Distribution and connectivity of nature conservation value forests in Ecopark Käringberget

Oskar Eriksson

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Faculty of Forest Sciences
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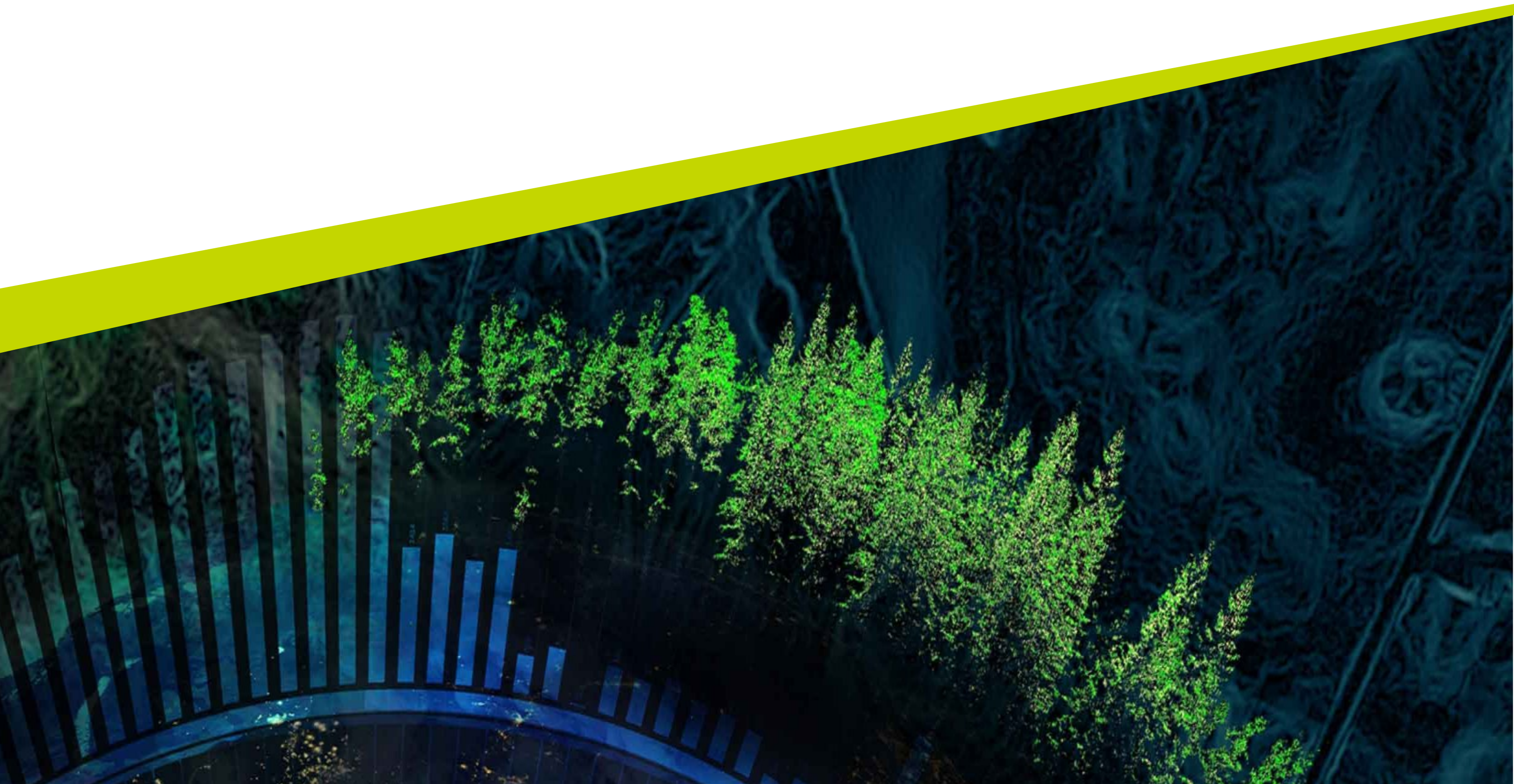

Distribution and connectivity of nature conservation value forests in Ecopark Käringberget.

Fördelning och konnektivitet av naturvärdesskog i Ekopark Käringberget.

Oskar Eriksson

Supervisor:	**Johan Svensson, SLU, Department of Wildlife, Fish and Environmental Studies**
Assistant supervisor:	Xiaoming Wang, SLU, Department of Wildlife, Fish and Environmental Studies
Examiner:	Therese Löfroth, SLU, Department of Wildlife, Fish and Environmental Studies

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Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Department of Forest Ecology and Management

Abstract

While site specific conditions are important for protected nature areas, connectivity enabling species movement also plays a key role in nature conservation. The purpose of this study was to examine the distribution of high nature conservation value forests and the ecological connectivity of such forests within one of Sveaskog's Ecoparks; the circa 14,000 ha area of Käringberget with combined forestry and heightened nature conservation. High conservation value forest density was modelled in QGIS, and connectivity was calculated with an Omniscape.jl analysis. The connectivity analysis was based on high nature conservation value forest data, national land coverage data and Sveaskog forest management goal class data. The connectivity significance of each dataset was determined following previous research. The study found a high density of high conservation value forests in the Ecopark and a connectivity network spanning the entire Ecopark. The connectivity analysis can inform future management. The recommendations for future management in the Ecopark from this study is to create new ecological corridors through restoration in fragmented areas, and to strengthen existing corridors.

Keywords: Connectivity analysis, Ecopark, High nature conservation value forests

Sammanfattning

Medan platsspecifika egenskaper är viktiga för skyddade naturområden, spelar konnektivitet, som möjliggör arters rörelse, en viktig roll inom naturvården. Syftet med denna studie var att undersöka fördelningen av skogar med höga naturvärden och konnektiviteten hos dessa skogar inom en av Sveaskogs ekoparker; käringberget, ett cirka 14 000 ha stort område med kombinerat skogsbruk och förstärkt naturvård. Tätheten av naturvärdesskogarna analyserades i QGIS och konnektiviteten modellerades med Omniscape.jl. Konnektivitetsanalysen baserades på data över naturvärdesskog, nationella marktäckedata, och data över Sveaskogs målklasser. Betydelsen för konnektivitet hos varje datamängd bestämdes följande tidigare forskning. Studien fann höga tätheter av naturvärdesskog i ekoparken och ett konnektivitetsnätverk som sträckte sig genom hela ekoparken. Konnektivitetsanalysen kan bidra med underlag för framtida skötsel. Rekommendationerna för framtida skötsel från denna studie är att skapa nya ekologiska korridorer genom restaurering i fragmenterade områden och att stärka befintliga korridorer.

Nyckelord: Konnektivitetsanalys, Ekopark, Naturvärdesskogar

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Abbreviations

SLU	Swedish University of Agricultural Sciences
PG	Forest production goal with general nature conservation consideration
PE	Forest production goal with enforced nature conservation consideration
NM	Nature conservation goal with management
NF	Nature conservation goal, free development
CCM	Cumulative current map
NCCM	Normalized cumulative current map
HCVFSw	High Conservation Value Forests, Sweden
NMD	National land coverage

1. Introduction

While high-quality patch-specific site conditions or substrates in protected nature areas are crucial for the long-term survival of many species of nature conservation concern, the impact of connectivity on various geographical scales should not be overlooked. Connectivity, a concept connected to the ease of which species move through the landscape, strengthens populations in many ways. Connectivity can lower inbreeding and increase intra-specific diversity (Coulon et al. 2004). Also, connectivity can facilitate species shifting range, which makes species more resilient against climate change as habitats become unsuitable due to climate related factors (Sgrò et al. 2010). In addition, populations can be aided through connectivity maintaining metapopulation dynamics e.g. by permitting patch colonization (Castorani et al. 2015).

The ecological connectivity of European forests has thus received increasing attention since the year 2000 (Martínez-Richart et al. 2024), for example in the context of the EU Nature Restoration Regulation (Svensson et al. 2025) as well as generally in conservation planning (Bovin et al. 2017).

In northern Sweden, the connectivity of high conservation value forests is high primarily along the foothills of the Scandinavian mountain range (Bovin et al. 2017; Mikusiński et al. 2021; Svensson et al. 2020). Coastal and other inland areas have lower connectivity, especially in Västerbotten County (Mikusiński et al. 2021; Svensson et al. 2020). Bovin et al. (2017) found low connectivity of high conservation forests in large areas of sub-mountainous Västerbotten. Thus, the large-scale connectivity in sub-mountainous Västerbotten may be low, indicating a need for connectivity restoration. Already available connectivity resources in Västerbotten may hence need to be assessed, as these could play a role in restoration. Additionally, connectivity on smaller scales has not been examined in Västerbotten.

For Swedish high conservation value forests, Sveaskog's Ecoparks can serve as crucial nodes in connectivity networks, enabling species dispersal (Mattson 2022). While connectivity of larger areas of Sveaskog-owned land areas has been studied, e.g. Elbakidze et al. (2011) and Mattson (2022), the connectivity within Ecoparks has not. In Västerbotten, as Ecoparks could aid in connectivity restoration, and as connectivity on smaller scales has not been studied, there is a need to study the connectivity of Ecoparks.

1.1 Purpose and research questions

Sveaskog and SLU have an ongoing research partnership to assess the connectivity in and around Sveaskog's Ecoparks and this study serves as a part of that partnership. The purpose of this study is to examine the connectivity in the Sveaskog Ecopark Käringberget forest landscape of northern Sweden. In this study, connectivity is assessed based on high conservation value forests following the model by Bubnicki et al. (2024) for Sweden and Sveaskog's Ecopark forest management plan, without further division into dominating tree species or forest habitat types. Hence, the study was directed to structural connectivity.

Research questions

1. How are forests with high nature conservation values distributed in Ecopark Käringberget, according to the nature conservation value assessments of Sveaskog and the map model High Conservation Value Forests, Sweden?
2. Where are high concentrations of forests with high nature conservation value located?
3. How does connectivity patterns differ between assessment based on the high conservation value forest model, and based on the management goal classes by Sveaskog?

2. Background

For this study, the concepts of connectivity and Ecoparks are crucial. The previous findings on the topic of forest connectivity in northern Sweden are also vital for understanding the context of this study.

2.1 Connectivity

A key and central concept in ecology and conservation biology is connectivity (Fagan & Calabrese 2006). The concept has a myriad of distinct definitions, however, making its meaning diffuse (Calabrese & Fagan 2004; Fagan & Calabrese, 2006; Kindlmann & Burel 2008). Authors may not even use one specific definition of connectivity, instead noting the plethora of separate definitions, such as in Liczner et al. (2024).

Two commonly quoted definitions, however, are by Taylor et al. (1993) and the Convention on Biological Diversity (2022). Taylor et al. (1993:571) defines landscape connectivity as "the degree to which the landscape facilitates or impedes movement among resource patches", while the Convention on Biological Diversity (2022:2) defines ecological connectivity as "the unimpeded movement of species and the flow of natural processes that sustain life on Earth". Thus, connectivity can be defined differently depending on the scope, ecological connectivity being a broader, general term, while landscape connectivity is narrower and seen as a component of the landscape. As such, landscape connectivity may be seen as a subcategory of ecological connectivity.

Kindlmann & Burel (2008) identify two main subsets of connectivity definitions; structural connectivity and functional connectivity. Structural connectivity is a connectivity description depending solely on landscape structure, while functional connectivity additionally takes species behaviour and movement into account. Functional connectivity can be divided further into the categories of potential connectivity and actual connectivity (Fagan & Calabrese 2006; Kindlmann & Burel 2008). Calabrese & Fagan (2004) define potential connectivity as connectivity depending on landscape structure as well as species movement abilities, while actual connectivity is defined as connectivity affected by the aforementioned factors, but where actual movement must be observed. As each of the definitions structural, functional, potential, and actual connectivity depend on the landscape, they may be considered subcategories of landscape connectivity.

2.2 Previous studies

Multiple previous studies have modelled or analysed the connectivity of boreal forest areas in northern Sweden.

The Norrbotten County Administrative Board together with the Mid Sweden University conducted density analyses of nature conservation value forests and wetlands throughout Norrbotten County, Sweden, and used the Omniscape algorithm to model the connectivity of both nature types (Nilsson & Englund 2024). The connectivity analysis for forests identified high connectivity in the sub-mountainous forests as well as in certain protected forest sites. It was argued the density analysis for forests was reliable enough for comprehensive planning, but that the forest connectivity analysis was limited in its use, requiring deep insights in the method, which limits its practical use in conservation planning.

Metria AB by commission of the Swedish Environmental Protection Agency, identified suggestions for key forest areas of nature conservation value in boreal Sweden through a model based on connectivity analyses of conservation value data (Bovin et al. 2017). Network analyses were also carried out based on core nature conservation forest sites identified, as well as on the key nature conservation forest areas. In total, 362 key nature conservation forest areas were identified. The largest continuous network of these spanned across all counties. It was argued that the results of this project can be used in nature conservation planning and that similar methodologies should be used in future projects.

Svensson et al. (2020) used the Circuitscape algorithm to analyse the connectivity of identified proxy continuity forests in boreal Sweden. The study identified a network of high forest connectivity along the foothills of the Scandinavian mountains, while lower inland and coastal areas had lower connectivity, though a scattered connectivity network was found in the northern inland and coastal regions.

Mikusiński et al. (2021) evaluated the overlap of protected forests, other high conservation value forests and proxy continuity forests in the landscape of northern Sweden, and additionally modelled connectivity of forests as well as estimated the habitat suitability in the landscape using a virtual species method. The connectivity analysis was done in Circuitscape and had three scenarios, one of which only included protected forests, while another additionally included other high conservation value forests, and the third also added proxy continuity forests. Like Svensson et al. (2020), high connectivity was found along the sub-alpine forests of the Scandinavian mountain range. There were no considerable differences in connectivity between including only protected forests and including all high conservation value forests. Including proxy continuity forests in the analysis, however, increased connectivity in the counties of Norrbotten and Jämtland.

Wang et al. (2025) used data from a national prediction model for high conservation value forests in Sweden (Bubnicki et al. 2024) to map green infrastructure density of forests in a river watershed in northern Sweden. This study modelled connectivity forests, i.e. forests of a range of conservation value likelihoods outside high conservation value forests, into the green infrastructure model. The study found a great capacity to increase green infrastructure density in the landscape by maintaining forests of likely conservation value and argued that connectivity assessments can be useful as planning tools for nature conservation, such as by indicating forests of connectivity importance to restore.

Bergsten et al. (2013) estimated the connectivity of old dry pine forests in the two northernmost counties of Sweden using a network approach based on habitat availability while considering different dispersal ranges of species. There were three scenarios of increasing inclusion of different area categories in the network. The study found habitat availability to be different from total protected habitat, because of connectivity effects. In addition, all area categories (nature reserves, less strict protected areas, areas of informal protection, and stepping stones) were found to increase connectivity, but to different degrees for species of different dispersal ranges. Older production forests were also found to serve as stepping stones for some species. The study concluded that planning of protected areas, but also forestry operations, should consider the dispersal ranges and habitat requirements of different species to ensure connectivity.

Mattson (2022) examined the connectivity of the forests holding of Sveaskog through two case studies; one in an area within the counties of Norrbotten and Västerbotten and another in an area within the counties of Dalarna and Gävleborg. In each area, a network connectivity analysis was made, identifying nodes of nature conservation value and least-cost pathways between them. Additionally, areas of high permeability surrounding nodes were identified; referred to as corridors. The study found a higher connectivity in the northern study area, attributed to a higher density of conservation value forests. In both case studies, the Ecoparks of Sveaskog were found to greatly facilitate connectivity in the landscape.

To evaluate the effects of the Forest Stewardship Council certification, Elbakidze et al. (2011) compared a Swedish and a Russian state-managed forest based on nature conservation criteria. Two of the criteria used were structural connectivity, determined using a morphological spatial pattern analysis, and functional connectivity, determined using a virtual focal species approach at different patch size requirement scales. The structural connectivity results for the Swedish forest, a 563,629-ha forest area in Bergslagen owned by Sveaskog, was that conservation forest were comprised mostly of core and edge forests or alternatively mostly islet forests, depending on the distance of edge influence used.

For functional connectivity, the Swedish forest was found to be sufficiently connected for species with 1 ha habitat requirements, though not for species with higher habitat requirements (10 ha and 100 ha).

Angelstam & Manton (2021) assessed the connectivity of Dalarna and Jämtland Counties by performing four focal species analyses. The study found a recent decrease in habitat network functionality of 15% or above for both Norway spruce and Scots pine.

2.3 Ecoparks

Ecoparks are continuous areas of at least 1,000 hectares with sites of high nature conservation values within (Sveaskog 2005). They are delineated by Sveaskog, a forest company owned by the Swedish state, and are hence exclusively located on Sveaskog-owned land. In Ecoparks, nature conservation ambitions are high with large areas classified with a nature conservation goal (either untouched or managed; i.e. with passive or active nature conservation strategies). Also, forestry is still conducted, but with enforced nature conservation consideration or with general nature conservation consideration. The Sveaskog objective is that forest production goals should not exceed 50% of the forest area. In the Ecopark management planning, the same forest management goal classes (målklasser) as elsewhere in the Swedish forest planning model are used: NF (nature conservation goal, free development), NM (nature conservation goal through management), PE (production goal with enforced nature conservation consideration), and PG (production goal with general nature conservation consideration).

3. Materials and Methods

In this section, materials and methods of the study are presented, including the study area, analyses, models, and the study procedure.

3.1 Study area

The study area was designated as Ecopark Käringberget together with the surrounding landscape, defined as a rectangle three times larger than the smallest possible rectangle that could encompass the Ecopark, as shown in Figure 1. While the aim of the study was to examine the conditions within the Ecopark, the surrounding landscape was also included in the analyses to minimize edge effects.

3.1.1 Ecopark Käringberget

Ecopark Käringberget is a Sveaskog Ecopark located near Fredrika in Västerbotten County (Sveaskog 2005), see Figure 1. The Ecopark has an area of approximately 14,000 hectares distributed across Åsele and Bjurholm municipalities. Ecopark Käringberget is elongated from northwest to southeast and additionally has two branches or salients. One salient, referred to as the northern salient, stretches northwest from the north of the Ecopark and is only a few hundred metres narrow at most. The other salient, referred to as the southern salient stretches southwest and then northwest from the centre of the Ecopark. The forests of Käringberget are primarily conifer stands such as Scots pine (*Pinus sylvestris*) forests, but also younger broadleaf stands are present. Hills, open water, and mires are characteristic of the area. Man-made non-forest land is comprised of roads and clearcuts. 10% of the forests of Käringberget are classified as the management goal class NF, while 35% are NM, 25.4% are PE, and 29.6% are PG.

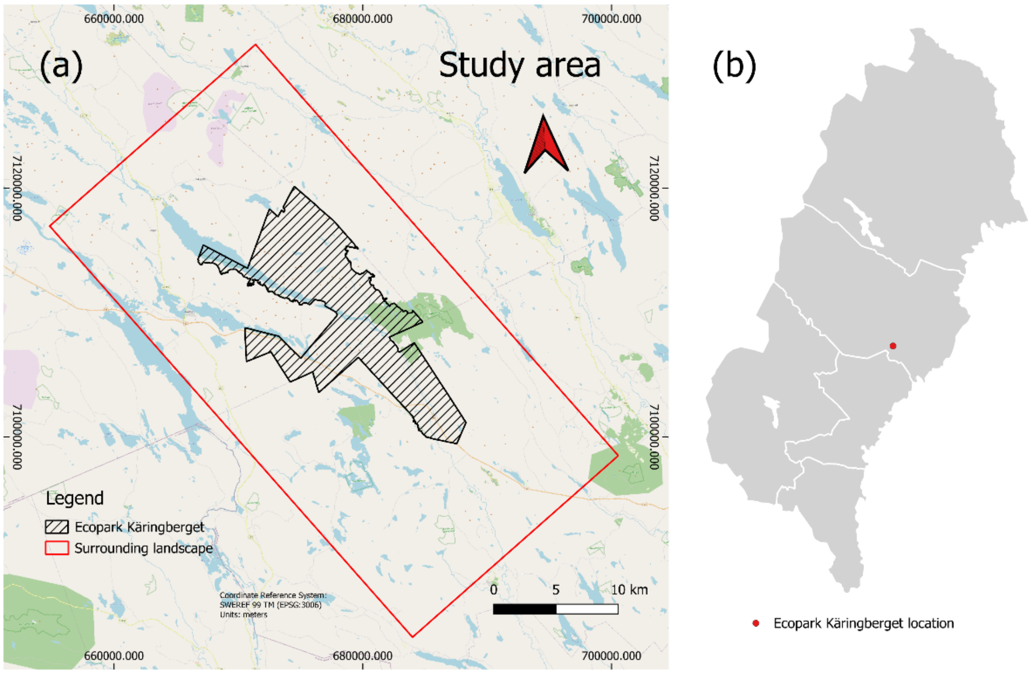

Figure 1. The study area extent and location. (a) The study area comprised of Ecopark Käringberget and the surrounding landscape. Background map from OpenStreetMap https://www.openstreetmap.org/copyright. (b) The location of Ecopark Käringberget within the five northernmost counites of Sweden. County borders © Statistics Sweden.

Nature conservation values

Ecopark Käringberget has many nature conservation values (Sveaskog 2005). The Ecopark contains a varied landscape, with habitats for many different species. There is variation in elevation, humidity, soil, forest type and forest stand age. Many stands contain nature value trees, i.e. trees with high nature conservation value. Pine is the most common species among the nature value trees, but other species include birch (*Betula ssp.*), spruce (*Picea abies*), *Salix caprea*, and aspen (*Populus tremula*). Though there is variation between species, nature value trees typically are old with thick trunks and rough bark, importantly acting as substrate for many lichens, some of which are of nature conservation status. There is additionally a high amount of broadleaf trees in the Ecopark, most of which is birch, but there are also many aspen clones. A total of 41 red listed species in the categories endangered, vulnerable or nearly threatened, have been found. Important natural disturbance regimes in Käringberget are the fire regime, which historically has had a large impact; and natural water disturbance, such as flooding caused by beaver dams.

3.2 Data

The analyses of this study were based on three datasets. All data used was limited to the study area, i.e. Käringberget and the surrounding landscape, see Figure 1.

One dataset used was High Conservation Value Forests, Sweden (HCVFSw) (Jonsson et al. 2024b), also referred to as Naturvärdeskarta skog (NVK skog) (Jonsson et al. 2024a), originally presented by Bubnicki et al. (2024). HCVFSw models the probability of high conservation value in forests throughout Sweden (Jonsson et al. 2024a). The model is trained on known and documented high conservation value forests and based on various variables at different geographical scales from each 1 ha pixel to more than 10,000 ha surrounding that pixel. The HCVFSw data resulting from the model is a raster of 100x100-meter pixels with the value of each pixel predicting the likelihood of containing high conservation value forest from 0-100%.

Another dataset used was Swedish national land cover data (nationell marktäckedata, NMD) version 1.1 (Swedish Environmental protection Agency n.d.). NMD is a nationwide land use mapping of Sweden made by the Swedish Environmental Protection Agency in collaboration with other State agencies (Swedish Environmental Protection Agency 2023). The resulting data is a raster with a pixel size of 10x10 meters of 25 separate land coverage classes. The land coverage classes include 16 forest types; one class of open wetlands; one farmland class; two types of other open land; three types of exploited land; and two types of open water.

The third dataset was a vector layer of the forest holdings of Sveaskog, including data for each stand such as the designated forest management goal classes of PG, PE, NM and NF, as well as restoration forest classes. The latter data includes forest stands where Sveaskog have or have planned to perform some type of restoration resulting in enhanced conservation value. This dataset will be referred to as the Sveaskog holding data.

3.3 Analyses and models

In this study, a density analysis and a connectivity model was used.

3.3.1 Density analysis

A spatial density analysis is an analysis that determines the spatial occurrence of a certain entity. Such algorithms generally work by sequentially moving through all pixels in a raster and determining how many pixels that qualify within a set radius around the pixel.

In this study, the SAGA Next gen tool Focal Statistics in QGIS was used as density analysis. For each pixel in a raster, the Focal Statistics tool computes various statistical measures for the values of the pixel and surrounding pixels (Conrad 2003). The surrounding area (i.e. the area which the tool uses as input for statistical measures for each pixel) is delineated by a radius which is defined specifically for the purpose. One of the statistical measures the tool can calculate is mean value within the radius.

3.3.2 Connectivity models

Many methods have been used to estimate or quantify connectivity (Fagan & Calabrese 2006). Among these are methods based on calculations from GIS data of landscape structure and habitat qualities for assessment of structural connectivity.

In this study, connectivity was modelled based on such spatial data. The model used was Omniscape.jl, a package for connectivity modelling based on the package Circuitscape.jl written in the programming language Julia (Landau et al. 2021).

Circuitscape.jl

Circuitscape.jl is a Julia package that models connectivity by simulating random species dispersal through the environment as an electric current through an electrical network (Anantharaman et al. 2020).

The package requires two forms of input. One is a resistance layer, which is a raster file that proxy how easy species can move within a landscape; i.e. simultaneously considering permeability and resistance. Each pixel has an assigned value signifying the level of difficulty for species movement through the pixel, adapted to the study at hand with the resistance values derived from reputable sources. The other input is focal nodes, a list of points in the landscape representing suitable habitats.

The algorithm works by connecting the nodes through a network based on the resistance layer and calculating each electrical current between all possible combinations of focal nodes representing electrical sources. The pixels of the resistance layer make up the network, connecting to neighbouring pixels and allowing amounts of current depending on their resistance values. The electrical model results in values for each pixel in the raster for different dispersal pathways. All values are then summed up for each pixel, representing the dispersal facilitating properties of the pixel. Together the pixels then form a raster showing patterns in the dispersal conditions of the landscape.

Omniscape.jl

Omniscape.jl is a Julia package for connectivity modelling based on Circuitscape.jl (Landau et al. 2021). Contrary to Circuitscape.jl, however, it does not require user determined focal nodes and instead uses a source strength raster covering the whole study area to identify focal nodes of various source strengths. Each pixel of this raster has a value corresponding to how easy species can disperse from that pixel, abstracted as electrical source strength. The source strength raster is defined before running the program and can be derived from the resistance layer. When derived from the resistance layer, the source (permeability) strength layer is the opposite of the resistance layer.

In Omniscape.jl, the Circuitscape.jl model is applied iteratively across the examined area for each pixel (or every pixel within a set distance interval) with a source strength greater than zero (or a source strength above a user-defined level). The pixel for which a specific iteration of the model is applied is referred to as the target pixel. Each Circuitscape.jl iteration is limited by a search window defined as a circle around the target pixel with a user determined radius. All pixels with a source strength greater than zero within the search window are set as focal nodes for each model iteration. When all iterations of the connectivity model are done, the current for each pixel is finally summed up into a cumulative current map (CCM). Additionally, a normalized cumulative current map (NCCM) can be returned, detailing the difference between the CCM and a different model output which only has the source layer as input and thus no resistance. The NCCM thereby shows a current map corrected for the effects of source distribution.

3.4 Procedure

The procedure of this study is described henceforth, including the density analysis, data preparation, connectivity modelling and spatial statistics.

3.4.1 Density analysis and data preparation

The density analysis of high nature conservation forests and the data preparation for the Omniscape.jl connectivity analysis were carried out in QGIS desktop 3.34.11. The density analysis of high nature conservation forests served as part of the data preparation for Omniscape.jl.

Initial data preparation

First, the HCVFSw data with probabilities of 40% or above were reclassified into six classes; probabilities of 40-49, 50-59, 60-69, 70-79, 80-89, and 90-97%. No values higher than 97% occurred. Values below 40 were set to zero. NMD was reclassified into the following four classes: forests; wetlands; open land, farmland, and temporarily non-forest land; and water and exploited land. The two rasters were then aligned with HCVFSw as reference layer. As a result, NMD was converted to a pixel size of 100x100 meters, aligned with HCVFSw. The Sveaskog holding data was then rasterized with the aligned NMD data as output extent. Finally, a raster of Sveaskog holding data aligned with NMD was created.

NMD forest

The aligned NMD data was used to create a binary raster of forest and non-forest land. The binary NMD forest data will henceforth be referred to as NMD forest. To ensure only forest data was used in the analysis, NMD forest was used to exclude data from non-forest pixels of both HCVFSw and Sveaskog holding data.

Density analysis

A binary HCVFSw raster was created by assigning all pixels from each of the six probability classes of 40% or above the value 1 and assigning all other forest pixels the value 0. A density analysis based on this binary HCVFSw data was then carried out using the SAGA Next gen tool Focal Statistics. The analysis was done with a circular search window with a radius of five pixels (500 meters), and the result was a mean value density map of HCVFSw. This HCVFSw density map was then classified into six classes between 0 and 100%. The classes were: ≥ 0% and < 0.0001%; ≥ 0.0001% and < 20%; ≥ 20% and < 40%; ≥ 40% and < 60%; ≥ 60% and < 80%; and ≥ 80% HCVFSw density.

Nature conservation forests based on Sveaskog's forest management goal classes

In order to map out the forest stands with nature conservation goal classes, a binary raster based on stand forest management goal classes was created from the Sveaskog holding data. The forest management goal classes NF and NM were given a value of 10 and the forest management goal classes PE and PG were given a value of 0.

Data compilation and resistance layer creation

The classified HCVFSw data within NMD forests and the classified HCVFSw density were combined to create a raster with classes for both datasets combined. Then, NMD forest was used to exclude non-forest pixels from the combined dataset. Two datasets were extracted from this data. The first was all areas (including non-forest areas) outside the six HCVFSw classes of 40% probability or higher. This dataset will be referred to as Outside HCVFSw data. The second dataset contained 30 classes (see Table 1) based on the six HCVFSw classes of 40% probability or higher, combined with the five HCVFSw density classes. This dataset will be referred to as HCVFSw and density data.

The aligned NMD data was combined with Sveaskog forest holding nature conservation data to create a raster with five classes: the three non-forest NMD classes as well as the Sveaskog nature conservation forests, and NMD forests outside of these conservation areas. To exclude areas within the HCVFSw and density data, data not overlapping with Outside HCVFSw data was removed from the NMD and Sveaskog nature conservation data.

To finally assemble the resistance layer for Omniscape.jl, HCVFSw and density data was combined with the NMD and Sveaskog nature conservation data. Because there was no overlap between the datasets, no new classes were created. The final resistance layer thus included 35 classes; the 30 combinations of HCVFSw and density classes, the one Sveaskog nature conservation class (outside HCVFSw and density), and the four NMD classes (outside HCVFSw and density as well as Sveaskog nature conservation data).

3.4.2 Omniscape.jl analysis

In Julia 1.10.11 with Omniscape v0.6.2 installed, a directory containing the resistance layer was set and from there, the resistance layer was selected as an input file. The resistance layer was set as resistance layer and provided projection and georeferencing information. Omniscape was configured to have a 30-pixel radius (3 000 meters) and a block size of 1 pixel, meaning the Circuitscape connectivity model was run for every source pixel with the set radius. The variable source_from_resistance was set to true, so that the source layer was to be derived from the resistance layer. Normalized current was set to be calculated. The program was set to reclassify the resistance layer and thus assign resistance values to the 35 resistance classes. The resistance values assigned to each class follow Nilsson & Englund (2024) with adaptations to the specific data of this study and is shown in Table 1. These resistance values were imported from an encoded .txt-file. Finally, the Omniscape.jl algorithm was run using the run_omniscape() function with the aforementioned options and inputs, to return a CCM and a NCCM over the landscape surrounding Ekopark Käringberget.

3.4.3 Spatial statistics

Spatial statistics were also carried out in QGIS Desktop 3.34.11 using the tool Zonal Histogram to ascertain the overlap between different data within Ecopark Käringberget. Spatial statistics were run for HCVFSw classes as well as for CCM classes and NCCM classes, for the overlap of each dataset with Sveaskog’s forest management goal classes.

Table 1. The resistance values assigned to each of the 35 classes of the resistance layer in the Omniscape.jl connectivity analysis.

Class		Resistance value
HCVFSw 90-97	Density ≥ 80%	1
	Density ≥ 60%, < 80%	2
	Density ≥ 40%, < 60%	3
	Density ≥ 20%, < 40%	4*
	Density < 20%	5*
HCVFSw 80-89	Density ≥ 80%	6
	Density ≥ 60%, < 80%	7
	Density ≥ 40%, < 60%	8
	Density ≥ 20%, < 40%	9
	Density < 20%	10*
HCVFSw 70-79	Density ≥ 80%	11
	Density ≥ 60%, < 80%	12
	Density ≥ 40%, < 60%	13
	Density ≥ 20%, < 40%	14
	Density < 20%	15*
HCVFSw 60-69	Density ≥ 80%	16
	Density ≥ 60%, < 80%	17
	Density ≥ 40%, < 60%	18
	Density ≥ 20%, < 40%	19
	Density < 20%	20
HCVFSw 50-59	Density ≥ 80%	21
	Density ≥ 60%, < 80%	22
	Density ≥ 40%, < 60%	23
	Density ≥ 20%, < 40%	24
	Density < 20%	25
HCVFSw 40-49	Density ≥ 80%	26
	Density ≥ 60%, < 80%	27
	Density ≥ 40%, < 60%	28
	Density ≥ 20%, < 40%	29
	Density < 20%	30
Sveaskog nature conservation forest		40
Other forest		50
Open wetlands		150
Open land, farmland, and temporarily non-forest land		150
Water and exploited land		300

*Values not included in the final resistance layer as no classes with such combinations of HCVFSw and density values were present in the current study.

4. Results

In this section, the results are presented. Results from the spatial statistics are shown as 100% stacked bar charts and results from the density and connectivity analyses are shown as maps. As only the results from Ecopark Käringberget are of concern, the results from the surrounding landscape are not included in the maps.

The forest management goal class distribution across HCVFSw classes showed an increasing percentage of both categories of nature conservation forests with increasing HCVFSw probability, and a complementarily decrease in both categories of production forests (Figure 2). Normal forestry goal (PG) had a larger share in the <30% HCVFSw-class than in forest land without any HCVFSw-prediction. The share of restoration forest was highest in the 60-69% HCVFSw-class but relatively stable across classes with HCVFSw-prediction. A lower restoration forest share in the highest HCVFSw compared with the previous two classes indicate that the nature conservation qualities more often are favourable.

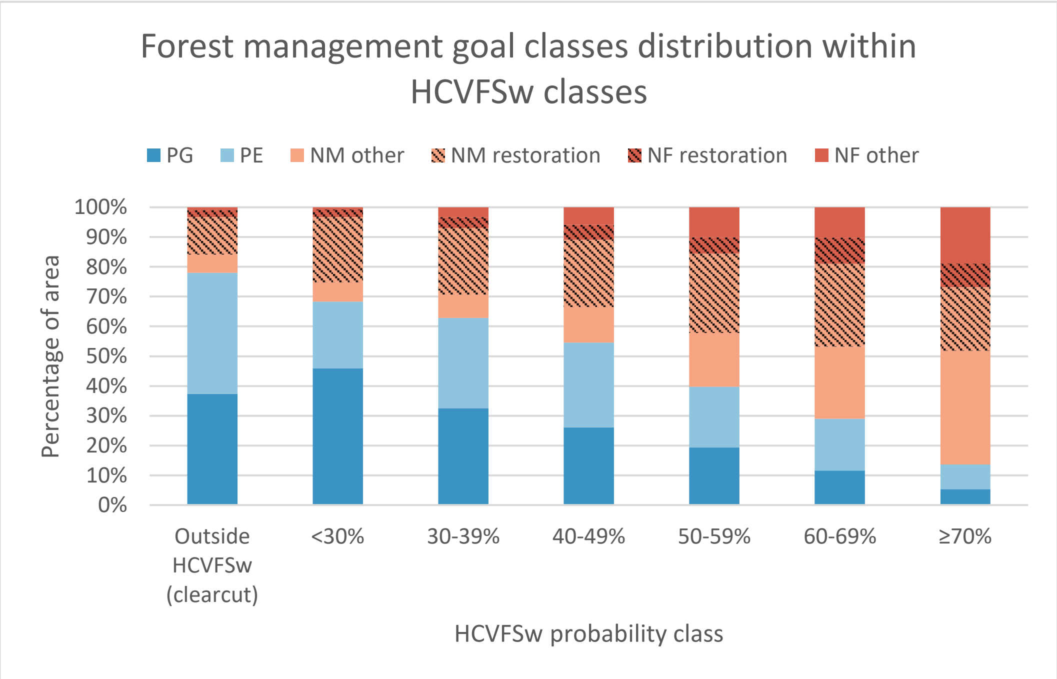

Figure 2. Forest management goal class distribution within HCVFSw classes shown as the area percentages of each HCVFSw class.

The HCVFSw density analysis identified high densities of high nature conservation value forests within Ecopark Käringberget, particularly in the southern and central parts (Figure 3). Apart from non-forest land, only a fraction of the Ecopark represented the lowest density class. The areas of high densities (e.g. density ≥ 80%) were, however, clusters separated by areas of lower density or non-forest land. The western part of the Ecopark generally had low HCVFSw density and so did some parts along the eastern edge.

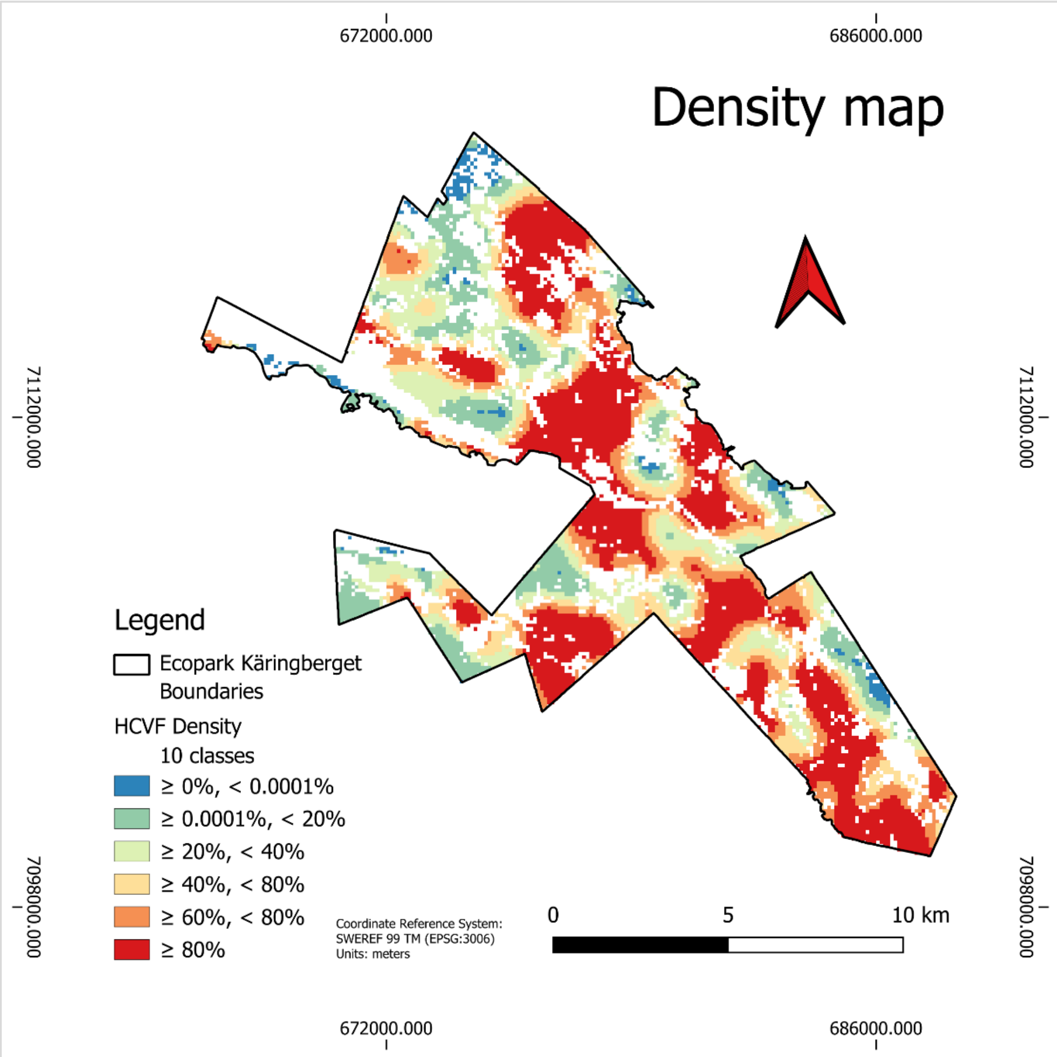

Figure 3. HCVFSw density map of Ecopark Käringberget, classified into six classes from 0% density to 100%.

Through the CCM, the connectivity analysis detected primarily six small areas within Ecopark Käringberget displaying especially high connectivity values (Figure 4). The six high-connectivity areas were located in the central or northern parts of the Ecopark.

According to the CCM, one main network of continuous connectivity is from the southeastern part through the central parts to the north, though the connectivity values are not continuously high throughout this network. This connectivity network covers a substantial share of the central part of the Ecopark area. An additional connectivity network stretched from the Ecopark centre along the southern salient extending westward. One thin network of connectivity could also be detected extending northwest from the centre, parallel to the water (seen as a dark streak in the northwest of Figure 4)

Areas of particularly low connectivity were the very north of the Ecopark, the northern salient extending to the west, and some areas along the eastern border.

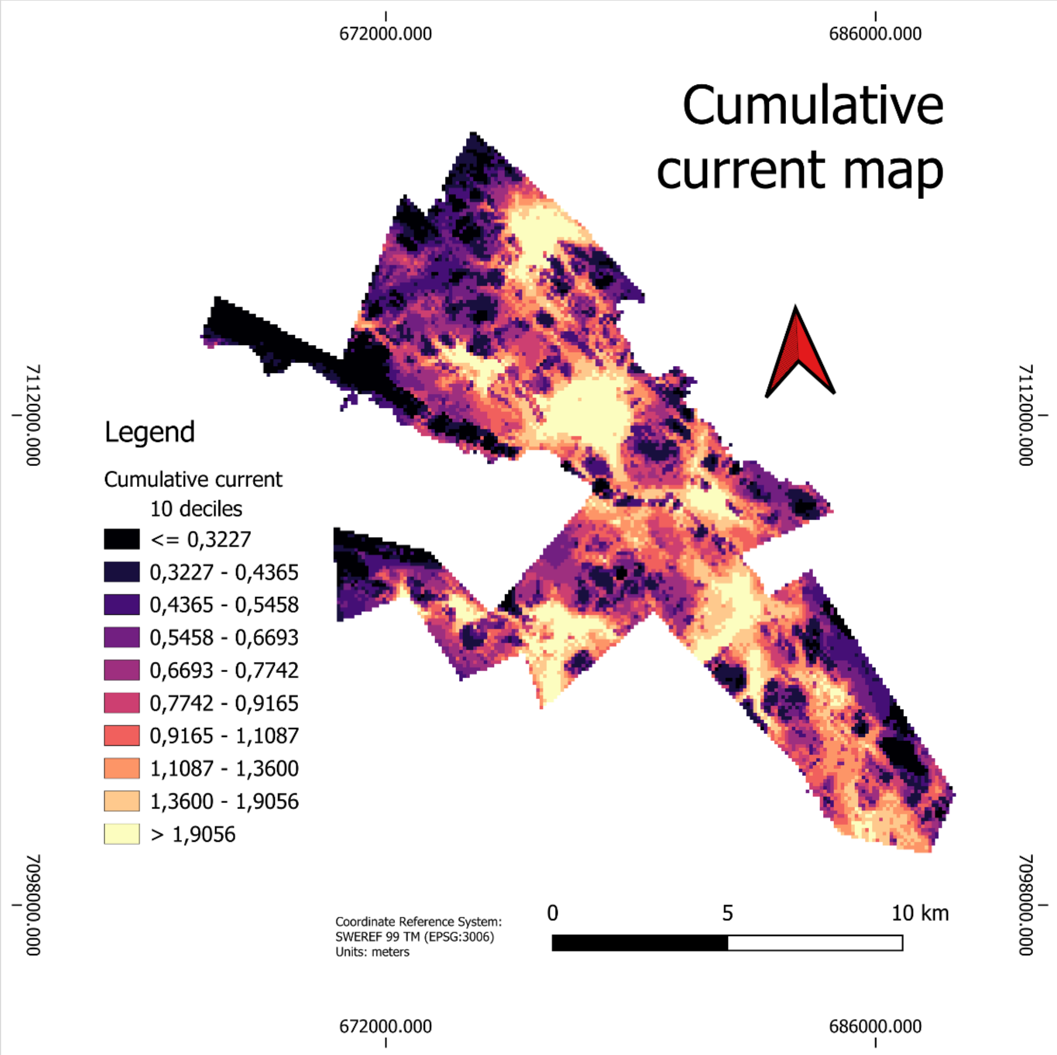

Figure 4. Cumulative current map (CCM) over Ecopark Käringberget divided into 10 deciles. Patches appear larger than in reality due to the decile colouration.

The NCCM yielded a different connectivity map with thinner networks of high connectivity and a larger share of area with low connectivity (Figure 5). Still, the same main connectivity pattern from the southeast to the north as seen in the CCM was detected in the NCCM but more fragmented in the NCCM. The network was particularly fragmented in the north where it was divided by several patches of very low connectivity, although the thin network in the northwest conversely appeared to be broader and have higher connectivity

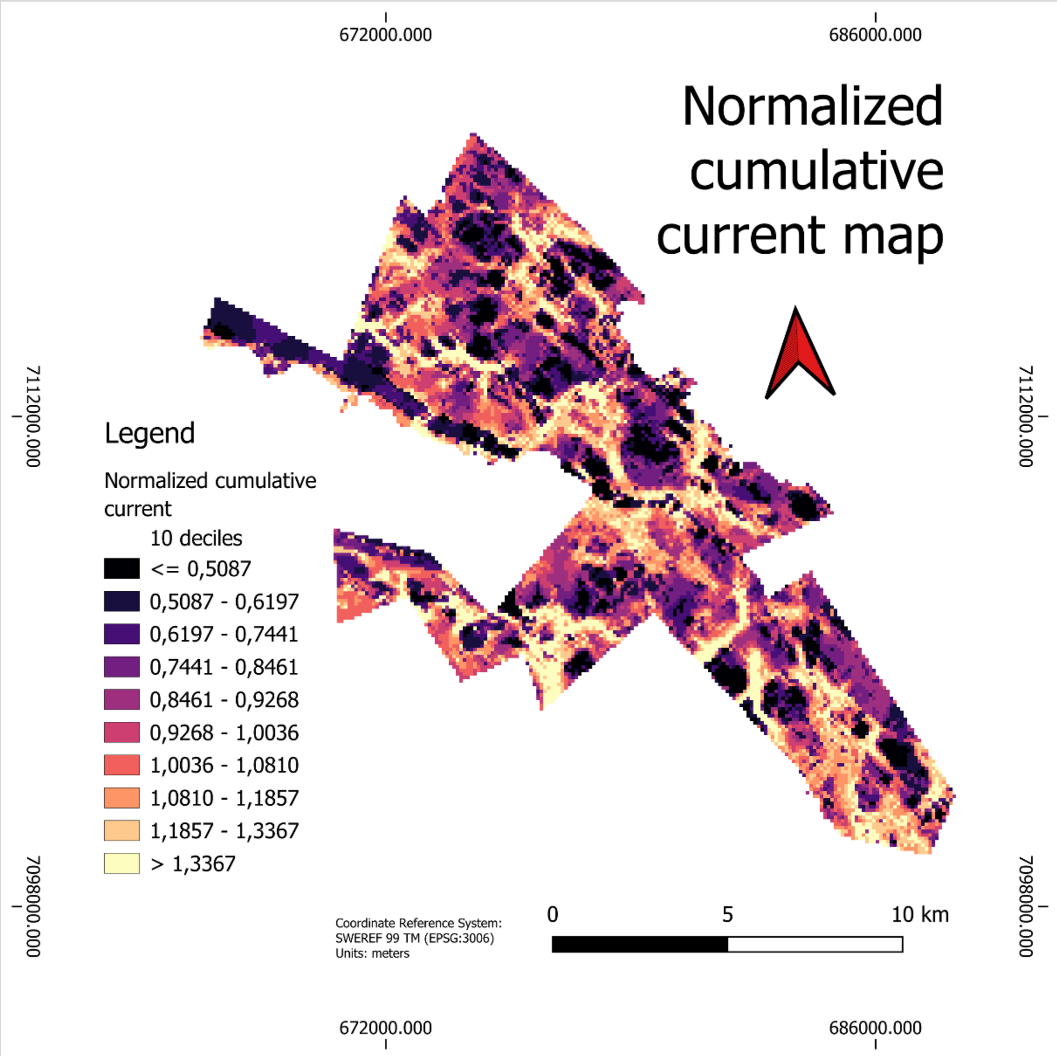

Figure 5. Normalized cumulative current map (NCCM) over Ecopark Käringberget divided into 10 deciles.

Spatial statistics analyses of forest management goal class distribution in both connectivity maps can be seen in Figure 6 for CCM and Figure 7 for NCCM. Both analyses showed the same patterns, with nature conservation classes increasing with increasing connectivity. The percentage of restoration forest within the nature conservation classes was also low in the highest connectivity classes in both analyses, indicating favourable conservation qualities.

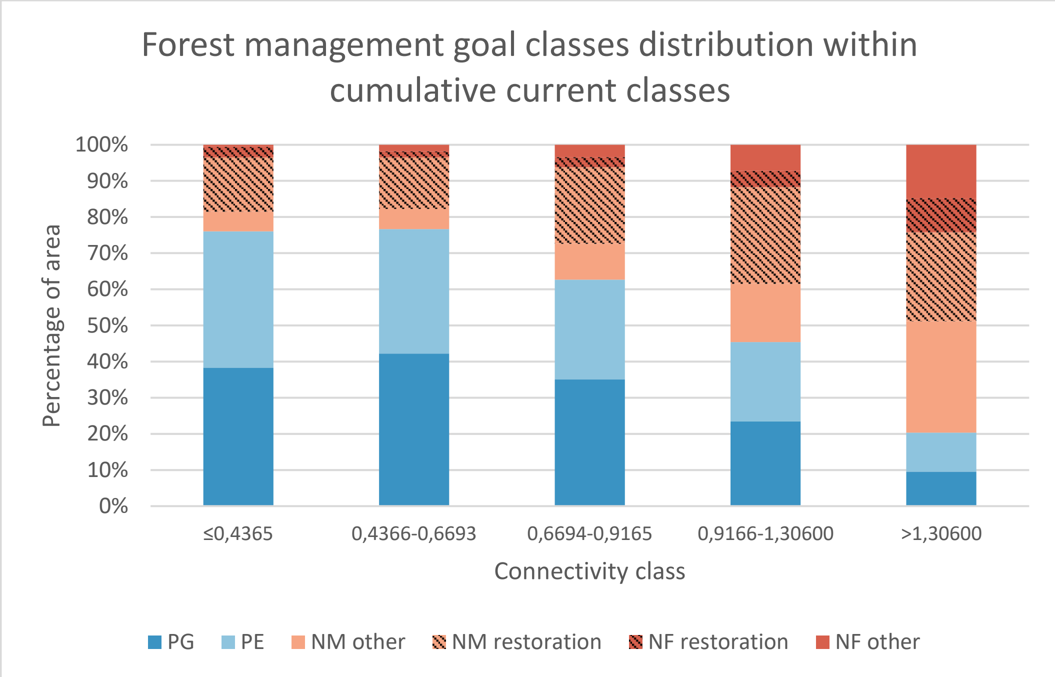

Figure 6. Forest management goal class distribution within cumulative current classes shown as the area percentages of each class.

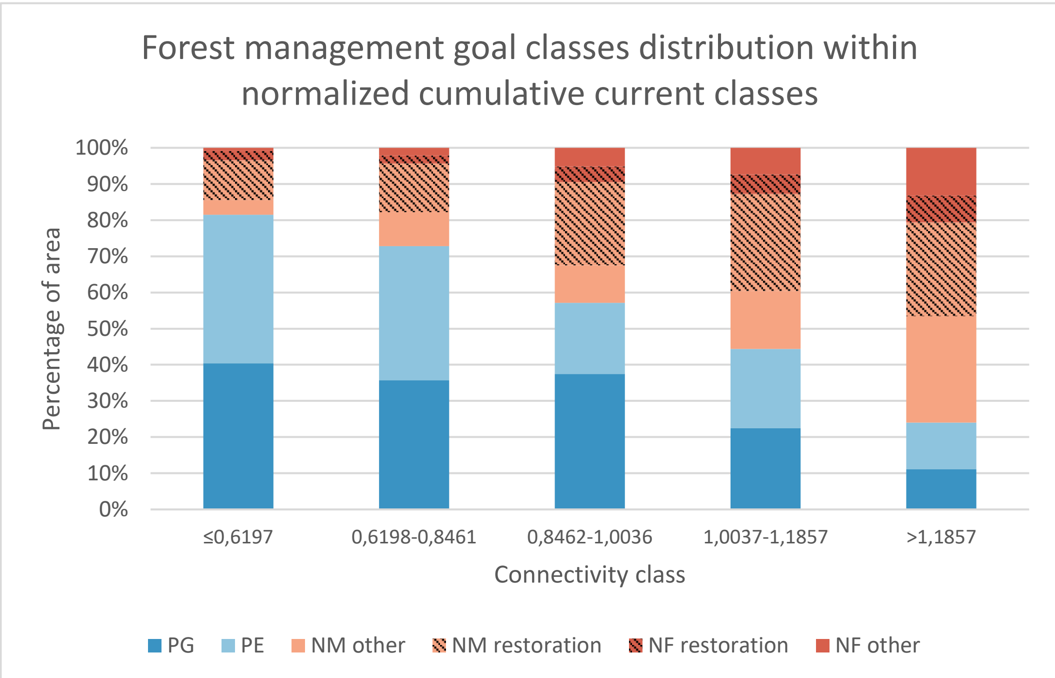

Figure 7. Forest management goal class distribution within normalized cumulative current classes shown as the area percentages of each class.

5. Discussion

Hereafter, the results of this study are discussed regarding relationships, management implications, large-scale connectivity, limitations, and research recommendations.

5.1 Key findings and relationships

The results indicate a similar distribution of high HCVFSw probability areas and Sveaskog's nature conservation areas. Ecopark Käringbeget was indicated to have high HCVFSw density. A connectivity network in the Ecopark stretching northward from the southeast with two westward branches was identified, both in the CCM and the NCCM. High connectivity areas were found to also largely overlap with Sveaskog's nature conservation areas.

Areas of high HCVFSw density in the density map largely overlap with areas of high connectivity in the CCM. This is likely due to the resistance layer for the CCM depending on the HCVFSw density map. Similarly, the same large-scale patterns were identified in the CCM and the NCCM alike.

The difference observed between the CCM and the NCCM is mainly the CCM showing nodes of particularly high connectivity more clearly, whereas the NCCM clearly shows thinner networks of connectivity throughout the landscape while the high connectivity nodes are less visible, thus identifying main stretches where restoration can be added to improve conservation values and connectivity, also concerning forests with intermediate or low-end HCVFSw predictions. In the CCM, the decrease in connectivity away from areas of high connectivity is more gradual than in the NCCM, where the decrease is more abrupt. Thus, areas immediately surrounding nodes of high connectivity in the CCM generally have higher connectivity than areas more distant, a pattern only seen at a smaller scale in the NCCM. This is likely due to distance effects being stronger in the CCM, meaning weak sources have higher connectivity simply for being closer to strong sources. The NCCM likely gives these areas low connectivity because it more strongly accounts for landscape resistance.

A specific geographical difference between the CCM and the NCCM is the NCCM showing higher connectivity in the eastern parts of Ecopark Käringberget, both in the northeast and in the east of the southern salient. These areas may thus be distant from larger key nodes of high connectivity, but have low resistance, allowing for species dispersal.

5.2 Management implications

The results of this study inform Sveaskog about the current connectivity status for further planning in Ecopark Käringberget, as one goal with Ecoparks is to ensure functional connectivity (Sveaskog 2005). As stated in Nilsson & Englund (2024), however, the results of an Omniscape.jl connectivity analysis should be used in nature conservation planning purposes with caution and only if the method and its shortcomings are fully understood. Thus, this method of assessing connectivity certainly includes uncertainties, however, can be useful in conservation planning. This method may be especially useful in Ecoparks if Sveaskog should want to be in the forefront of connectivity conservation. As shown by this study, Sveaskog's nature conservation forest management goal classes already largely overlap with areas of high HCVFSw and high connectivity. This indicates a strong basis of management practices facilitating connectivity. Thus, few changes in management practices may be necessary to fulfill Sveaskog's goal of ensuring connectivity within the Ecopark. Measures increasing connectivity would additionally be uncontroversial as Ecoparks have a single owner (Sveaskog) meaning few stakeholder conflicts may arise. Also, as Ecoparks have increased nature conservation goals, some production losses resulting from attempts to increase connectivity are accepted. This indicates less conflict in forest landscape planning toward integrated conservation, restoration and production, possibly making Ecoparks key areas where connectivity can be increased. Here, the mapping of present restoration forests to HCVFSw-predictions and the CCM- and NCCM-models provide input on location of restoration to improve connectivity on landscape-scale on top of improving conservation value within single stands.

As such, it is beneficial to determine how the two outputs of the present connectivity analysis differ in their possible planning applications. As the CCM is directly calculated from the source and resistance layers, thus taking barrier and habitat distributions into account, it may be the most accurate depiction of the total connectivity. The NCCM corrects for the effects of source distribution and may hence depict how local landscape structures facilitate connectivity. For Sveaskog's nature conservation planning in Ecopark Käringberget, both connectivity depictions may be useful; the CCM showing total connectivity and the NCCM highlighting areas of relative connectivity importance within smaller contexts. For large-scale planning of the whole Ecopark the CCM may therefore be of more use, and for planning management of individual stands or other smaller units the NCCM may thus be more useful.

I identify four main conservation planning and management challenges in the connectivity network of Ecopark Käringberget. First, there are many bottlenecks in the connectivity network, shown as thin passages of high connectivity in the NCCM, potentially restricting species movement. Second, the north of the Ecopark is fragmented with an area of high HCVFSw density and high connectivity according to the CCM surrounded by barriers according to the NCCM. Third, the connectivity network of the southern salient is poorly connected to the rest of the network according to both the CCM and the NCCM. Fourth, there is an area important for connectivity according to both maps which is classified as production forest. This area is in the center of the Ecopark, at the base of the southern salient, below an area of water shown as a dark stripe in Figure 5. Here, the results indicate that management goal classification may need to be revised, if conservation goals are restricted to the two conservation goal classes, and as discussed above, if connectivity is the conservation, and/or restoration focus.

Thus, despite the uncertainties involved in the connectivity model (Nilsson & Englund 2024), the current connectivity status suggests additional attentions on the following four areas in the future management of Ecopark Käringberget: 1) those thin passages of high connectivity and their surrounding areas all over Käringberget; 2) the fragmentation in the north of the Ecopark where connecting areas of high HCVFSw density are in lack; 3) the overall connection between the main network stretching from the southeast to the north and the westward branch on the southern salient; and 4) the central production forest of high connectivity value. Actions within these areas may include restoration and increasing nature protection areas. Such actions would decrease the amount of production forests in the Ecopark, so one other option might be to plan forestry operations such that connectivity is always ensured, even in a dynamic forest, as older production forests can facilitate connectivity (Bergsten et al. 2013). Since close to nature forestry is in accordance with the implementation of the EU Nature Restoration Regulation (Svensson et al. 2025), increased use of this forest management model and decreasing use of rotation forestry is also optional.

5.3 Large-scale connectivity

While the connectivity analysis of this study is limited to Ecopark Käringberget and thus cannot indicate the larger connectivity role of the Ecopark, other evidence could provide valuable information on the topic. High HCVFSw density in Ecopark Käringberget indicate that the Ecopark is important as a large connectivity node in the inland of Västerbotten county, where forest conservation conditions are not satisfactory (Svensson et al. 2020). Additionally, Mattson (2022) found Ecoparks to be central for large-scale connectivity. Bovin et al. (2017) found a connectivity network disconnected from the largest identified network in northern Sweden, located near Käringberget. Ecopark Käringberget may be able to further strengthen this network, which would be important due to its disconnected nature. Svensson et al. (2020) and Mikusiński et al. (2021) found generally low connectivity in the non-mountainous forest areas of Västerbotten, which might indicate Ecopark Käringberget is not well connected with other valuable forest areas. However, in the study by Wang et al. (2025), covering the Vindelälven watershed just north of Käringberget, it was shown that connectivity can be strengthened through modelled connectivity forests in proximity to high conservation forest areas. That study applied the same model for high conservation value forests, i.e. the Bubnicki et al. (2024) HCVFSw-model, as in this study. These results might suggest Ecopark Käringberget could play a key role if the high nature conservation value forest connectivity network in Västerbotten should be restored.

5.4 Limitations

Because the connectivity maps illustrate connectivity based on a largely arbitrary metric of connectivity, it is difficult to compare the results of this study with others. Only the relative connectivity of separate areas within the Ecopark can be examined, though this may also not be accurate as the model operates locally and results from separate parts of the map may as such not be fully comparable (Nilsson & Englund 2024). This should be considered a source of uncertainties when interpreting the maps.

One limitation with Omniscape.jl connectivity analyses is that their results are difficult to validate through, e.g., field measurements, so no validation was done in this study. Also, the results of the Omniscape.jl model could strongly depend on how the resistance layer was constructed. For example, running the model with different land use classification and resistance values for the resistance layer could generate different results. By running the model with different inputs and configurations, how stable the model is and which datasets have the most influence could have been ascertained. In the present study no such analysis was done. Future studies, however, could model the connectivity upon different resistance layers and computational configurations (such as different moving window radius).

Additionally, converting the NMD data from a 10x10 meter resolution raster to one of a 100x100 meter resolution is a loss of accuracy, potentially leading to errors.

Another limitation in the study is connected to the spatial statistics analysis of the relation between Sveaskog's forest management goal classes and the connectivity classes of the CCM and the NCCM. The forest management goal classes are used to create the resistance layer, meaning some pixels in the connectivity maps are defined by the forest management goal classes. There is thus some circular reasoning involved when drawing conclusions from Figures 6 and 7.

As these pixels are very few in number in the present study, though, this limitation may be negligible.

Finally, this study is on structural connectivity with forests treated as one single entity regardless of dominating tree species or forest habitat types. For functional connectivity modelling, finer resolution is needed. Yet, this study provides a methodological approach to be further developed.

5.5 Research recommendations

Further research should analyze the connectivity of several Ecoparks through the Omniscape.jl connectivity analysis. With more data on the connectivity within Ecoparks, Sveaskog could work towards increasing connectivity in Ecoparks in a systematic way, also making use of field data and current conservation and restoration forest stands. The effects of Ecoparks on the larger connectivity of the landscape should also be further examined, such as in Mattson (2022) and, in extension, Wang et al. (2025).

Within Ecopark Käringberget, further research could focus on the connectivity of different forest ecosystems (such as broadleaf forests, pine forests, and spruce forests) or connectivity for focal species. Connectivity of different ecosystems would be more useful in guiding management and conservation for species dependent on a particular ecosystem. Such species may not be able to disperse across ecosystems they are not adapted to and would as such need an ecosystem-specific connectivity analysis. Focal species-centered analyses would perhaps be more ecologically relevant compared to the very general connectivity analysis of the present study. By focusing on umbrella species, the connectivity for many species or other taxonomical groups could be ascertained, which would have high value for conservation and restoration planning.

Finally, this study relates directly to connectivity as a mandatory indicator in the EU Nature Restoration Regulation, to be addressed by each EU Member State in their Nature Restoration Plan (Svensson et al. 2025). The methodological approach as well as the application of Sveaskog Ecoparks, serve as an important input.

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