2.3.11 Making threshold corridors between patches

In the fourth step *corridors* below the threshold distances between all pairs of patches were calculated (figure 5d). They are similar to least-cost paths but instead of revealing single path they reveal areas below a threshold. I consider the corridors as possible movement zones (Rayfield et al. 2010) to compliment the least-cost paths as the least-cost paths can change routes quite drastically depending on resistance settings, while corridors covering thresholds are more stable with different settings (Pinto & Keitt 2009). The corridors are built using the resistance landscape maps, making it possible to build corridors not only with Euclidean distances but with cost-distances which takes the landscape heterogeneity of different categories with pCF and HCVF into account. With this approach corridors expand shorter through areas with unfavorable features and further through areas with suitable features making it useful to find core areas between two patches or in proximity to patches.

In the QGIS plugin version of Graphab I converted Euclidean distances to estimated cost-distances automatically when calculating threshold corridors with the cost-resistance landscape maps. I used the approximate cost-distances for 1000m, 3000m and 5000m (appendix 5) and calculated all corridors for each scenario. These corridors were then styled with singleband pseudocolor in QGIS to reveal how many times a pixel is covered by a corridor. All pixels without any corridors were made transparent to only illustrate areas lower than the cost-distance thresholds in each scenario. In the Norrbotten/Västerbotten study area I included a vector layer with Sveaskog ecoparks to illustrate overlap between the corridors and the ecoparks and how the ecoparks in this study area could be further developed.

2.3.12 Adding connectivity metrics to nodes and least-cost paths

To assess the importance of the patches within each scenario I used connectivity metrics. For this study I decided to use the Betweenness Centrality index (BC) (Freeman 1978). The BC-value is commonly used to identify important patches and links between patches (Bodin & Norberg 2007; Minor & Urban 2007; Estrada & Bodin 2008; Zetterberg et al. 2010; Baranyi et al. 2011) as it calculates the number of least-cost paths between any pair of patches that passes through a targeted patch. In this way the centrality of any targeted patch within a network of patches is measured at a local level (appendix 6). Although other indexes are available, the BC metric has been identified by Bodin & Norberg (2007) as a good way to find important stepping-stones within an ecological network, so I used this connectivity metric.

I assumed a maximum dispersal probability of 0.05 in all scenarios for all distances. This was repeated in both study areas. As the BC-value can be hard to interpret with a large span of values that differs greatly between scenarios, I divided all nodes using *Jenks natural breaks* (Jenks 1967) in QGIS, as it can be used to find the most relevant patches relative to each scenario (Huang et al. 2021) by finding natural breaking points in a dataset. Using a method with equal quantiles is not relevant as patches that are isolated will have no BC-value. The betweenness centrality index was illustrated by adding a white to red color scheme on the nodes with dark red indicating very high values and white illustrating lesser value.

I divided all least-cost paths into 5 levels ranging from very low to very high with the QGIS *equal quantiles* as all least-cost paths between patches have a BC-value. The least-cost paths were then given a thickness depending on their value were thicker lines indicates higher values.

3. Results

3.1 Stratification of the Sveaskog forest holdings

Approximately 298 429 ha of Sveaskog forests were mapped with a combination of high conservation value forest and proxy continuity forest (Fig. 7). About 200 254 ha were also mapped as pCF without HCVF. About 125 160 ha was mapped as HCVF but not as pCF and hence mapped as non-pCF. The largest category was non-pCF forest without HCVF which equals about 1 910 238 ha. In total 245 693 of forest was found to be overestimated pCF.

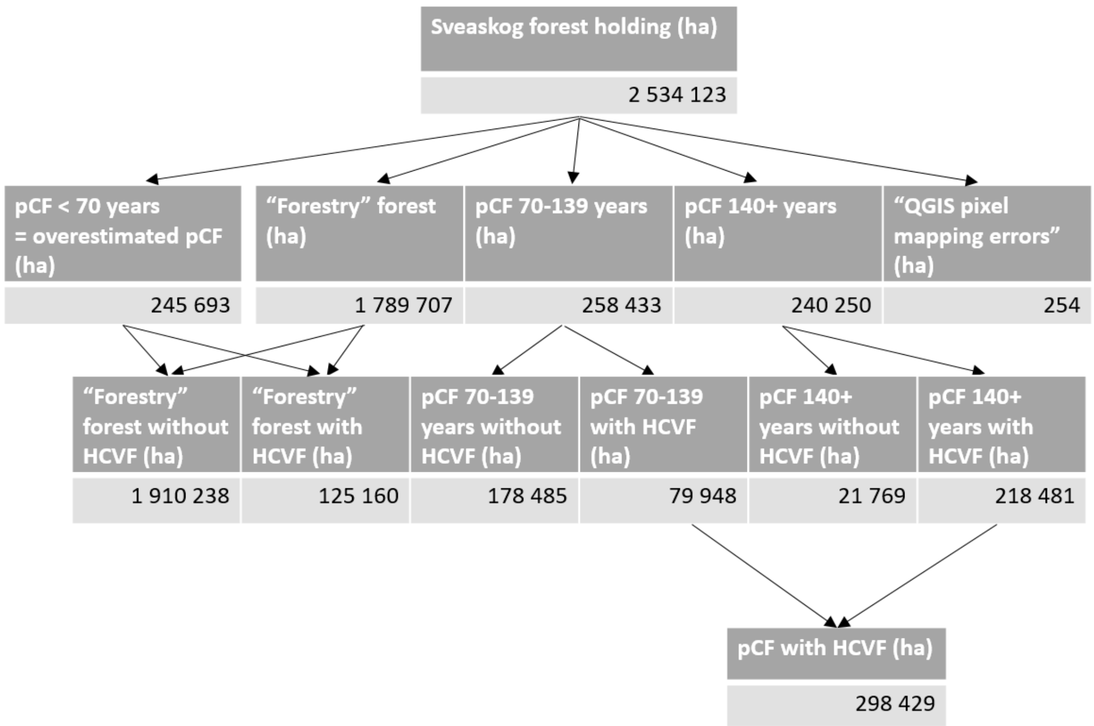


Figure 7. Distribution of HCVF, pCF and "forestry" forest within the Sveaskog forest holdings. Overestimated pCF is further categorized into "forestry" forest with or without HCVF qualities.

The spatial distribution of the six different categories across the 11 regions reveals that the largest amount of HCVF and pCF is located in Norrbotten and Västerbotten (Fig. 8). However, all mountain regions except the Jämtland southern mountain region stands out with higher shares of pCF and HCVF compared to the inland or coastal regions. The Norrbotten and Dalarna mountain regions (37% and 35%) have the largest shares of categories with pCF or HCVF. In the Norrbotten mountain region, more than 80 000 ha are pCF and HCVF combined, with almost 70 000 ha being older than 140 years. Both regions in Dalarna and the region of Gävleborg has a high share of younger pCF (70-139y) and HCVF combined compared with the other regions.

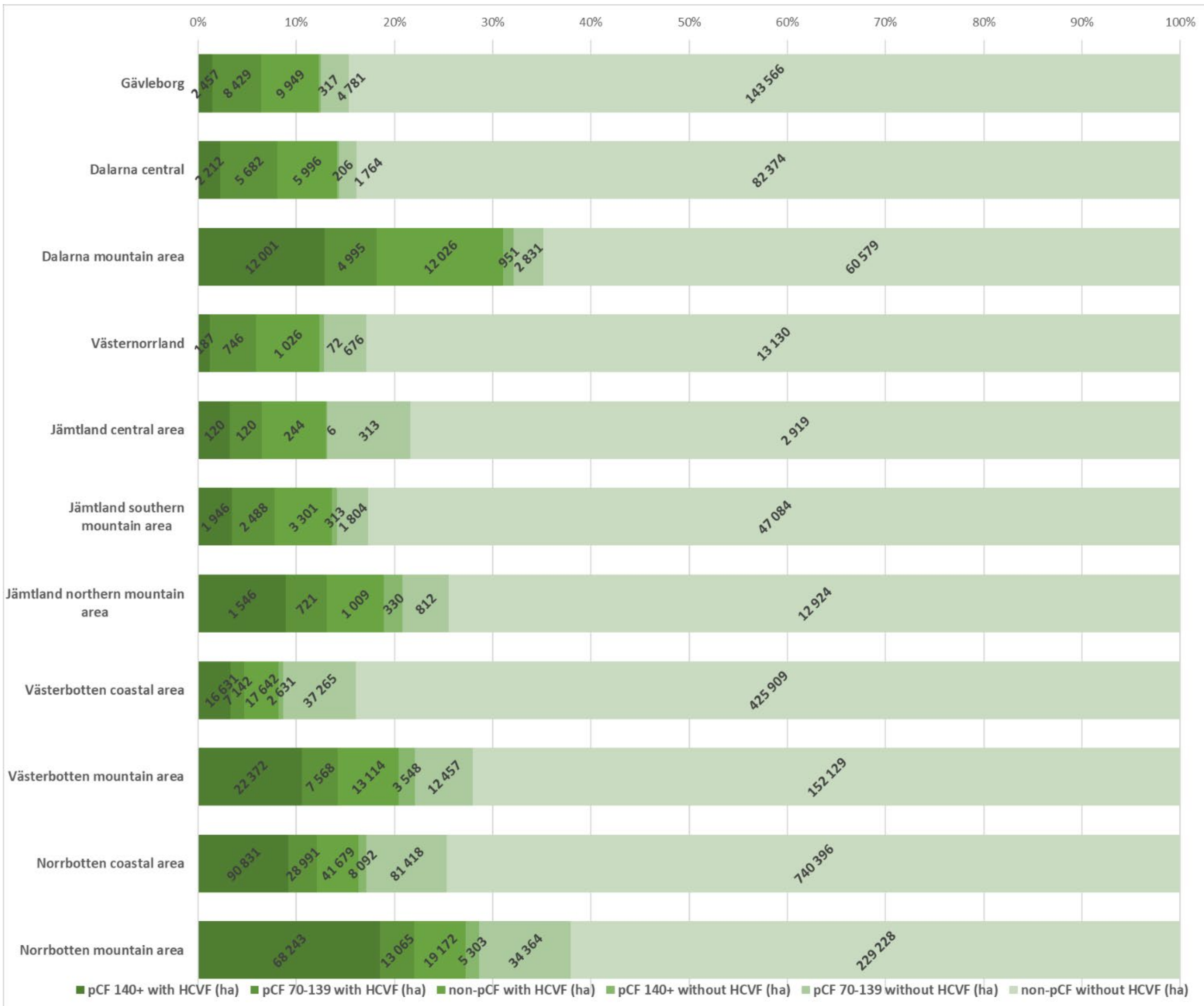


Figure 8. Spatial distribution within each region with amount (in ha) and shares of the different combinations of pCF, HCVF and "forestry" forest.

3.2 Dalarna-Gävleborg case study

3.2.1 Patches of pCF with HCVF

The analyses on different land coverage revealed a large difference in number of patches for the different forest types. The analysis on all forest land in Dalarna/Gävleborg shows 396 patches of pCF and HCVF combined larger than 3 ha (figure 9). Out of these, 106 patches consist of pine forest and 72 of spruce forest.

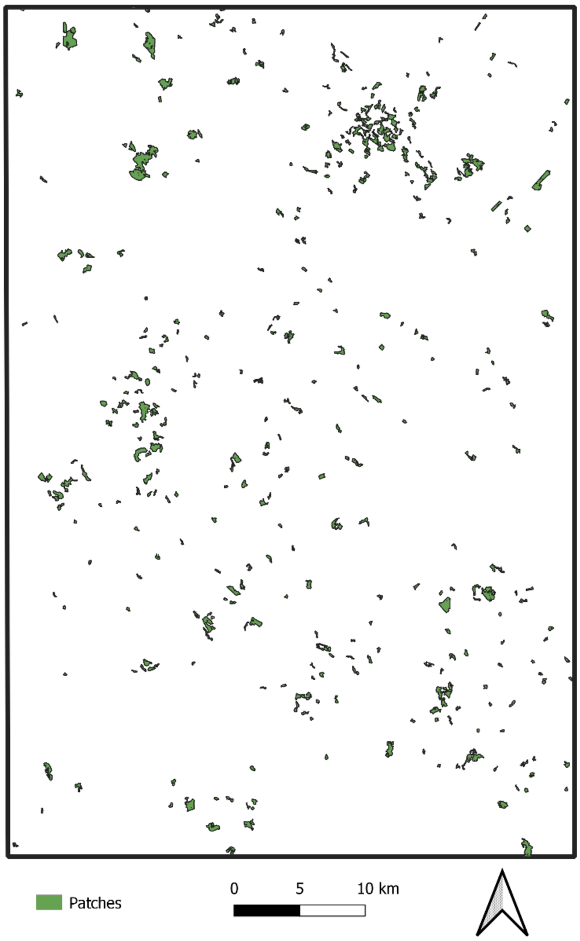


Figure 9. All forest patches (both pine and spruce) larger than 3 ha of pCF and HCVF combined for the Dalarna-Gävleborg case study

3.2.2 Betweenness centrality for patches and least-cost path

The entire case study consists of one connected component when applying a network dispersal distance of 20 000m (Fig. 10). All least-cost paths between patches and nodes are connected. Their relative BC-importance is more evenly spread throughout the landscape compared to shorter distances where the network is divided into isolated components. The northeastern area is a hotspot with the highest BC-values in all scenarios. Patches in the pine forest scenario have the highest values in the northern part of the study area, while the spruce forest scenario have some patches in the central western area and also in the southern area.

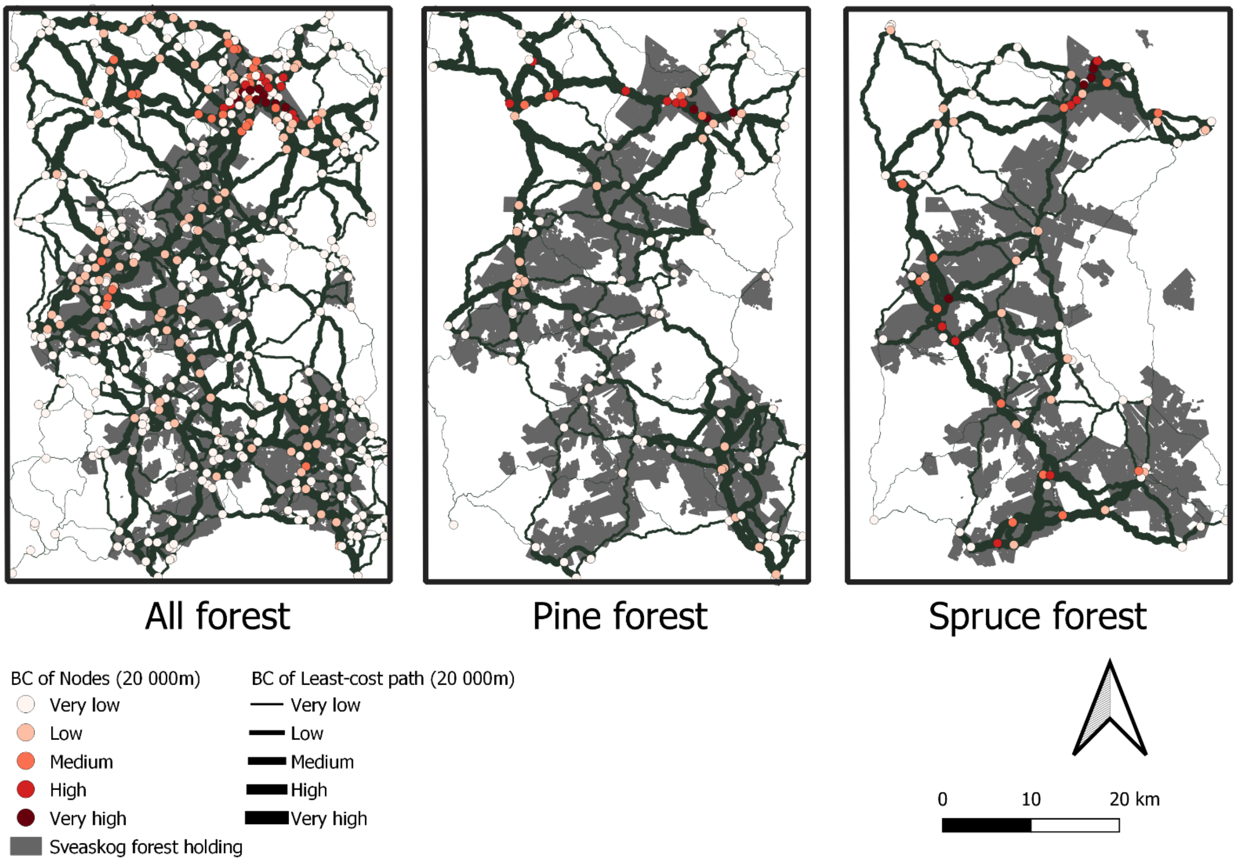


Figure 10. Connectivity importance for patches (represented by nodes) of pCF and HCVF combined for ***all forest, pine forest and spruce forest, respectively,*** *analysed with least-cost paths for a dispersal distance of 20.000m. The patches are divided in 5 classes with Jenks natural break (Jenks 1967) while the least-cost paths are divided in 5 classes with an equal count in each class. Grey area in the background shows the Sveaskog forest holdings.*

Applying 5 000, 3 000 and 1 000 m distances, the nodes with the highest BC-values and thus least costs can be found in the northeastern corner for all three distances (Fig. 11). The number of nodes per component differs between the distance thresholds from about 15.23 for the 5 000m distance, 5.35 for the 3 000m distance and 1.76 for the 1 000m distance. Increasing distances reveal important least-cost paths stretching mainly from northwest to southeast, i.e. diagonally across the case study. At the 5000m distance, some of the larger components detected in the 3000m analysis have been connected.

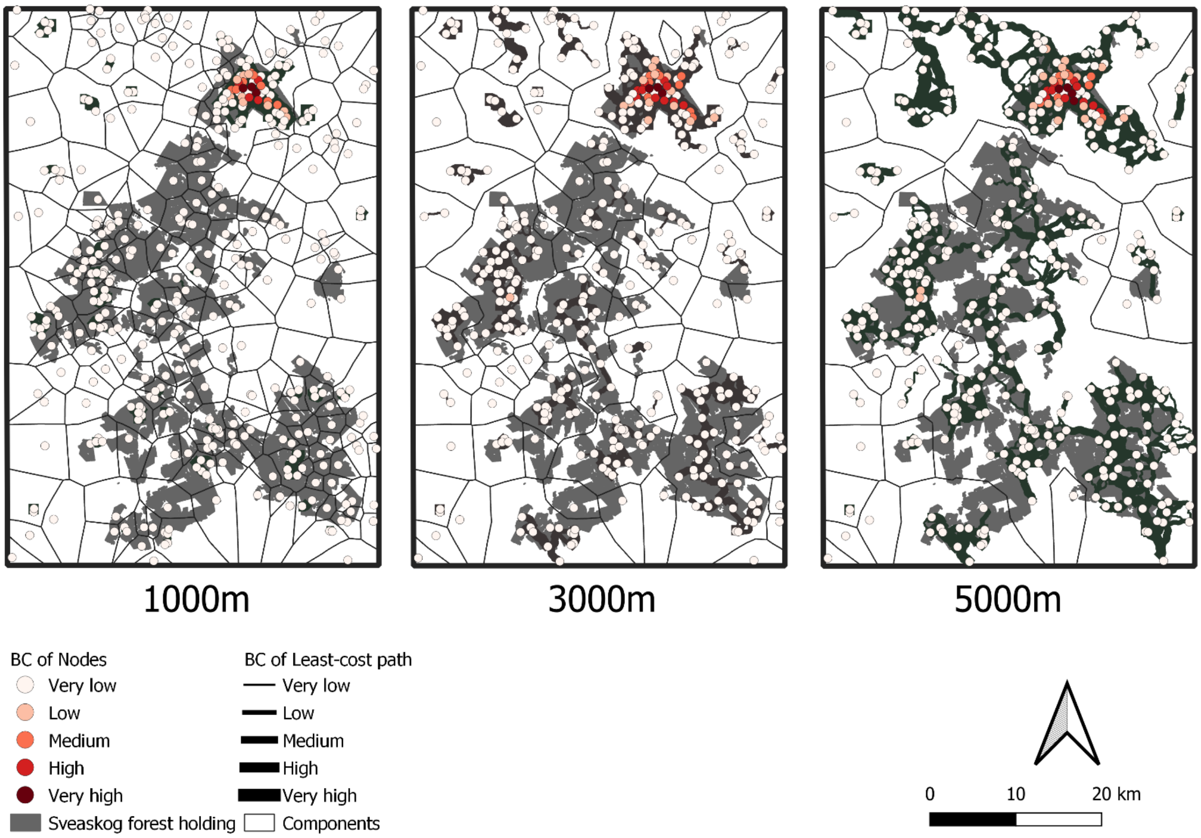


*Figure 11. Connectivity importance for patches of pCF and HCVF combined for **all forest** (represented by nodes) and least-cost paths for the three different distances. The patches are divided in 5 classes with Jenks natural break while the least-cost paths are divided in 5 classes with an equal count in each class. Grey area in the background shows the Sveaskog forest holdings.*

The BC-analysis for pine forests (Fig. 12) shows patches with the highest BC-values in the northeastern corner for all distances. More nodes are connected with an increasing distance, with three additional components having patches with a BC-importance above "very low". However, these areas are still considered to be of low BC-importance compared to the patches in the northeast. The number of nodes per component is 2.59, 1.68 and 1.38 for the 5000m, 3000m and 1000m distances, which thus for pine only differs a lot compared with all forests (see Fig. 12). Most high or very high BC-values for least-cost paths are found in the northern part of the study area, especially in the northeastern hotspot. A few least-cost paths are found with a medium BC in the southestern component when scaling up to the 5000m distance.

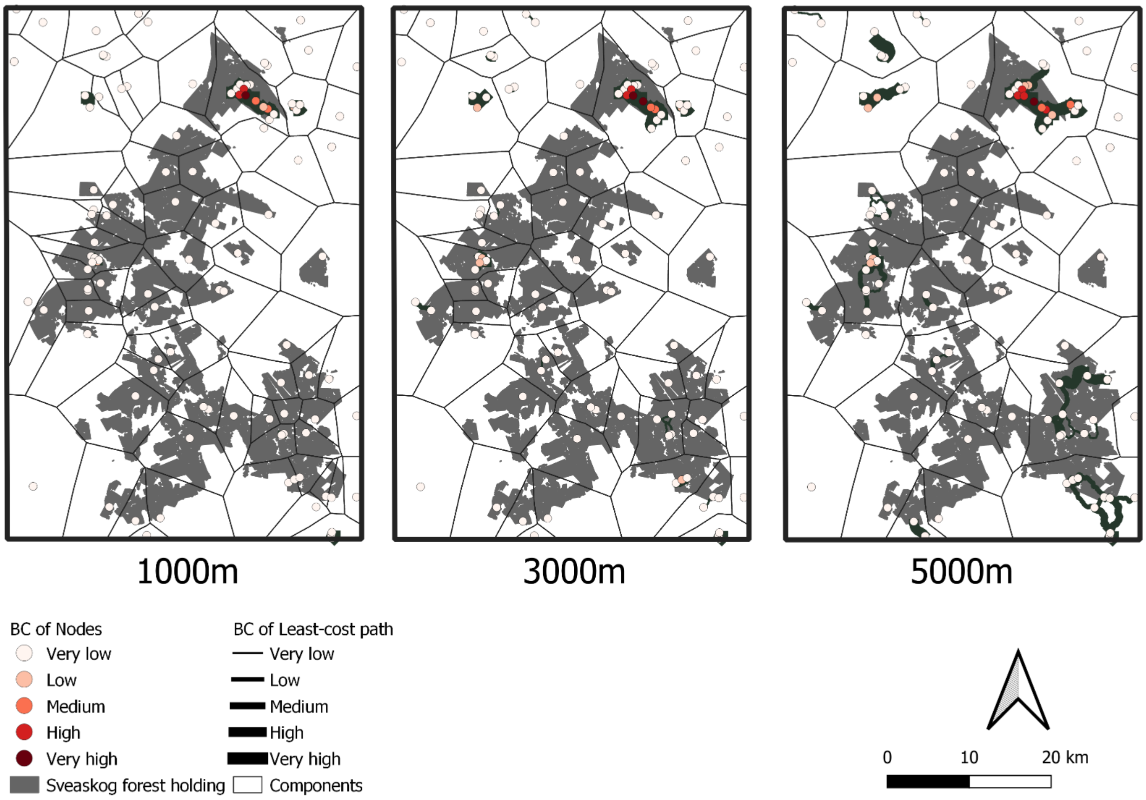


*Figure 12. Connectivity importance for patches of pCF and HCVF combined for **pine forests** (represented by nodes) and least-cost paths for the three different distances. The patches are divided in 5 classes with Jenks natural break while the least-cost paths are divided in 5 classes with an equal count in each class. Grey area in the background shows the Sveaskog forest holdings.*

Spruce forests have a few components at short distance where patches are connected (Fig. 13). As dispersal distance increase, more nodes are connected and more nodes with important BC-values are revealed. Three components have connected nodes with BC-values above "*low*" at 5000m distance. The one with highest BC-values was found in the northeast, a second in the west and a third in the south. The number of nodes per component was 2.88, 1.95 and 1.36 for the 5000m, 3000m and 1000m dispersal ranges which is similar to the number of nodes per component for pine but very different from the all forests. Least-cost paths with highest BC-values were found in the north-eastern component, in the western part and in a southern part.

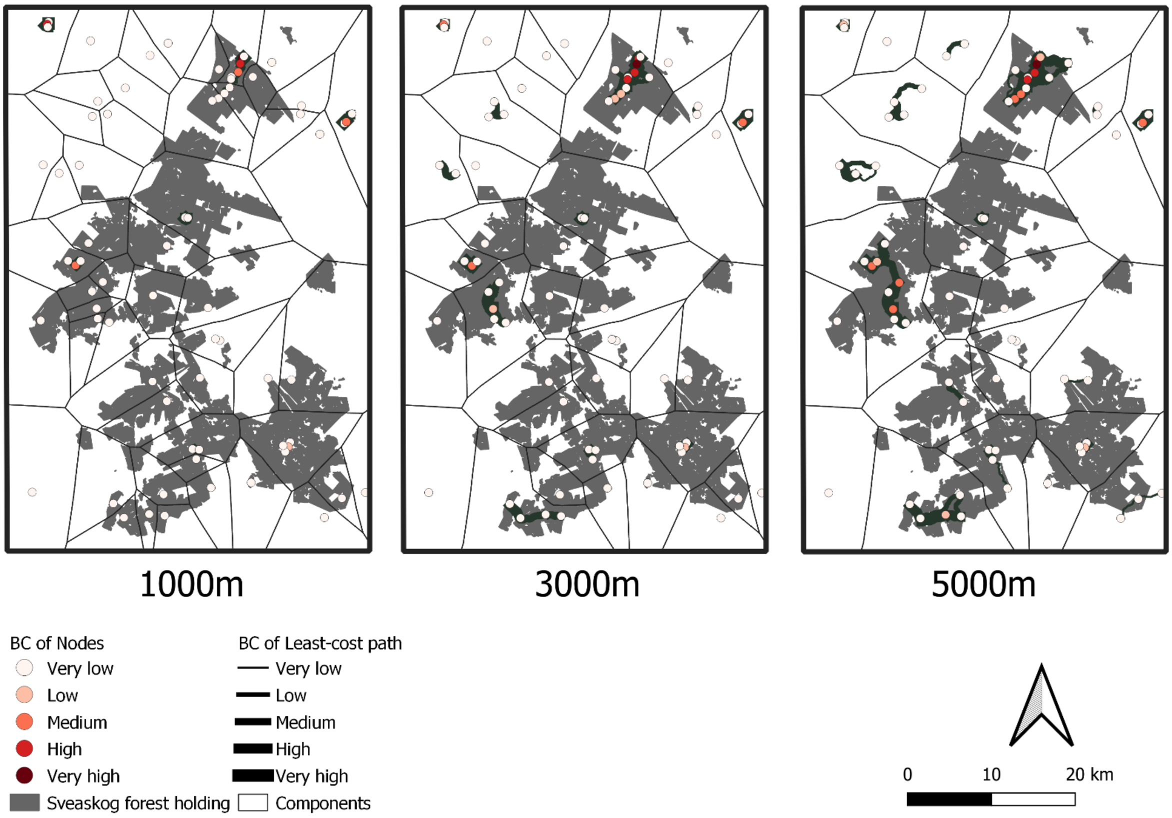


Figure 13. Connectivity importance for patches of pCF and HCVF combined for ***spruce forest*** *(represented by nodes) and least-cost paths for the three different distances. The patches are divided in 5 classes with Jenks natural break while the least-cost paths are divided in 5 classes with an equal count in each class. Grey area in the background shows the Sveaskog forest holdings.*

3.2.3 Corridors connecting patches

Figure 14 illustrates corridors calculated under relative threshold levels to complement the other measures and shows that the all forest scenario (figure 14) has a similar cost-distance threshold value as pine on the 1000m distance, but lower values at longer distances (appendix 5). The northeastern area has the highest abundance of corridors on all distances. When scaling up to 3000m additional areas become covered by corridors. In the 5000m analysis, two very large areas are connected; the northern with wide corridors and the central/southern with a few narrow corridors. Narrow corridors can be regarded as bottlenecks of suitable forest matrix (figure 15).

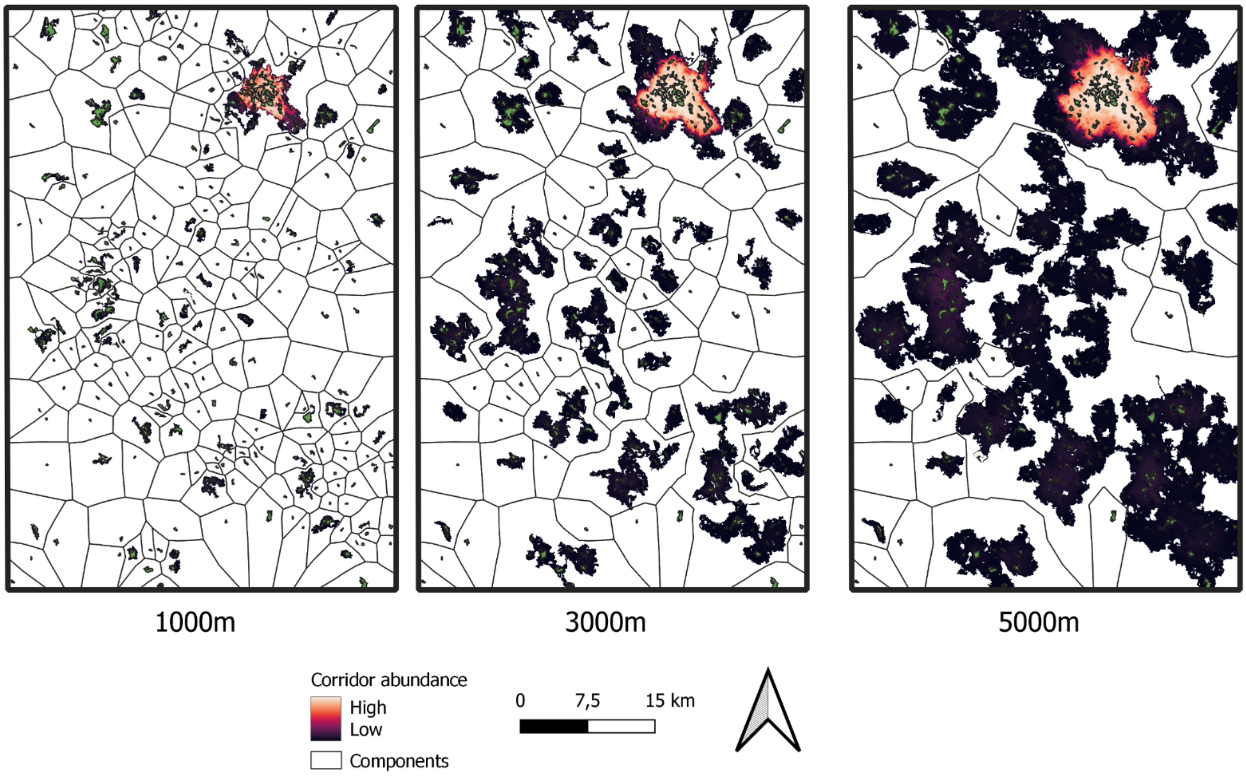


*Figure 14. Patches of pCF and HCVF combined for **all forest** with corridors between patches below thresholds for the three distances of 1000m, 3000m and 5000m. Each group of isolated patches are considered a component.*

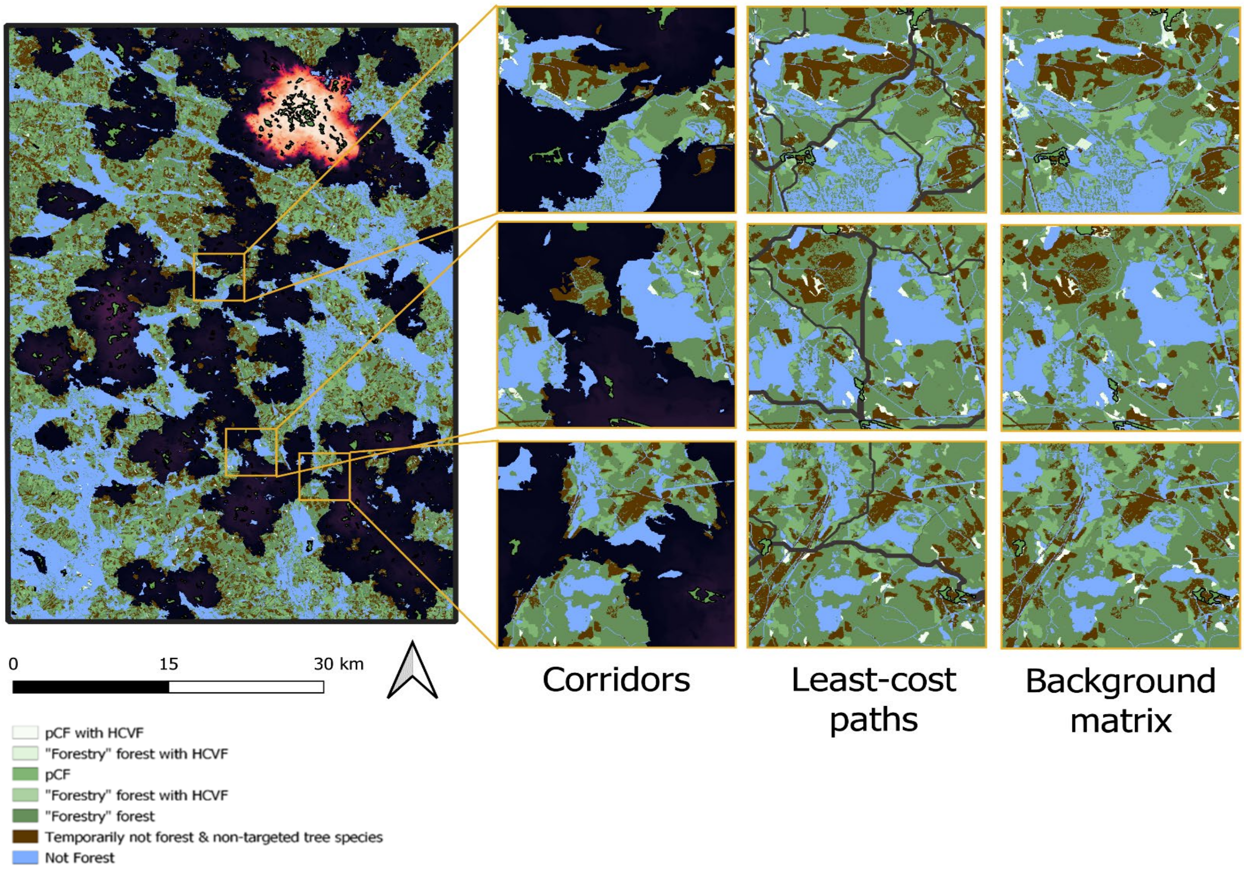


*Figure 15. Three examples from the **all forest** analysis, displaying three examples of bottleneck areas for a 5000m distance with least-cost paths and corridors connecting large areas. A background matrix is included to display how corridors and least-cost paths expands.*

The corridors in the pine forest scenario (figure 16) have the highest abundance in the northeastern component at all distances. As distances are increased, larger components are revealed. A few narrow corridors are detected in the western area and the southeastern area. Cost-resistance threshold values for each distance are slightly higher compared to the cost-resistance values of all forest land, but considerably lower compared to the cost-resistances for spruce forest (appendix 5).

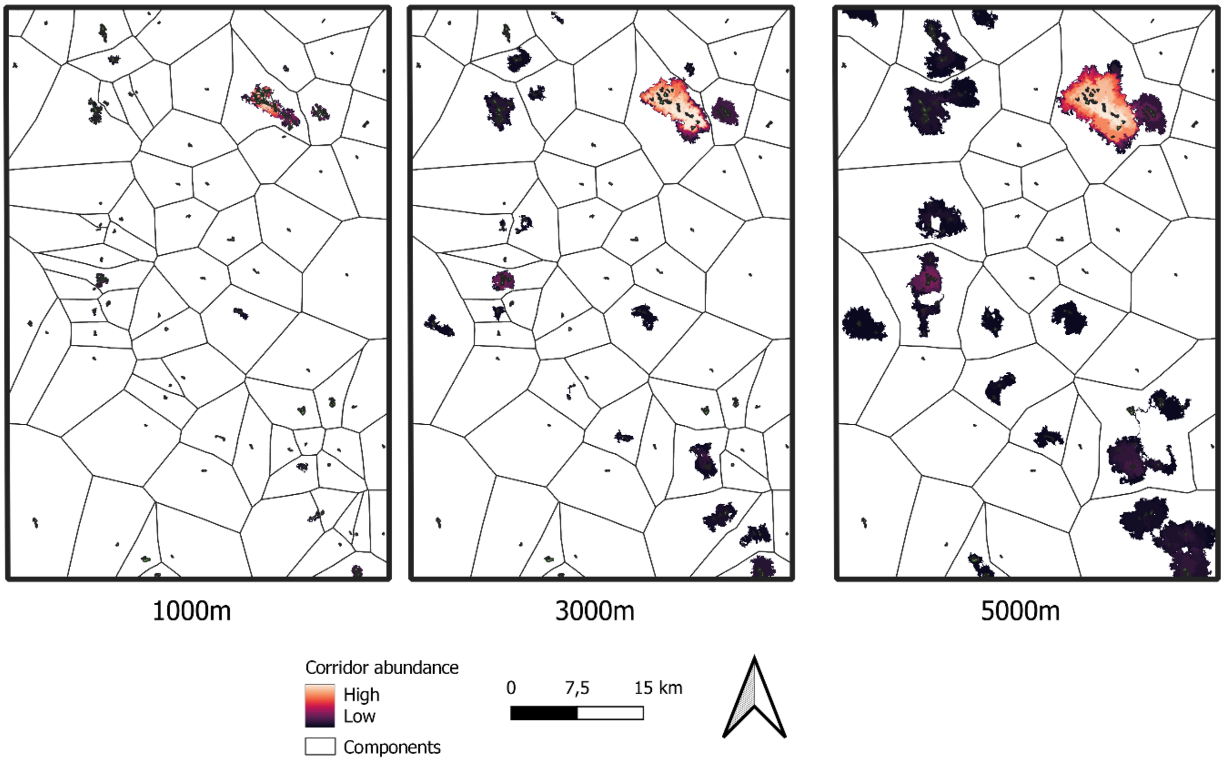


*Figure 16. Patches of pCF and HCVF combined for **pine forest** with corridors between patches below thresholds for the three distances of 1000m, 3000m and 5000m. Each group of isolated patches are considered a component.*

The most important area in the spruce forest scenario (figure 17) is located in the northeastern part, at all distances. However, at the 1000m distance most other areas are displayed as having high importance as no areas stands out with a relatively high number of patches connected. As distances increase, the corridor abundance increase in the western area and the areas illustrated with high abundance for 1000m are now considered being low abundance. The cost-resistance values for spruce differs substantially from both the all forest scenario and the pine forest scenario, as the spruce land coverage computes much higher cost-resistance values with the 5000m distance standing out as very high (appendix 5).

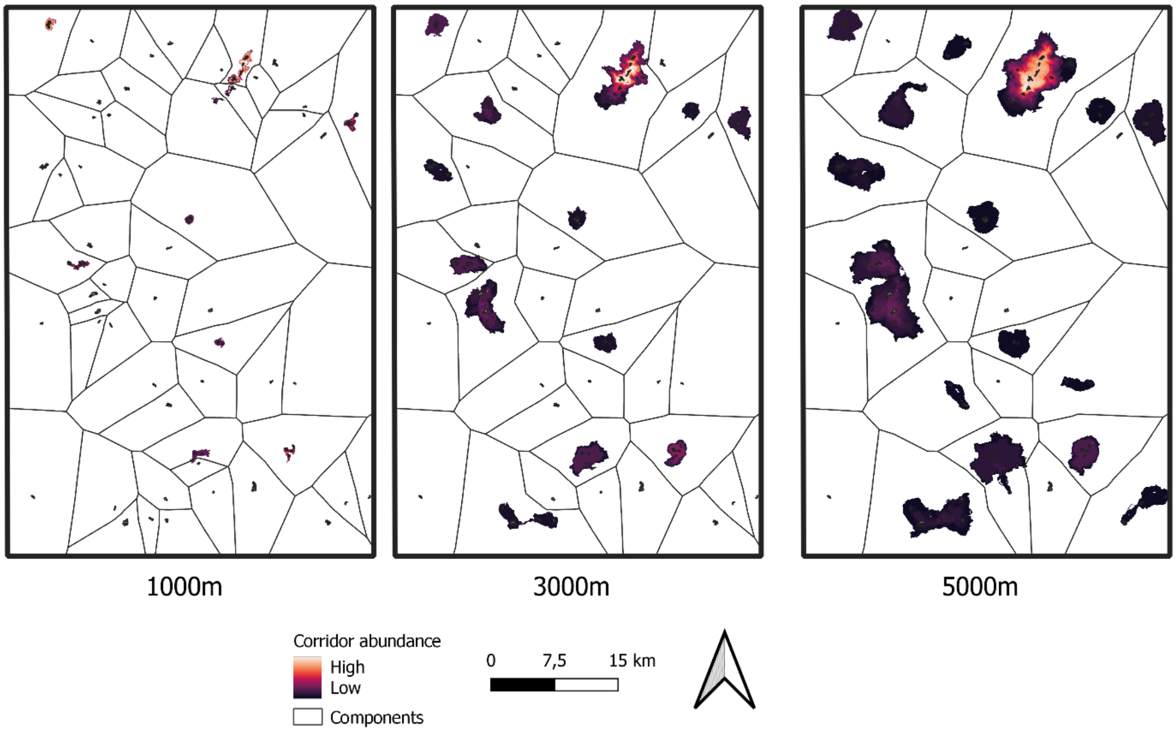


Figure 17. Patches of pCF and HCVF combined for ***spruce forest*** *with corridors between patches below thresholds for the three distances of 1000m, 3000m and 5000m. Each group of isolated patches are considered a component.*

3.3 Norrbotten/Västerbotten case study

The connectivity study area for all forest land in Norrbotten and Västerbotten has included patches (figure 18a) with a few patches consisting of ecoparks or nature reserves being very large. The number of patches per component are approximately 5.95 for the 3000m threshold distance. Three large clusters of patches with higher importance were found (figure 18b). One of these clusters stretches along the western part of the study area while the other is in the northern part of the study area. The corridor abundancy analysis revealed a few core areas with a high abundancy of corridors (figure 18c). Areas with a high abundance of corridors overlap to a large extent with the current Sveaskog ecoparks (figure 18d). Areas with a lower abundance could be managed for increasing the connectivity in the vicinity to the ecoparks and to increase their component functionality.

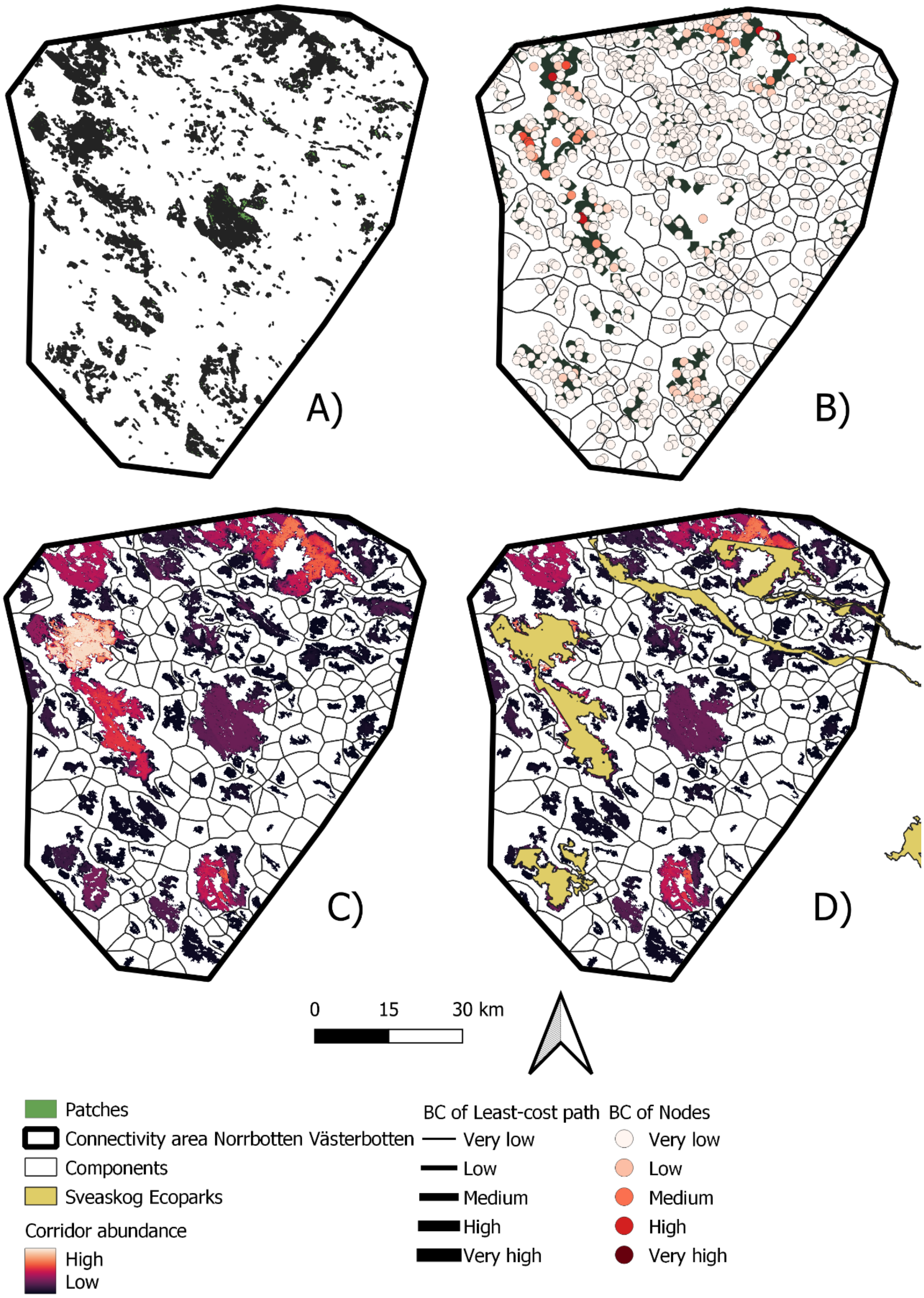


Figure 18. Example from the connectivity analysis in the Norrbotten/Västerbotten connectivity study area. A) illustrate the patches of pCF and HCVF combined. B) illustrate relative BC-value for nodes and least-cost paths, C) illustrate corridor abundance with many areas having a high corridor abundance. D) illustrates how the areas with a high corridor abundance overlap to a large extent with the Sveaskog ecoparks.

4. Discussion

4.1.1 Distribution of continuity forests with high nature conservation values

From my results I find that there is about 245 693 ha of overestimated pCF (figure 7) following from Metrias mapping of continuity forests, given that forests below 70 years are overestimations. This is interesting as it might have a direct impact within the model I use and therefore also on what management Sveaskog chose to apply continuity forests and non-continuity forests. I also find that almost 300 000 ha is continuity forests with high nature conservation values and that most of these forests are found in the mountain regions of Norrbotten, Västerbotten or Dalarna (figure 8). This is in line with other findings (Svensson et al. 2020, 2022) that recognize forests within or in proximity to the mountain forest border as areas important for the green infrastructure. For Sveaskog the area defined here as Norrbotten coastal region also has a large amount and share of continuity forests with high nature conservation values. In general, this implies that forestry in the mountain regions and Norrbotten region can be more focused on protection of forests that already have high nature values and long forest continuity as connectivity between such valuable areas are higher than outside of these regions. Meanwhile, management in southern coastal or southern inland regions could focus on developing new forests that can contribute to connectivity between the sparse amount of continuity forests with high nature conservation values to contribute to connectivity between such forests.

The areas targeted as possible connectivity study areas (figure 4) could likely be developed and managed with similar approaches as either Dalarna/Gävleborg or Norrbotten/Västerbotten, depending on whether they are mountain regions or coastal regions. However, to know where to target management focused on connectivity improvements, the connectivity method I have used on Dalarna/Gävleborg and Norrbotten/Västerbotten should be applied to all Sveaskog forests to reveal forests more or less important as connectivity forests.

4.1.2 Connectivity within Sveaskog forest holdings

The results shows that there are substantial areas of Sveaskog forestland that can be defined as standard forests with no documented high conservation values and that also often disconnected from areas with aggregated high conservation values. Assessing different dispersal distances for a general forest type can reveal if a patch or a group of patches can be considered isolated. If so, corridors of importance between patches can’t be found, or found as narrow and potentially sensitive forest belts. Applying different distances provide information on what spatial scale, i.e.

movement or dispersal area, connected patterns appear. This is not controversial as the number and distribution of patches sets the basis for how connectivity can be modeled. If the number of patches in the network are few and far apart, the connectivity between them is less. This is illustrated in the results as neither the pine nor spruce scenario reveal any large improvements in connected nodes per component in comparison to the scenario with all forest patches where the number of connected nodes per component have a large increase. Thus, the approach taken in this study is a step forward in stratifying the Sveaskog forest holdings into units that can be assigned for either continued forestry, restoration to improve connectivity on longer term, or set asides to add to connectivity and green infrastructure functionality within and in the vicinity of already know conservation hot spot areas as the Ecoparks.

The cost-resistance thresholds calculated (appendix 5) is useful as the threshold values between each scenario explain the "cost" of connectivity for the metric distances of each scenario. As expected, improving connectivity for the spruce scenario at a 5000m distance includes less good matrix and becomes very costly as the landscape is dominated by pine. This implies that connectivity over large distances perhaps should be focused on all conifer forests or all forest.

Based on the results, areas important for linking patches together can be discovered. The most important areas within all scenarios were those where Sveaskog ecoparks were established as they contributed with the highest relative abundance of corridors in all scenarios and all distances. This was both the case for Dalarna/Gävleborg (figure 14; figure 16; figure 17) and for Norrbotten/Västerbotten (figure 18C; figure 18D). The areas covered by ecoparks also revealed the highest relative BC-importance for both nodes and least-cost paths. The model validates that Sveaskog ecoparks contains important patches of valuable forest and indicate a high contribution of connectivity in the landscape.

4.1.3 Interpreting least-cost paths and landscape resistance

Using the corridors as predictors of possible dispersal routes, some parts of the study areas apparently have better premises for connecting patches (i.e. higher corridor abundance) than others. Furthermore, some parts have no corridors passing at all and hence do not contribute to the model. However, such an assumption is most likely not fully valid as actual species dispersal relies on multiple factors and is much difficult to assess (Palmer et al. 2011), which implies that species-agnostic models such as this should only be regarded as complementary to other fine-tuned data and decision-making tools.

When the length of least-cost paths is not restricted to the thresholds of 1000-, 3000-, or 5000-meters, possible routes connecting the entire study area is visible and the relative importance for all patches in the network can be assessed (Bodin & Norberg 2007).

As discussed in other studies using landscape-resistance, the least-cost paths and corridors are very dependent on the cost-resistance values set in the model (Pinto & Keitt 2009; Zetterberg et al. 2010; Huang et al. 2021). Least-cost paths follow routes that avoid areas of temporarily not forest or with other types of land cover (appendix 8A), but still paths may be modeled. This happens as a path through unfavorable matrix has a lower accumulative cost-resistance compared to the accumulative cost of an alternative route through more suitable matrix becomes higher because it is much longer (appendix 8b).

The corridors in this study complement least-cost paths in several ways. Corridors display environments that are more probable to have features evaluated as important, and not only illustrate a least-cost path. From the results, areas of patches connected by corridors with intense red colors are to be considered as very valuable areas where connectivity is good. These areas are already well-connected and should be targeted for further protection. However, corridors illustrated with black/purple corridors could be targeted for further development which would then strengthen connectivity on all levels.

Using the corridors as predictors of possible dispersal, some areas can be interpreted as having better values for connecting patches (high corridor abundance) while others have less good values for connecting patches (low corridor abundance).

The areas with corridors for spruce forest and pine forest is about the same (figure 16; figure 17). However, as the cost-distance threshold values calculated are relative to each scenario, we must include the approximate cost-distance values (appendix 5). These reveal that the approximate cost for spruce coverage at a 1000m dispersal range is almost 4 times higher than that of pine coverage, indicating that connectivity for species dependent on pine forests is higher and potentially also more easy to improve even further, as supported by the resistance maps.

Further, corridors and corridor abundance can be used and divided into areas with different targets. Areas with a high abundance of corridors can be interpreted as suitable areas for further protecting or management that is oriented towards increasing high conservation patch area, continuity forests and generally enhance nature conservation values, while areas with lower corridor abundance could be oriented towards developing a multifunction approach to maintain their stepping-stone importance (Peura et al. 2018), or be targeted for continued forestry. With reference to the results, areas with patches connected by corridors with intense red colors are to be considered as very valuable areas where connectivity is good. These areas are already well-connected and should be targeted for further protection. However, corridors illustrated with black/purple corridors could be targeted for further development which would then strengthen connectivity on all levels.

Depending on how much forest a forest owner is prepared to set aside or develop to forests with high nature values, one could argue for that all areas detected with any corridors, even areas with low corridor abundancy, could be developed to have old forest characteristics and eventually become very large patches in the landscape. As discussed by Saura and Rubio (2010), the choice of where to develop new patches should be considered a trade-off between the connectivity gain for the entire network and the intrinsic value already at place at areas suitable for development, even if they contribute less to the connectivity. This is important to keep in mind as strict addition of patches that only maximize connectivity within the network, might result in that other areas with higher nature values are neglected.

4.1.4 Management suggestions for Sveaskog

To start with, I think that the applied methodology has a great advantage as it allows easy visualization which can be interpreted intuitively as areas of importance or not. This can be useful for Sveaskog as complementary to their other decision-making tools or applied on top of stand information in GIS-programs.

The results provide very clear information about corridors and least-cost paths found in the study area with these settings. If an area has a least-cost path passing through, this indicates a suitable area for further management approaches with focus on conservation. Corridors add a great supplement to this as they provide entire areas that can further support connectivity between patches. Corridors illustrated with more intense colors in this study should be considered important and left for protection or further managed to increase connectivity. Other corridors can be combined with connectivity metrics to assess their value and prioritize management. I suggest development around patches found in the 20 000m analysis and least-cost paths between these and the core areas to strengthen connectivity within the entire forest holding network. Forest areas regarded as most suitable along these least-cost paths can then be developed and protected.

The results from the different scenarios also reveal that connecting only pine forests or only spruce forests can prove difficult and at a high cost. It could therefore be appropriate to target connectivity of conifer forests as an entity as it can become highly connected by prioritizing core areas (figure 15). Such recommendations are found in other studies where bottlenecks are found (Huang et al. 2021). The scenario of all forests represents the possibilities for conifer forests well as most of the forests within the study are pine forests, spruce forests, or mixed conifer forests.

There is an option between choosing development and protection of areas already recognized as well-functioning (meaning corridors with high abundances or least-cost paths with high BC-values) or developing areas that are recognized in the study with lower abundancies and lesser BC-values. Least-cost paths revealed with a lower BC-importance are still found within the limits of the model and are thus representing the best way to connect patches in a way that takes landscape heterogeneity into account. Ideally, a combination of both these approaches would provide the best background landscape planning information.

At the same time, for Sveaskog it is also interesting to see where in the given landscape they can continue with rotation forestry. As this model map areas currently important for connectivity it also reveal areas that cannot contribute to functional green infrastructure given the spatial locations and thus rotation forestry could be performed. That is, outside of corridors or in areas within corridors where they evaluate that the connectivity between patches won't be large. However, areas with pCF and HCVF should not be targeted with rotation forestry as all known values should be considered important. Also, other scenarios including more patches could reveal other corridors and areas where forestry should be managed with a multifunction approach to maintain their stepping-stone importance (Peura et al. 2018).

Illustrated with landscape resistance, the Dalarna-Gävleborg study area is dominated by pine (figure 6b). This affects possible development scenarios as connectivity among continuity forests with spruce that consist of high nature conservation values can be harder to develop compared to connectivity between valuable pine forest. For this reason, perhaps connectivity between spruce forest should be more focused to certain areas or applied for longer dispersal distances. The possibilities of high connectivity for pine forest looks much more promising as pine forests dominates the landscape and development of conservation values can be performed in many areas and higher connectivity can be reached for shorter dispersal distances.

4.1.5 Importance of resistance values

The setting of resistance values to include heterogeneity in the landscape is difficult and the results can be greatly influenced by the chosen values and ranges (McRae et al. 2008). In this study I chose to set the resistance values to similar values of previous studies working with ecological networks (Clauzel et al. 2013, 2015; Foltête et al. 2014; Huang et al. 2021) combined with trial and error during modelling. I also chose to apply contrasting values that represent suitable and unfavourable habitats, as suggested by Clauzel et al. (2013). Although any chosen resistance value is a generalization, these settings make it possible to locate routes with a matrix more suitable for development than the surrounding matrix, even if it does not reflect on current species movement. Although I am using a similar approach as in many of other similar studies, this specific study targets a specific landscape.

Setting inappropriate values based on assumptions that does not reflect reality can lead to negative effects and movement routes or more species-specific data is needed to support appropriate settings (Russell et al. 2003). Also, least-cost paths might not reveal the path crossing through the most optimal matrix if an alternative route produces a much lower accumulated cost, even though this route might pass through an unsuitable matrix. With my settings, some obvious flaws are visible in a few cases due to the resistance settings. Mostly least-cost paths follow routes that avoid areas of temporarily not forest or with other types of land cover (appendix 8A). But eventually, some paths crosses such land. This happens as a route through unfavorable matrix has a lower accumulative cost-resistance compared to the accumulative cost of an alternative route through more suitable matrix becomes higher because it is much longer (appendix 8b) as can be the case when crossing a water body compared to finding a path around it. For reasons like this, least-cost paths and changes of these paths should be further tested to find the most optimal areas for conservation restoration by making multiple models with different settings (Spear et al. 2010; Sawyer et al. 2011).

Rayfield et al. (2010, 2011) found that fragmented landscapes with low shares of hospitable matrix were most sensible to resistance settings and suggests multiple low-cost paths instead of working with a single least-cost path. The circumstances described by Rayfield et al. are very similar to those regarding the pine and spruce scenarios in this model where patches are fragmented, and the matrix can be considered less hospitable. Indeed, changing some the resistance values of the forested unhospitable matrix in the pine forest scenario altered some of the least-cost paths drastically (appendix 7).

4.1.6 Limitations of the model

To start with, I must acknowledge that the results from this study lack proper validation and would benefit from comparisons of different resistance settings validated by field measurements. It is also commonly discussed whether generalizations of connectivity for groups of species is reflected in reality. Gurrutxaga et al. (2011) and Zeller et al. (2012), for example, point out that studies using surface resistances too often rely on expert opinions that lack proper scientific validation.

When making large-scale computer analyses, time is a crucial factor. I decided to work with Graphab mainly because of the possibility for me to understand the processes as it is very illustrative and easy to understand. However, as I progressed, limitations within the software prevented me from making a complete analysis on the entire Sveaskog forest holdings in northern Sweden. Because of memory capacity limits within the QGIS plugin version it does not include the “add patch” option which is included in the standalone version of Graphab. With more time I would have improved the analysis within the standalone version using this function, where it is possible to compute where in the landscape new patches should be placed to make the largest contribution to a global connectivity value.

Despite the many strengths with using least-cost paths, many previous studies have addressed the problem with interpretation and direct management without careful consideration of actual species dispersal. Adriaensen et al. (2003) argued that a least-cost path might pass through pixels regardless of path width, while a very thin path in a reality can be a limiting factor for species dispersal. Furthermore, Gustafsson and Gardner (1996) showed that models revealing generalized results can worsen dispersal for some species. This highlights the importance of having good data inputs.

Delineating stand age as the only separator between pCF is simply practical but might not be very relevant in reality. A forest with a mean stand age of 139 years and a forest aged 140 years can both be developed and managed in a similar way to develop values high nature values. However, they are separated in this study which can be considered a weakness.

Another important factor to mention as a limitation of this model is that I have separated between the Sveaskog forest holding and forests owned by others. For example, I have only investigated overestimations of pCF on the Sveaskog forest holding. I have neither separated pCF into 70-139 years and 140+ years on forests outside of Sveaskog forest holding. This could perhaps result in that the model underestimates least-cost paths and corridors outside of the Sveaskog forest holding. However, it still gives relevant results for Sveaskog when assessing connectivity within their forest holdings. In the end, the most interesting thing from a Swedish perspective would be to assess connectivity on the entire Swedish forest landscape, and beyond to neighbouring countries, without making study area borders and having the same categories for the entire landscape as this could reduce errors that occur because of delineation of the forests into study areas.

4.1.7 Future modelling

To further develop this kind of model for analysing connectivity, I have found that the following should be considered. First, different settings of cost-resistances should be set and tested to see how least-cost paths are affected.

Secondly, a study investigating changes of a global connectivity metric could be used to further target and locate areas suitable for restoration to develop nature conservation values. This could be done for example by adding all areas with continuity forest and test how the global connectivity increases. It could also be done by applying a grid to the landscape map with patches and use the standalone Graphab software to calculate where in the grid a chosen number of patches should be placed to maximize an increase of the global connectivity.

Thirdly, one approach not applied in this study due to time limits and other constraints, is to model improved connectivity by creating new patches where there currently are gaps and where the new patches contribute the most to the network connectivity (Foltête et al. 2014; Tarabon et al. 2019).

Finally, graph theory resulting in "optimal" connectivity areas are very theoretical. Therefore, this method should be continuously developed and evaluated as knowledge about dispersal improves. Thus, the results from this study should only be regarded as complementary to other ecological decision-making tools.

4.2 Conclusion

Based on the Sveaskog forest holdnings and with focus in particular on one specific case study, this study modelled the importance of patches and areas that possibly connect patches, based on features of pCF and HCVF in the landscape. As forest managers face great challenges in protecting and developing areas important for green infrastructure, this study presents an approach which can support such management decisions. Applying graph theory to find specific landscape features such as pCF and HCVF reveal core patches and possible routes connecting these. Connectivity metrics and corridor abundance reveal the relative importance of different areas, which can assist in management prioritisation. As size and range of areas important for connectivity differ much depending on dispersal distances, forest managers must take dispersal distances under consideration when developing connectivity between patches to include differences among species. Shorter dispersal distances points to development of local core areas while longer dispersal distances require a wider landscape approach to protect or develop connectivity between existing patches currently very far apart.

For Sveaskog, I propose continuous use or development of this study design to find and discuss suitable management approaches to protect or develop connectivity between forests with conservation value and in particular high conservation value. As the aspects of continuity forest and nature conservation values develop over time, this methodology could be repeated with intervals to assess the progression of response to a higher ambition of landscape planning. I also suggest an increasing use of alternative forestry methods such as continuous cover forestry where both conservation and production aspects can be regarded. Alternative forest management methods could be increasingly used within corridors to limit the negative effects clearcuts have on the areas modelled as important for connectivity. However, the settings of resistance values and its impact on connectors must be evaluated and patch addition/patch removal can be included in a future model to assess how management proposals affect connectivity prior to field execution.

References

Adriaensen, F., Chardon, J.P., De Blust, G., Swinnen, E., Villalba, S., Gulinck, H. & Matthysen, E. (2003). The Application of 'Least-Cost' Modelling as a Functional Landscape Model. *Landscape and Urban Planning*, 64, 233–247. https://doi.org/10.1016/S0169-2046(02)00242-6

Ahlkrona, E., Gilljam, C. & Wennberg, S. (2017). *Kartering av kontinuitetsskog i boreal region*. Metria AB på uppdrag av Naturvårdsverket. https://www.skogsstyrelsen.se/globalassets/aga-skog/skydda-skog/bilaga-3-kartering_av_kontinuitetsskog_boreal_region.pdf [2022-05-23]

Andersson, C., Andersson, E., Blomqvist, S., Eriksson, A., Eriksson, H., Karlsson, S. & Jean-Michel, R. (2019). *Skogsstyrelsen följer upp Levande skogar*. Skogsstyrelsen. https://www.skogsstyrelsen.se/miljo-och-klimat/miljomal/levande-skogar/ [2022-05-27]

Angelstam, P., Manton, M., Green, M., Jonsson, B.-G., Mikusiński, G., Svensson, J. & Maria Sabatini, F. (2020). Sweden does not meet agreed national and international forest biodiversity targets: A call for adaptive landscape planning. *Landscape and Urban Planning*, 202, 103838. https://doi.org/10.1016/j.landurbplan.2020.103838

Baranyi, G., Saura, S., Podani, J. & Jordán, F. (2011). Contribution of habitat patches to network connectivity: Redundancy and uniqueness of topological indices. *Ecological Indicators*, 11 (5), 1301–1310. https://doi.org/10.1016/j.ecolind.2011.02.003

Bodin, Ö. & Norberg, J. (2007). A Network Approach for Analyzing Spatially Structured Populations in Fragmented Landscape. *Landscape Ecology*, 22 (1), 31–44. https://doi.org/10.1007/s10980-006-9015-0

Bourdouxhe, A., Duflot, R., Radoux, J. & Dufrêne, M. (2020). Comparison of methods to model species habitat networks for decision-making in nature conservation: The case of the wildcat in southern Belgium. *Journal for Nature Conservation*, 58, 125901. https://doi.org/10.1016/j.jnc.2020.125901

Bovin, M., Elcim, E. & Wennberg, S. (2017). *Landskapsanalys av skogliga värdekärnor i boreal region. Preliminär slutrapport*. Metria AB på uppdrag av Naturvårdsverket. [2022-02-21]

Bradshaw, R.H.W. (1993). Tree species dynamics and disturbance in three Swedish boreal forest stands during the last two thousand years. *Journal of Vegetation Science*, 4 (6), 759–764. https://doi.org/10.2307/3235612

Bunn, A., Urban, D. & Keitt, T. (2000). Landscape Connectivity: A Conservation Application of Graph Theory. *Journal of Environmental Management*, 59, 265–278. https://doi.org/10.1006/jema.2000.0373

Clauzel, C., Bannwarth, C. & Foltete, J.-C. (2015). Integrating regional-scale connectivity in habitat restoration: An application for amphibian conservation in eastern France. *Journal for Nature Conservation*, 23, 98–107. https://doi.org/10.1016/j.jnc.2014.07.001

Clauzel, C., Girardet, X. & Foltête, J.-C. (2013). Impact assessment of a high-speed railway line on species distribution : Application to the European tree frog

(Hyla arborea) in Franche-Comté. *Journal of Environmental Management*, 127, 125–134. https://doi.org/10.1016/j.jenvman.2013.04.018
Congalton, R. (1997). Exploring and Evaluating the Consequences of Vector-to-Raster and Raster-to-Vector Conversion. *Photogrammetric Engineering and Remote Sensing*, 63, 425–434
Cousins, S.A.O., Auffret, A.G., Lindgren, J. & Tränk, L. (2015). Regional-scale land-cover change during the 20th century and its consequences for biodiversity. *AMBIO*, 44 (1), 17–27. https://doi.org/10.1007/s13280-014-0585-9
Driezen, K., Adriaensen, F., Rondinini, C., Doncaster, C.P. & Matthysen, E. (2007). Evaluating least-cost model predictions with empirical dispersal data: A case-study using radiotracking data of hedgehogs (Erinaceus europaeus). *Ecological Modelling*, 209 (2), 314–322. https://doi.org/10.1016/j.ecolmodel.2007.07.002
Ecke, F., Magnusson, M. & Hörnfeldt, B. (2013). Spatiotemporal changes in the landscape structure of forests in northern Sweden. *Scandinavian Journal of Forest Research*, 28 (7), 651–667. https://doi.org/10.1080/02827581.2013.822090
Ericsson, S., Östlund, L. & Axelsson, A.-L. (2000). A forest of grazing and logging:Deforestation and reforestation history of a boreal landscape in central Sweden. *New Forests*, 19. https://doi.org/10.1023/A:1006673312465
Estrada, E. & Bodin, Ö. (2008). Using Network Centrality Measures to Manage Landscape Connectivity. *Ecological Applications*, 18 (7), 1810–1825. https://doi.org/10.1890/07-1419.1
European Commission (2021). *EU biodiversity strategy for 2030: bringing nature back into our lives*. LU: Publications Office of the European Union. https://data.europa.eu/doi/10.2779/677548 [2022-05-27]
Fahrig, L. (2007). Non-optimal animal movement in human-altered landscapes. *Functional Ecology*, 21 (6), 1003–1015. https://doi.org/10.1111/j.1365-2435.2007.01326.x
Foltête, J.-C., Clauzel, C. & Vuidel, G. (2012). A software tool dedicated to the modelling of landscape networks. *Environmental Modelling and Software*, 38, 316–327. https://doi.org/10.1016/j.envsoft.2012.07.002
Foltête, J.-C., Girardet, X. & Clauzel, C. (2014). A methodological framework for the use of landscape graphs in land-use planning. *Landscape and Urban Planning*, 124, 140–150. https://doi.org/10.1016/j.landurbplan.2013.12.012
Foltête, J.-C., Vuidel, G., Savary, P., Clauzel, C., Sahraoui, Y., Girardet, X. & Bourgeois, M. (2021). Graphab: An application for modeling and managing ecological habitat networks. *Software Impacts*, 8, 100065. https://doi.org/10.1016/j.simpa.2021.100065
Food And Agriculture Organization Of The United Nations (2020). *Global forest resource assessment 2020, Terms and Definitions*. Rome.
Freeman, L.C. (1978). Centrality in social networks conceptual clarification. *Social Networks*, 1 (3), 215–239. https://doi.org/10.1016/0378-8733(78)90021-7
Gonzales, E.K. & Gergel, S.E. (2007). Testing assumptions of cost surface analysis—a tool for invasive species management. *Landscape Ecology*, 22 (8), 1155–1168. https://doi.org/10.1007/s10980-007-9106-6
Gurrutxaga, M., Rubio, L. & Saura, S. (2011). Key connectors in protected forest area networks and the impact of highways: A transnational case study from the Cantabrian Range to the Western Alps (SW Europe). *Landscape and Urban Planning*, 101 (4), 310–320. https://doi.org/10.1016/j.landurbplan.2011.02.036

Gustafson, E. & Gardner, R. (1996). The Effect of Landscape Heterogeneity on the Probability of Patch Colonization. *Ecology*, 77, 94. https://doi.org/10.2307/2265659

Gustafsson, L., Kouki, J. & Sverdrup-Thygeson, A. (2010). Tree retention as a conservation measure in clear-cut forests of northern Europe: a review of ecological consequences. *Scandinavian Journal of Forest Research*, 25 (4), 295–308. https://doi.org/10.1080/02827581.2010.497495

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-X. & Townshend, J.R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*,. https://doi.org/10.1126/sciadv.1500052

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, 342 (6160), 850–853. https://doi.org/10.1126/science.1244693

Hanski, I. (2005). Landscape fragmentation, biodiversity loss and the societal response. *EMBO reports*, 6 (5), 388–392. https://doi.org/10.1038/sj.embor.7400398

Hanski, I. (2011). Habitat Loss, the Dynamics of Biodiversity, and a Perspective on Conservation. *AMBIO*, 40 (3), 248–255. https://doi.org/10.1007/s13280-011-0147-3

Huang, L., Wang, J., Fang, Y., Zhai, T. & Cheng, H. (2021). An integrated approach towards spatial identification of restored and conserved priority areas of ecological network for implementation planning in metropolitan region. *Sustainable Cities and Society*, 69, 102865. https://doi.org/10.1016/j.scs.2021.102865

IPBES (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Zenodo. https://doi.org/10.5281/zenodo.6417333

Jenks, G.F. (1967). *The Data Model Concept in Statistical Mapping*. (International Yearbook of Cartography)

Jonsson, B.G., Ekström, M., Esseen, P.-A., Grafström, A., Ståhl, G. & Westerlund, B. (2016). Dead wood availability in managed Swedish forests – Policy outcomes and implications for biodiversity. *Forest Ecology and Management*, 376, 174–182. https://doi.org/10.1016/j.foreco.2016.06.017

Keitt, T., Urban, D. & Milne, B. (1997). Detecting Critical Scales in Fragmented Landscapes. *Conservation Ecology*, 1 (1). https://doi.org/10.5751/ES-00015-010104

Koivula, M. & Vanha-Majamaa, I. (2020). Experimental evidence on biodiversity impacts of variable retention forestry, prescribed burning, and deadwood manipulation in Fennoscandia. *Ecological Processes*, 9 (1), 11. https://doi.org/10.1186/s13717-019-0209-1

Kool, J.T., Moilanen, A. & Treml, E.A. (2013). Population connectivity: recent advances and new perspectives. *Landscape Ecology*, 28 (2), 165–185. https://doi.org/10.1007/s10980-012-9819-z

Kuuluvainen, T., Tahvonen, O. & Aakala, T. (2012). Even-Aged and Uneven-Aged Forest Management in Boreal Fennoscandia: A Review. *Ambio*, 41 (7), 720–737

Lindenmayer, D.B., Franklin, J.F. & Fischer, J. (2006). General management principles and a checklist of strategies to guide forest biodiversity

conservation. *Biological Conservation*, 131 (3), 433–445. https://doi.org/10.1016/j.biocon.2006.02.019
Linder, P. & Östlund, L. (1998). Structural changes in three mid-boreal Swedish forest landscapes, 1885–1996. *Biological Conservation*, 85 (1), 9–19. https://doi.org/10.1016/S0006-3207(97)00168-7
McRae, B.H., Dickson, B.G., Keitt, T.H. & Shah, V.B. (2008). Using Circuit Theory to Model Connectivity in Ecology, Evolution, and Conservation. *Ecology*, 89 (10), 2712–2724. https://doi.org/10.1890/07-1861.1
Mikusiński, G., Orlikowska, E.H., Bubnicki, J.W., Jonsson, B.G. & Svensson, J. (2021). Strengthening the Network of High Conservation Value Forests in Boreal Landscapes. *Frontiers in Ecology and Evolution*, 8. https://www.frontiersin.org/article/10.3389/fevo.2020.595730 [2022-01-17]
Minor, E.S. & Urban, D.L. (2007). Graph Theory as a Proxy for Spatially Explicit Population Models in Conservation Planning. *Ecological Applications*, 17 (6), 1771–1782. https://doi.org/10.1890/06-1073.1
Minor, E.S. & Urban, D.L. (2008). A Graph-Theory Framework for Evaluating Landscape Connectivity and Conservation Planning. *Conservation Biology*, 22 (2), 297–307. https://doi.org/10.1111/j.1523-1739.2007.00871.x
Naturvårdsverket (2004). *Skyddsvärda statliga skogar och urskogsartade skogar: Huvudrapport över uppdrag om naturvärdesbedömning och skydd av viss skog*. (5339). Naturvårdsverket. [2022-05-20]
Naturvårdsverket (2020). Nationella marktäckedata 2018 – basskikt. (2:2), 58
Nordén, B., Dahlberg, A., Brandrud, T.E., Fritz, Ö., Ejrnaes, R. & Ovaskainen, O. (2014). Effects of ecological continuity on species richness and composition in forests and woodlands: A review. *Écoscience*, 21 (1), 34–45. https://doi.org/10.2980/21-1-3667
Palmer, S.C.F., Coulon, A. & Travis, J.M.J. (2011). Introducing a 'stochastic movement simulator' for estimating habitat connectivity. *Methods in Ecology and Evolution*, 2 (3), 258–268. https://doi.org/10.1111/j.2041-210X.2010.00073.x
Peura, M., Burgas, D., Eyvindson, K., Repo, A. & Mönkkönen, M. (2018). Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation*, 217, 104–112. https://doi.org/10.1016/j.biocon.2017.10.018
Pinto, N. & Keitt, T.H. (2009). Beyond the least-cost path: evaluating corridor redundancy using a graph-theoretic approach. *Landscape Ecology*, 24 (2), 253–266. https://doi.org/10.1007/s10980-008-9303-y
Potapov, P., Hansen, M.C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S. & Esipova, E. (2017). The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances*,. https://doi.org/10.1126/sciadv.1600821
Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E. & Zhuravleva, I. (2008). Mapping the World's Intact Forest Landscapes by Remote Sensing. *Ecology and Society*, 13 (2). https://doi.org/10.5751/ES-02670-130251
QGIS Development Team (2022). *QGIS Geographic Information System*. Version: 3.22.4. Open Source Geospatial Foundation Project. http://qgis.osgeo.org [2022-02-01]
Rayfield, B., Fortin, M.-J. & Fall, A. (2010). The sensitivity of least-cost habitat graphs to relative cost surface values. *Landscape Ecology*, 25 (4), 519–532. https://doi.org/10.1007/s10980-009-9436-7

Rayfield, B., Fortin, M.-J. & Fall, A. (2011). Connectivity for Conservation: A Framework to Classify Network Measures. *Ecology*, 92, 847–58. https://doi.org/10.1890/09-2190.1

Russell, R.E., Swihart, R.K. & Feng, Z. (2003). Population Consequences of Movement Decisions in a Patchy Landscape. *Oikos*, 103 (1), 142–152

Sahraoui, Y., De Godoy Leski, C., Benot, M.-L., Revers, F., Salles, D., van Halder, I., Barneix, M. & Carassou, L. (2021). Integrating ecological networks modelling in a participatory approach for assessing impacts of planning scenarios on landscape connectivity. *Landscape and Urban Planning*, 209, 104039. https://doi.org/10.1016/j.landurbplan.2021.104039

Saura, S. & Rubio, L. (2010). A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. *Ecography*, 33 (3), 523–537. https://doi.org/10.1111/j.1600-0587.2009.05760.x

Saura, S. & Torné, J. (2009). Conefor Sensinode 2.2: A software package for quantifying the importance of habitat patches for landscape connectivity. *Environmental Modelling & Software*, 24 (1), 135–139. https://doi.org/10.1016/j.envsoft.2008.05.005

Sawyer, S.C., Epps, C.W. & Brashares, J.S. (2011). Placing linkages among fragmented habitats: do least-cost models reflect how animals use landscapes? *Journal of Applied Ecology*, 48 (3), 668–678. https://doi.org/10.1111/j.1365-2664.2011.01970.x

Shukla, P.R., Skea, J., Calvo Fuendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughhey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. & Malley, J. (2019). *IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food securit, and greenhouse gas fluxes in terrestrial ecosystems*

Simonsson, P., Gustafsson, L., & Östlund (2015). Retention forestry in Sweden. Driving forces, debate and implementation, 1968–2003. *Scandinavian Journal of Forest Research*, 30. https://doi.org/10.1080/02827581.2014.968201

Skogsstyrelsen (2011). *Kontinuitetsskogar och hyggesfritt skogsbruk: Slutrapport för delprojekt naturvärden*. (7). Jönköping: Skogsstyrelsen. [2022-05-26]

SLU Artdatabanken (2020). *Rödlistade arter i Sverige 2020*. SLU, Uppsala. http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-37182 [2022-05-27]

Spear, S.F., Balkenhol, N., Fortin, M.-J., Mcrae, B.H. & Scribner, K. (2010). Use of resistance surfaces for landscape genetic studies: considerations for parameterization and analysis. *Molecular Ecology*, 19 (17), 3576–3591. https://doi.org/10.1111/j.1365-294X.2010.04657.x

Stevenson-Holt, C.D., Watts, K., Bellamy, C.C., Nevin, O.T. & Ramsey, A.D. (2014). Defining Landscape Resistance Values in Least-Cost Connectivity Models for the Invasive Grey Squirrel: A Comparison of Approaches Using Expert-Opinion and Habitat Suitability Modelling. *PLOS ONE*, 9 (11), e112119. https://doi.org/10.1371/journal.pone.0112119

Sveaskog (2022). *Om våra skogar*. https://www.sveaskog.se//om-sveaskog/var-verksamhet/om-vara-skogar/ [2022-04-10]

Svensson, J., Andersson, J., Sandström, P., Mikusiński, G. & Jonsson, B.G. (2019). Landscape trajectory of natural boreal forest loss as an impediment to green infrastructure. *Conservation Biology*, 33 (1), 152–163. https://doi.org/10.1111/cobi.13148

Svensson, J., Bubnicki, J.W., Angelstam, P., Mikusiński, G. & Jonsson, B.G. (2022). Spared, shared and lost—routes for maintaining the Scandinavian

Mountain foothill intact forest landscapes. *Regional Environmental Change*, 22 (1), 31. https://doi.org/10.1007/s10113-022-01881-8

Svensson, J., Bubnicki, J.W., Jonsson, B.G., Andersson, J. & Mikusiński, G. (2020). Conservation significance of intact forest landscapes in the Scandinavian Mountains Green Belt. *Landscape Ecology*, 35 (9), 2113–2131. https://doi.org/10.1007/s10980-020-01088-4

Swedish NFI (2022). *Skogsdata 2022 Aktuella uppgifter om de svenska skogarna från Riksskogstaxeringen*. Umeå: Instirutionen f. skoglig resurshushållning, Sveriges Lantbruksuniversitet. [2022-05-20]

Tang, T., Li, J., Sun, H. & Deng, C. (2021). Priority areas identified through spatial habitat suitability index and network analysis: Wild boar populations as proxies for tigers in and around the Hupingshan and Houhe National Nature Reserves. *Science of The Total Environment*, 774, 145067. https://doi.org/10.1016/j.scitotenv.2021.145067

Tarabon, S., Bergès, L., Dutoit, T. & Isselin-Nondedeu, F. (2019). Maximizing habitat connectivity in the mitigation hierarchy. A case study on three terrestrial mammals in an urban environment. *Journal of Environmental Management*, 243, 340–349. https://doi.org/10.1016/j.jenvman.2019.04.121

Tiang, D.C.F., Morris, A., Bell, M., Gibbins, C.N., Azhar, B. & Lechner, A.M. (2021). Ecological connectivity in fragmented agricultural landscapes and the importance of scattered trees and small patches. *Ecological Processes*, 10 (1), 20. https://doi.org/10.1186/s13717-021-00284-7

Urban, D. & Keitt, T. (2001). LANDSCAPE CONNECTIVITY: A GRAPH-THEORETIC PERSPECTIVE. *Ecology*, 82 (5), 1205–1218. https://doi.org/10.1890/0012-9658(2001)082[1205:LCAGTP]2.0.CO;2

Vogt, P. & Riitters, K. (2017). GuidosToolbox: universal digital image object analysis. *European Journal of Remote Sensing*, 50 (1), 352–361. https://doi.org/10.1080/22797254.2017.1330650

Watson, J.E.M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J.C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J.G., Painter, M., Wilkie, D., Filardi, C., Laurance, W.F., Houghton, R.A., Maxwell, S., Grantham, H., Samper, C., Wang, S., Laestadius, L., Runting, R.K., Silva-Chávez, G.A., Ervin, J. & Lindenmayer, D. (2018). The exceptional value of intact forest ecosystems. *Nature Ecology & Evolution*, 2 (4), 599–610. https://doi.org/10.1038/s41559-018-0490-x

Watts, K., Eycott, A.E., Handley, P., Ray, D., Humphrey, J.W. & Quine, C.P. (2010). Targeting and evaluating biodiversity conservation action within fragmented landscapes: an approach based on generic focal species and least-cost networks. *Landscape Ecology*, 25 (9), 1305–1318. https://doi.org/10.1007/s10980-010-9507-9

Wilson, M.C., Chen, X.-Y., Corlett, R.T., Didham, R.K., Ding, P., Holt, R.D., Holyoak, M., Hu, G., Hughes, A.C., Jiang, L., Laurance, W.F., Liu, J., Pimm, S.L., Robinson, S.K., Russo, S.E., Si, X., Wilcove, D.S., Wu, J. & Yu, M. (2016). Habitat fragmentation and biodiversity conservation: key findings and future challenges. *Landscape Ecology*, 31 (2), 219–227. https://doi.org/10.1007/s10980-015-0312-3

Zeller, K.A., McGarigal, K. & Whiteley, A.R. (2012). Estimating landscape resistance to movement: a review. *Landscape Ecology*, 27 (6), 777–797. https://doi.org/10.1007/s10980-012-9737-0

Zetterberg, A., Mörtberg, U.M. & Balfors, B. (2010). Making graph theory operational for landscape ecological assessments, planning, and design. *Landscape and Urban Planning*, 95 (4), 181–191. https://doi.org/10.1016/j.landurbplan.2010.01.002

Östlund, L., Laestander, S., Aurell, G. & Hörnberg, G. (2022). The war on deciduous forest: Large-scale herbicide treatment in the Swedish boreal forest 1948 to 1984. *Ambio*, 51 (5), 1352–1366. https://doi.org/10.1007/s13280-021-01660-5

Acknowledgements

I would like to express an enormous thank you to Wiebke Neumann for assisting me in data preparations and sharing software expertise during the early stages of this thesis. This helped me immensely as I assessed methods to move forward. Also, thank you Bengt-Gunnar Jonsson for your assistance when discussing aspects of connectivity and the overall report. Additionally, I would like to say thank you to Sveaskog and Tommy Ek for providing me with Sveaskog data so that I could do undertake this master thesis. Above all, I would like to express my appreciation to my supervisor Johan Svensson for helping me moving forward during the entire thesis process and move on in appropriate directions. I do also want to thank John Ball for computer assistance in the VFM computer lab and Mikael Egberth for allowing me to use and helping me to set up, a computer in Ljungbergslabbet. I would also like to acknowledge the development team of Graphab and especially Paul Savary who has helped me understand certain features of Graphab which I had trouble understanding. Finally, I would like to thank my friends Maja, Svante and William for taking the time to go halibut fishing in Norway as a much-needed break for me in the middle of the semester.

I have gained a lot of insight in ways that can be used to assess connectivity and learnt about the complexity of modelling landscape connectivity. I am thankful for the opportunity to gain such knowledge and will keep investigating such methods in my future work with curiosity.

Simon Mattsson

Appendix 1.

Appendix 1. Pixel values for each raster layer before they are merged, eventually describing "yes/no" when they are merged.

Mapped as pCF by Metria	Sveaskog land cover class	Sveaskog stand age	High Conservation Value Forest	National Landcover data
pCF = 10 000 000	Sveaskog forest = 1 000 000	140 + years = 200 000	Nature Conservation values (Swedish EPA) = 10 000	Not forest = 2, 3, 41, 42, 51, 52, 53, 61, 62
		70-139 years = 100 000	Conservation class (Sveaskog) = 20 000	Pine forest = 111, 121
		Below 70 years = 500 000		Spruce forest = 112, 122
				Mixed conifer forest = 113, 123
				Mixed conifer and deciduous forest = 114, 124
				All deciduous forest = 115, 116, 117, 125, 126, 127
				Temporary not forest = 118, 128

Appendix 2

Appendix 2. Example of the 8 raster layers merged into the summarized layer "sum.raster". Value represents the unique raster value (n=1131), count describes how many 10x10m pixels can be found with that value, m2 calculates the area in sqaure meter and ha is the approximate area after transformation from square meters to ha.

	A	B	C	D
1	value	count	m2	ha
107	1100052	3956	395600	40
108	1100053	373986	37398600	3740
109	1100061	50923	5092300	509
110	1100062	23	2300	0
111	1100111	6621386	662138600	66214
112	1100112	1567100	156710000	15671
113	1100113	956744	95674400	9567
114	1100114	1096749	109674900	10967
115	1100115	301815	30181500	3018
116	1100116	170	17000	2
117	1100118	425787	42578700	4258
118	1100121	206642	20664200	2066
119	1100122	61532	6153200	615
120	1100123	30191	3019100	302
121	1100124	106502	10650200	1065
122	1100125	52465	5246500	525
123	1100128	2662	266200	27
124	1103002	2000	200000	20
125	1103041	49	4900	0
126	1103042	530	53000	5
127	1103051	5	500	0
128	1103053	480	48000	5
129	1103061	638	63800	6
130	1103111	6390	639000	64
131	1103112	2559	255900	26

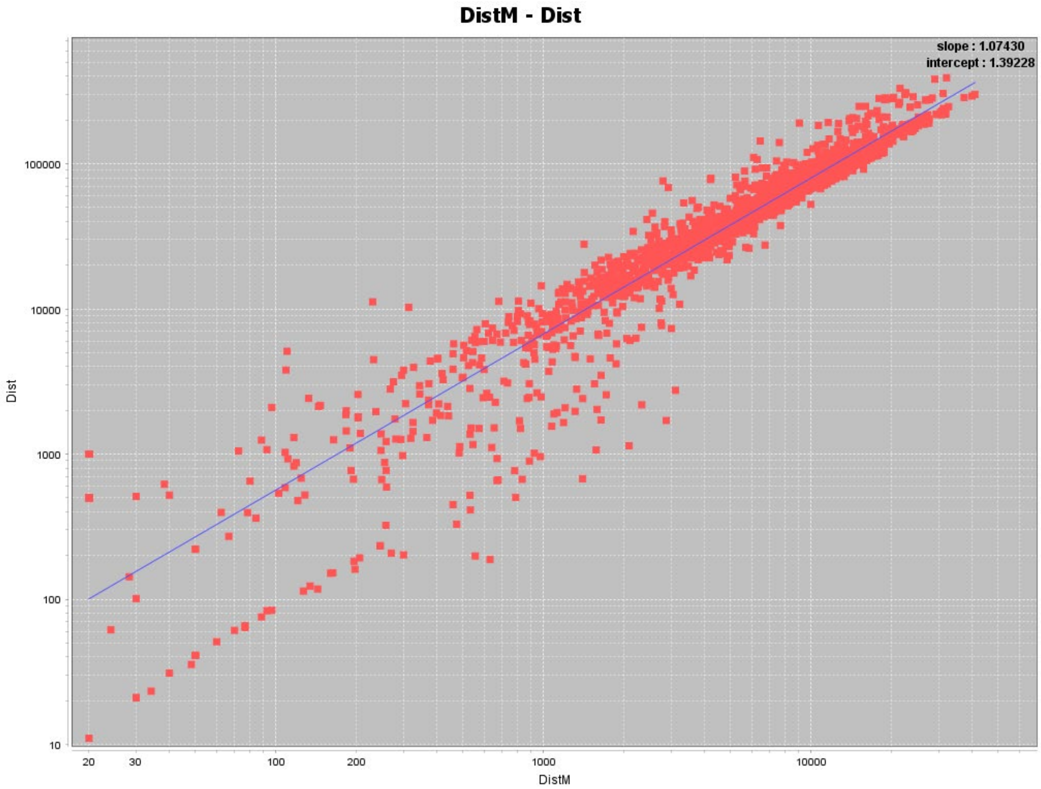
Appendix 3

Appendix 3. Information about land coverage applied from NMD to each category of pCF and HCVF. "Codes" were made in QGIS for each type of forest land coverage. A cost-resistance value corresponding to each type of landscape were set in Graphab. This represents the approach for "All forests" while all non-targeted forest land coverage were set to 500 in all categories during pine forest and spruce forest specific analyses.

		Sveaskog		Not Sveaskog	
		Code	Resistance	Code	Resistance
	Not forest	110	1000		
pCF 70-139 with HCVF	Pine	111	1	101	1
	Spruce	112	1	102	1
	Mixed conifer forests	113	1	103	1
	Deciduous	115	1	105	1
	Temporarily not forest	118	500	108	500
	Not forest	210	1000		
pCF 140+ with HCVF	Pine	211	1	101	1
	Spruce	212	1	102	1
	Mixed conifer forests	213	1	103	1
	Deciduous	215	1	105	1
	Temporarily not forest	218	500	108	500
	Not forest	320	1000		
pCF 70-139 without HCVF	Pine	321	50	301	50
	Spruce	322	50	302	50
	Mixed conifer forests	323	50	303	50
	Deciduous	325	50	305	50
	Temporarily not forest	328	500	308	500
	Not forest	420	1000		
pCF 140+ without HCVF	Pine	421	25	301	50
	Spruce	422	25	302	50
	Mixed conifer forests	423	25	303	50
	Deciduous	425	25	305	50
	Temporarily not forest	428	500	308	500
	Not forest	520	1000		
"Forestry" forest with HCVF	Pine	521	10	501	10
	Spruce	522	10	502	10
	Mixed conifer forests	523	10	503	10
	Deciduous	524	10	505	10
	Temporarily not forest	525	500	508	500
	Not forest	620	1000		
"Forestry" forest without HCVF	Pine	621	100	601	100
	Spruce	622	100	602	100
	Mixed conifer forests	623	100	603	100
	Deciduous	625	100	605	100
	Temporarily not forest	628	500	608	500
Not Forest (Not Sveaskog)				9999	1000

Appendix 4

*Appendix 4. Calculation from metric distance to approximate cumulative least-cost distance were made using log-log scatter plots. This conversion was done for all distances and all analyses in both study areas. The formula used is "Cost distance = exp^(intercept+slope*log(distM))" where distM represents any of the three different metrics chosen.*



Appendix 5

Appendix 5. Values for each type of land coverage for each distance after conversion from Euclidian distances to cost-resistance distances.

Dalarna/Gävleborg > 3 ha	1000m	3000m	5000m
All forest	5756	18 948	32 972
Pine	5640	22 029	41 506
Spruce	22 519	70 838	120 696
Norrbotten/Västerbotten > 6 ha	1000m	3000m	5000m
All skog	4 337	12 535	20 533
Tall	6 696	21 287	36 448
Gran	11 153	32 912	54 434

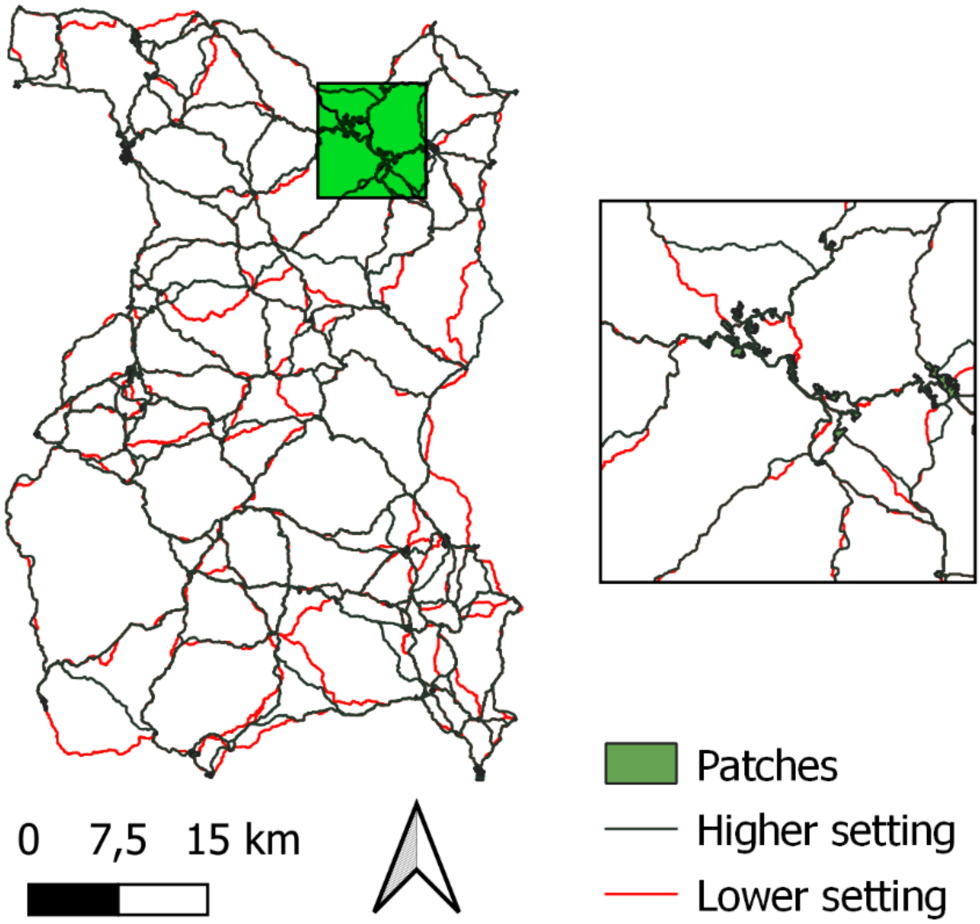
Appendix 6

Appendix 6. Description of the Betweenness Centrality index as calculated in Graphab.

Betweenness Centrality index (BC)	Formula	Meaning
Local level	$BC_i = \sum_j \sum_k a_j^\beta a_k^\beta e^{-\alpha d_{jk}}$ $j, k \in \{1..n\}, k < j, i \in P_{jk}$	Sum of the shortest paths through the focal patch i, each path is weighted by the product of the capacities of the patches connected and of their interaction probability. Pjk represents all the patches crossed by the shortest path between the patches j and k.
Values	Values depend on the configuration. They correspond to a weight of potential transit. Minimum value: 0 Maximum value: square of the total area of habitat.	

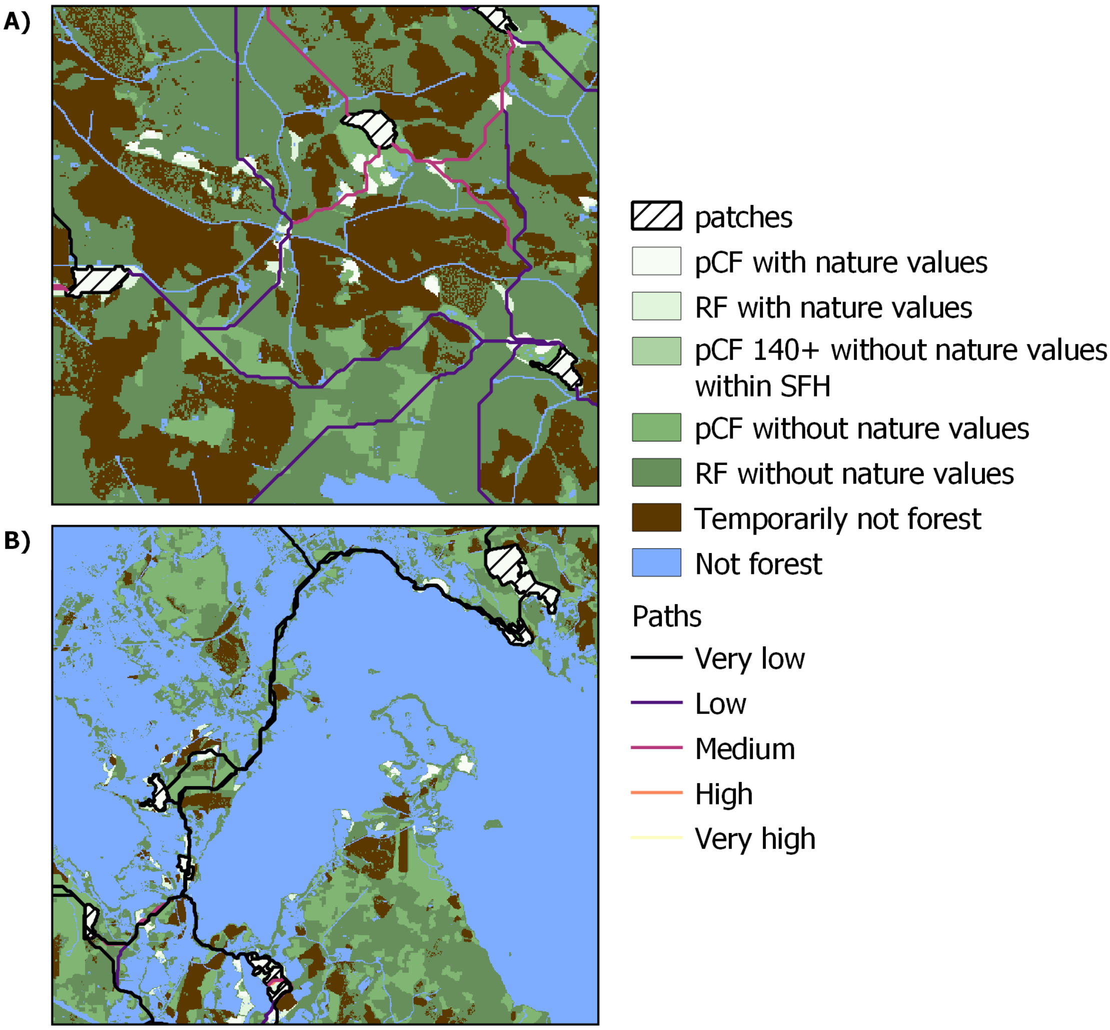
Appendix 7

Appendix 7. Illustration of how least-cost paths alter depending on settings of the landscape resistance. Black routes illustrate the higher setting of 500 to all non-targeted tree species in a pine forest land coverage example, while red routes is with a setting of 250.



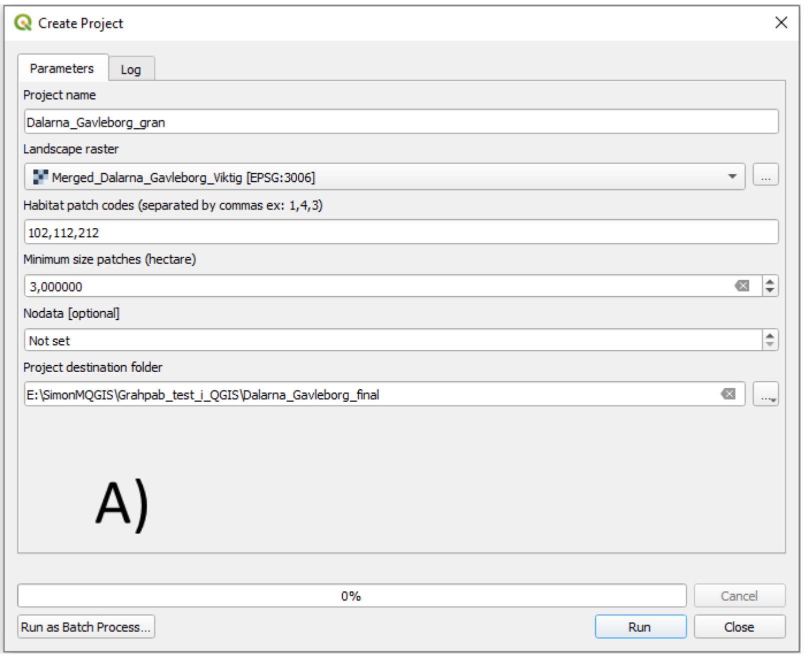
Appendix 8

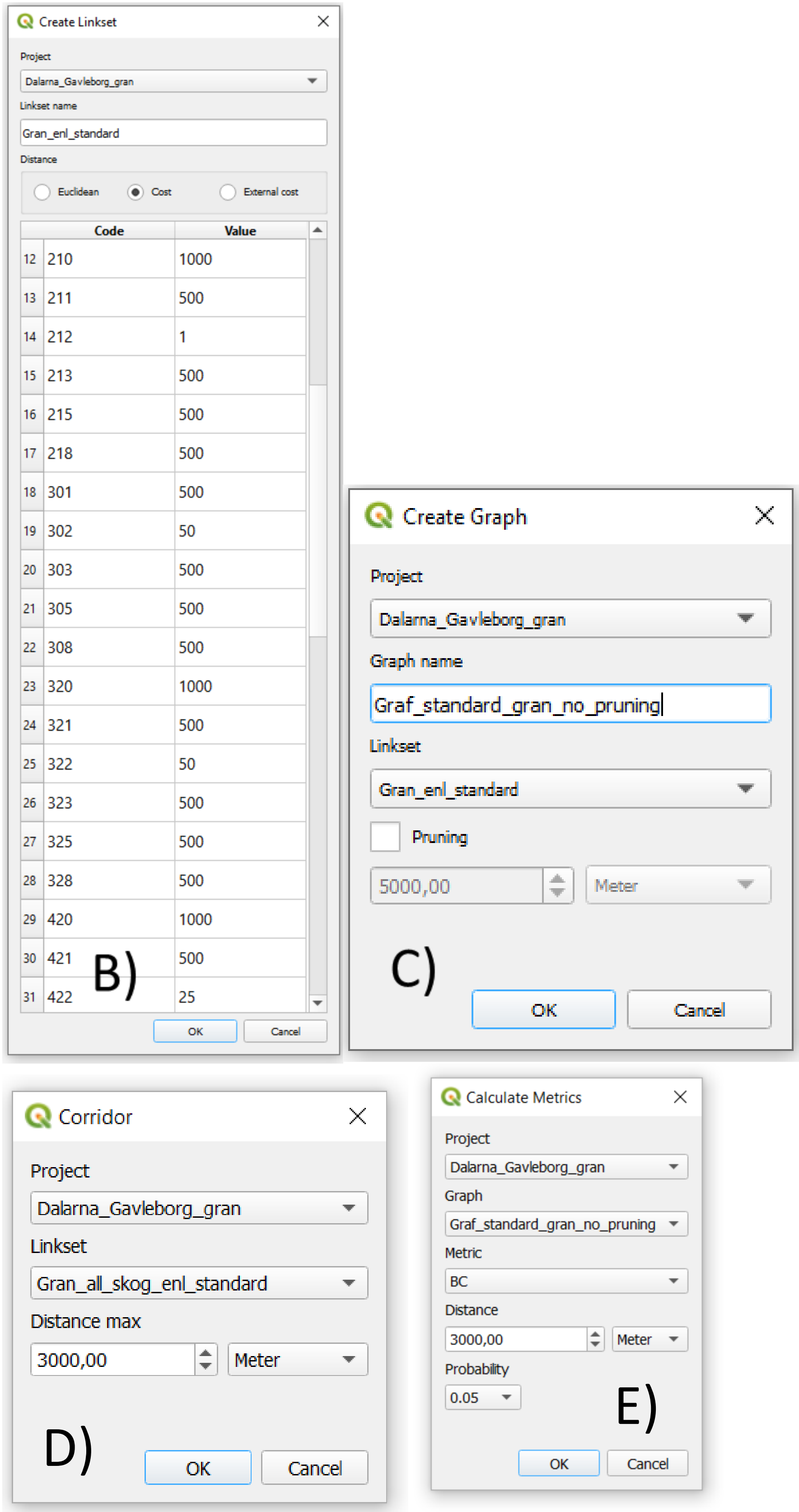
Appendix 8. Least-cost paths in relation to forest background. Example A) illustrate several examples of how least-cost paths stretches through areas with lower resistance (higher conservation values) instead of passing through temporarily not forest which would make paths with a shorter distance. Example B) illustrate when least-cost paths cross through areas without forest as the accumulated path-cost is lower crossing here than making a path entirely through forest areas with lower resistance values. Betweenness centrality values for least-cost paths are illustrated with colors ranging from black (very low importance) to yellow (very high importance).



Appendix 9

Appendix 9. Figures illustrating the steps and settings in the QGIS-plugin of Graphab. A) illustrated the creation of a project with habitat patch codes from a landscape map and the minimum patch size. B) is an example of the linkset and the cost-resistance values set for different categories of HCVF&pCF when focusing on spruce forest. I have chosen to work with cost-resistance distances instead of Euclidean distances. C) illustrate the step of transforming the linkset into a graph with the possibility of pruning. D) illustrates the making of a corridor. It is important to note that when working with cumulative cost-resistance distances choosing a metric distance of 3000 (like I have done in the example) Graphab automatically calculates the metric distance into a cost-resistance threshold. E) illustrate the settings for the betweenness centrality metric (BC).




Create Linkset
Project
Dalarna_Gavleborg_gran
Linkset name
Gran_enl_standard
Distance
Euclidean
Cost
External cost
Code
Value
12 210 1000
13 211 500
14 212 1
15 213 500
16 215 500
17 218 500
18 301 500
19 302 50
20 303 500
21 305 500
22 308 500
23 320 1000
24 321 500
25 322 50
26 323 500
27 325 500
28 328 500
29 420 1000
30 421 500
31 422 25
B)
OK
Cancel
Create Graph
Project
Dalarna_Gavleborg_gran
Graph name
Graf_standard_gran_no_pruning
Linkset
Gran_enl_standard
Pruning
5000,00
Meter
C)
OK
Cancel
Corridor
Project
Dalarna_Gavleborg_gran
Linkset
Gran_all_skog_enl_standard
Distance max
3000,00
Meter
D)
OK
Cancel
Calculate Metrics
Project
Dalarna_Gavleborg_gran
Graph
Graf_standard_gran_no_pruning
Metric
BC
Distance
3000,00
Meter
Probability
0.05
E)
OK
Cancel