Woodland key habitats for functional forest landscape green infrastructure in the Swedish mountain region

Nyckelbiotopers roll för en funktionell grön infrastruktur i nordvästra Sveriges fjällnära skogslandskap

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Master's thesis • 30 credits
Swedish University of Agricultural Sciences, SLU
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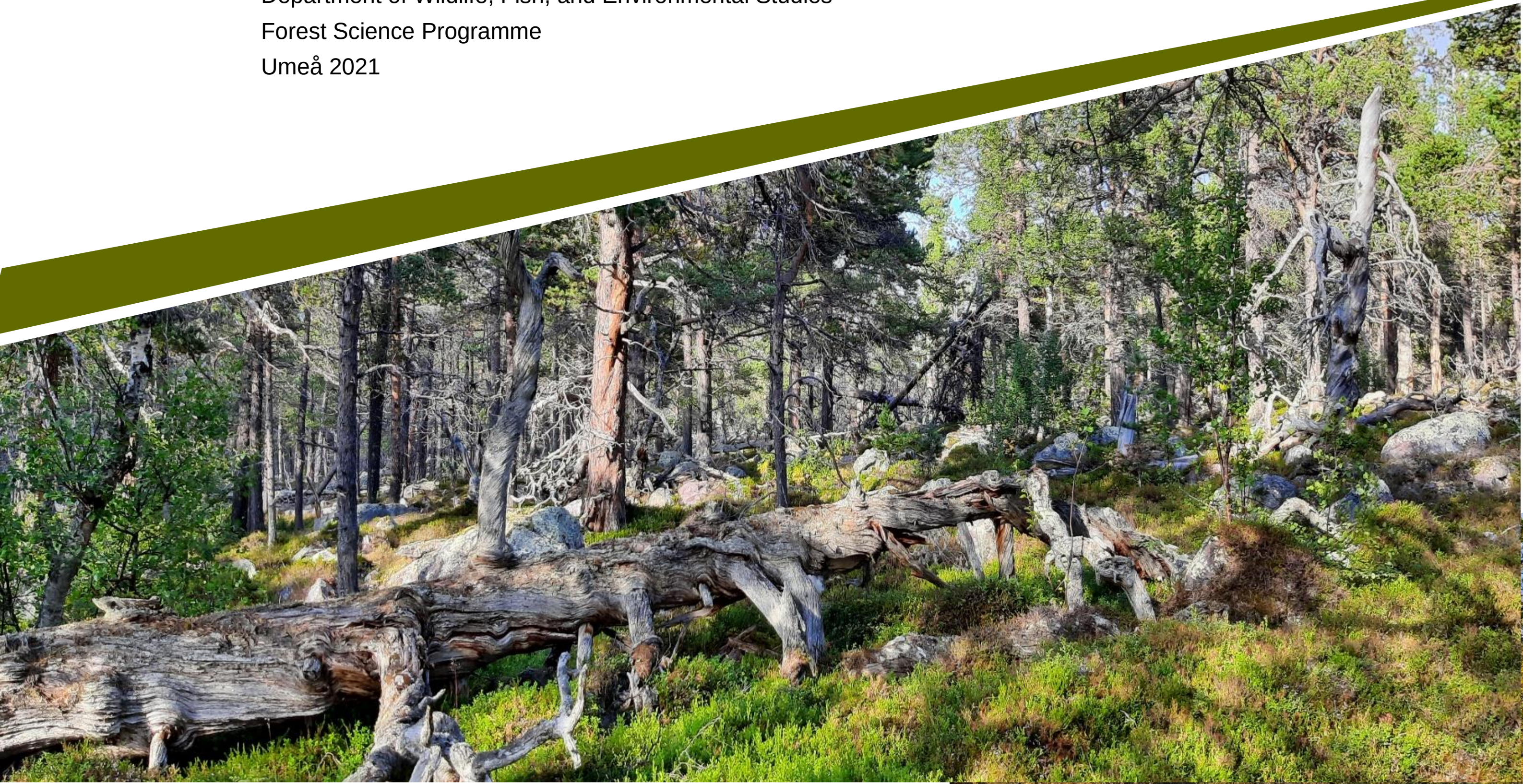
Forest Science Programme
Umeå 2021



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Credits:	30 hp
Level:	A2E
Course title:	Master’s thesis in Forest Science, A2E - Wildlife, Fish, and Environmental Studies
Course code:	EX0968
Programme/education:	Forest Science Programme
Course coordinating dept:	Department of Wildlife, Fish, and Environmental Studies
Place of publication:	Umeå
Year of publication:	2021
Cover picture:	Natural pine forest in Stora Sjöfallet national park, Britta Sterner
Title of series:	
Part number:	
ISSN:	
Keywords:	Woodland key habitat, green infrastructure, connectivity, forest biodiversity, NW Sweden

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Faculty of forest science

Department of Wildlife, Fish, and Environmental Studies

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Abstract

The intact forest landscapes along the Scandinavian Mountain range are of very high conservational value both nationally and internationally, due to their intact characteristics and biodiversity. The high nature conservation values have remained as a result of restricted forest clear-cutting above the so-called mountain forest border (MFB). The Swedish Forest Agency (SFA) has mapped Woodland Key Habitats (WKHs) and Woodland habitats (ONVs) that hold high or semi-high biodiversity qualities in 38 squares (5 x 5 km) in NW Sweden to test the newly developed regionally adapted WKH inventory. This study aims to evaluate how previously registered WKHs of three focal WKH-types and corresponding newly identified WKHs and ONVs, as well as baseline forests with no documented conservation values, contribute to a functional forest landscape green infrastructure in NW Sweden. I arranged field inventory data (collected by the SFA in 2018) in four assessment sets with various nature conservation values and used national land cover data to assign these sets to the three focal WKH-types. By performing a Morphological Spatial Patter Analysis, data were stratified into *core*, *edge*, and *corridor* for analyses of their spatial arrangement and connectivity. Here, increased connectivity was set equal to increased core and corridor area. I found that *natural coniferous forest* is a strongly dominating WKH-type and that most other WKH-types occurs at low frequency and areal cover. Moreover, I found a general significant increase in *natural coniferous forest* core, edge, and corridor absolute area from the previously registered WKHs to the following assessment sets of various nature conservation values, representing a potential increase in connectivity. In addition, the MFB represents an actual border, with a notable larger *natural coniferous forest* core area above the border and a higher edge/core-ratio below. Importantly, my results highlight a higher potential to meet the Aichi target #11 of 17 % protected area important for biodiversity above the MFB, while substantially larger areas of conservational value and functionality will have to be added below. My results clearly show that especially the newly identified WKHs, but also the newly identified ONVs, are key elements in improving the functional forest landscape green infrastructure in NW Sweden.

Keywords: Woodland key habitat, green infrastructure, connectivity, forest biodiversity, NW Sweden

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Abbreviations

HCVF	High conservation value forest
MFB	Mountain forest border
NMD	National landcover data
NW Sweden	Northwest Sweden
ONV	Woodland habitat with semi-high conservation value (Sw: *object med naturvärden*)
pCF	Proxy Continuity forests
SFA	Swedish Forest Agency
WKH	Woodland key habitat (Sw: *nyckelbiotop*)

1. Introduction

1.1. Background

1.1.1. Swedish boreal forests and forestry – premises for biodiversity conservation

Life on Earth is exposed to a global anthropogenic climate and environment transformation, with considerable negative impacts on terrestrial ecosystems, species, and biodiversity (IPBES 2019; IPCC 2019). For example, more than 37,400 species are currently in risk for extinction globally (IUCN 2021), and loss of biodiversity is acknowledged to undermine provision of ecosystem services and threatens human life (WWF 2020). The current situation is alarming and knowledge, capacity, and actions to reduce further loss is critically needed. To prevent ecosystem and species loss and to improve ecological resilience towards climate change related disturbances, intact forest landscapes play a vital role (e.g. Buchwald 2005; Potapov et al. 2017; Watson et al. 2018; Svensson et al. 2020). According to Potapov et al. (2017, p. 1), an intact forest landscapes is ”a seamless mosaic of forests and associated natural treeless ecosystems that exhibit no remotely detected signs of human activity or habitat fragmentation and are large enough to maintain all native biological diversity […]”. Despite their crucial role, many intact forests around the world are currently under increasing pressure (Watson et al. 2018), with industrial timber extraction as their primary threat (Potapov et al. 2017).

In Sweden, the transformation and degradation of intact boreal forest landscapes have been substantial (Ecke et al. 2013; Svensson et al. 2019a) and only few fragmented remnants exist outside NW Sweden (Potapov et al. 2008; Angelstam et al. 2020; Svensson et al. 2020; Appendix 1). Before industrial forestry developed, natural biotic and abiotic disturbances shaped boreal forests into heterogenous complexes with a variety of structures and compositions (Ericsson & Östlund 2000; Potapov et al. 2017). In the 1950s, large-scale mechanical clear-cut systems were initiated in northern Sweden (Ecke et al. 2013), which still is the strongly dominating forest management method. Clear-cut forestry is an intensive managed rotational system where most or all mature trees in a forest management unit are simultaneously harvested and the subsequent regeneration is commonly done by planting following soil scarification (Seedre et al. 2018). Consequently, the earlier heterogenous natural boreal forests have been transformed into even-aged homogenous monocultures (Ericsson & Östlund 2000; Ecke et al. 2013).

The industrial clear-cut forestry has caused severe fragmentation and loss of natural forests in large areas in boreal Sweden (Jonsson et al. 2019). Thus, it has interrupted the spatial connectivity and the temporal continuity of forest cover (Svensson et al. 2020), which are features of prime importance for many elements of biodiversity and prerequisites for maintained ecosystem functioning (Aune et al. 2005; Buchwald 2005; Potapov et al. 2017). Consequently, forestry is degrading ecosystems and is acknowledged as one of the main drivers to the global biodiversity crisis (Timonen et al. 2011; Watson et al. 2018). For example, 2,040 species that to some extent are dependent on forest ecosystems were red listed in Sweden in 2020 and clear-cut forestry has strong negative impact on 69 % of those (SLU Artdatabanken 2020).

To counteract the negative effects of clear-cut forestry on natural ecosystems and biodiversity, Sweden has agreed upon national and international environmental and biodiversity conservation targets. For example, Sweden has signed the international Aichi target #11 within the Convention on Biological Diversity, which recommends ecological representativeness and connectivity by 2020 for terrestrial protected areas important for biodiversity that corresponds to 17 % of the country's land area (CBD 2021). Sweden further act on national Environmental Quality Objectives (Sw: *Miljökvalitetsmål*; Naturvårdsverket 2020b), of which one particularly relates to forests – *Sustainable forests* (Sw: *Levande skogar*). *Sustainable forests* aims for forest biodiversity conservation, allowance of secured species' dispersal possibility, recovery of threatened species, and restoration of habitats of high conservation value (Skogsstyrelsen 2021a). Nevertheless, neither the Aichi target #11 nor the *Sustainable forests* were met by 2020 as aimed for (Angelstam et al. 2020; Skogsstyrelsen 2021a).

In nature conservation, it is important to secure representation of different forest ecosystems and to ensure sufficient size, quality, and functional connectivity among forest patches (Pimm et al. 2014), aspects that are key in the so-called green infrastructure planning. Green infrastructure is a strategically planned network of natural and semi-natural areas designed and managed to deliver various ecosystem services, to enhance biodiversity, and to improve environmental conditions as well as human's quality of life (European Commission 2021b). In a functional forest ecosystem green infrastructure, intact forest landscapes are acknowledged to play an important role (Svensson et al. 2020).

1.1.2. The intact forest landscapes along the Scandinavian Mountain range

Despite the overall extensive forestry, Sweden hosts one of Europe's last intact forest landscapes (Jonsson et al. 2019), which consists of northern boreal and sub alpine forests stretching from south to north along the Scandinavian Mountain range. These foothill forests have in general not been as subjected to intense forestry as lowland forests have (Jonsson et al. 2019), and thus are important nodes for a functional forest landscape green infrastructure. Nevertheless, from the beginning of the 1970s, forest harvesting increased dramatically in the mountain region, which caused public and political reactions and gave rise to the establishment of a nature conservation border (Jonsson et al. 2019). This mountain forest border (MFB; Sw: *fjällnära gränsen*) was suggested by von Sydow (1988) and is a policy instrument that restricts forest harvesting above the MFB more strictly than below (Jonsson et al. 2019). The MFB became recognised in the Swedish Forestry Act in 1991 and has contributed to the maintenance of intact forest landscapes with high or very high nature conservation values above the MFB (Jonsson et al. 2019; Svensson et al. 2020). For example, 61 % of the forests above the MFB are older than 120 years (Jonsson et al. 2019), in contrast to a fraction of 19.5 % in the whole country (SLU 2020).

Today, the intact forests along the Scandinavian Mountain range and their future use are once again debated. Two main lines arguing for contradicting goals can be discerned. One line is promoting intensified biomass and wood production to provide the industry with raw material and to implement a bioeconomy (Jonsson et al. 2019). The other line is promoting maintenance and development of multiple forest values and value chains associated with biodiversity, carbon sequestration, tourism and recreation, and indigenous Sámi culture and reindeer husbandry.

1.1.3. Woodland key habitats in NW Sweden

As part of the Swedish green infrastructure planning and as a decision knowledge basis for the Swedish environmental and nature conservation work in general, woodland key habitats (WKHs) play an important role (Wester & Engström 2016). AWKH is defined as a forest patch that by an overall assessment of its ecological structure, species content, forest history and physical environment has a high importance for the forest's flora and fauna today, and harbours or can be expected to harbour red-listed species (Wester & Engström 2016). WKHs are not formally protected. The inventory method was originally developed to detect and delineate isolated conservation forest patches embedded in a commercially managed forest or agricultural landscape (Timonen et al. 2010).

The WKH identification was earlier part of a systematic national inventory performed by the SFA, but since 2006 WKHs have only been identified in association with the administration of clear-cut notifications (Wester & Engström 2016). As WKHs are identified by the SFA, they become classified according to one to three (out of more than 50) predetermined WKH biotope types (hereafter WKH-types) to secure representation of various habitats (Skogsstyrelsen 2020). In other words, one specific WKH might be classified as up to three WKH-types of which one defined as the dominating.

WKHs are acknowledged as biodiversity hotspots since they commonly have high occurrence of indicator species and red-listed species and hold high biodiversity qualities (e.g. diversity and volume of dead wood, old trees of various species, and intact characteristics; Timonen et al. 2011; Wester & Engström 2016; Fig. 1). They are further expected to potentially improve connectivity of scattered habitats (Timonen et al. 2010) and despite their generally small size, they might be valuable complements to nature reserves (Wester & Engström 2016).

The distribution of WKHs in Sweden is not evenly spread as the by far largest area of WKHs is located in NW Sweden (Wester & Engström 2016). The WKHs in municipalities in the mountain region hold higher nature conservation values with a larger share of red-listed species than the national mean value (Wijk 2017b). This has led to difficulties in the application of the WKH-inventory in that area, especially delimitation difficulties due to the large areas of intact forests that clearly meet the WKH-criteria (Timonen et al. 2011; Claesson 2018).

To improve the WKH-inventory in NW Sweden and to make it more objective, the SFA developed a new inventory method, which was adapted to locally and regionally conditions (Wester et al. 2019; see 2.3.1). Consequently, the criteria for what object is classified as a WKH became higher within NW Sweden than outside (Wester et al. 2019). The new method was only developed for five of the over 50 WKH-types; *coniferous forest*, *natural coniferous forest*, *broadleaf-rich coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland- forest mosaic* (Wester et al. 2019), since they are dominating by area in NW Sweden (Roberge 2018).

Beside WKHs, the SFA registered woodland habitats with semi-high conservation values (ONVs; Sw: *object med naturvärden*). ONVs are delineated forests with slightly lower qualities than WKHs, but indeed have nature conservation values important for biodiversity and can develop WKH qualities within a relatively short period of time (Wester & Engström 2016).

Currently, the WKH-inventory has been closed and it was assessed nationally by the Forest policy inquiry (SOU 2020), including a suggestion to eliminate parts of the existing data associated with the WKH mapping. This suggestion is based on legal considerations, but the value of the WKH database and continued data collection remain high for research, and for bringing knowledge into planning for additional protection and identification of areas where forest management potentially can continue (Jonsson et al. 2019). Additionally, the value of the WKH-inventory remain high to secure biodiversity and to realise a functional forest landscape green infrastructure (Timonen et al. 2010; Wester & Engström 2016).

Figure 1. Spruce dominated forest in Aptasvare fjällurskog nature reserve that contain high nature conservation values with WKH quality (e.g. large dead trees and old living trees).

1.2. Knowledge gap

Many studies and reports have recently been published in Sweden regarding the structure of the high nature conservation value forests in NW Sweden, national green infrastructure and habitat connectivity, as well as on forest and biodiversity loss (e.g. Claesson 2018; Svensson et al. 2019a, 2020; Angelstam et al. 2020). However, only few studies are performed on a narrower scale (e.g. Mikusinski et al 2021) and in particular with consideration to different biotope and forest types, which is of high importance for an ecologically functional green infrastructure in the landscape (Svensson et al. 2019b). This study aims to add knowledge to fill a part of that gap.

1.3. Aim

To evaluate how WKHs, ONVs, and forestlands with no documented conservation values generally contribute to a functional forest landscape green infrastructure in NW Sweden.

1.4. Research questions

With a focus on three commonly occurring focal WKH-types (i.e. *natural coniferous forest, broadleaf-rich natural coniferous forest,* and *wetland-forest mosaic*) in NW Sweden, as well as on previously registered WKHs, newly identified WKHs and ONVs, and on baseline forests with no documented conservation values, the following two research questions guided the analyses:

i) How can the local connectivity in NW Sweden be strengthened by adding the newly identified WKHs and ONVs, as well as the baseline forests, to the previously registered WKHs?

ii) What is the difference between above and below the mountain forest border with respect to local connectivity for the previously registered WKHs, the newly identified WKHs and ONVs, as well as for the baseline forests?

1.5. Delimitation of the study

Focus in the analyses will be on three pre-selected WKH-types, i.e. those types that occur most commonly in NW Sweden (Roberge 2018). Other types will be included only to some extent for providing a context of the WKHs. Connectivity will be evaluated within the squares separately, without any attention to their surrounding environments or their internal spatial configuration. Although the analyses will be based on very detailed data, specific management plans for certain areas will not be developed as part of this project. Instead, the results might generate input to such management plans in other contexts. Different forest management alternatives, multifunctional management objectives, land ownership, specific WKH-inventory improvements, and specific restoration and management actions to improve forest nature conservation values are not included.

2. Materials and Methods

2.1. Research questions in context

Connectivity can be assessed with different approaches and tools and varies in general with species' requirements for persistence. In this study, connectivity is defined by the amount of coherent area that contains high or semi-high nature conservation values (termed core) and by the amount of area available for species dispersal (termed corridor). In other words, increased connectivity is here equal to increased core and corridor area. Hence, connectivity is treated with a more general approach linked to different habitat types. More specifically, I evaluated connectivity for three focal biotope types of previously registered WKHs and its increase by the addition of newly identified WKHs and ONVs, and of all existing forestland independent of its nature conservation values. This evaluation was performed on a local scale, i.e. in randomly distributed 5 x 5 km test squares in NW Sweden.

2.2. Study area

The study area is located in NW Sweden across an area of 8.5 million ha (8,467,163 ha; Fig. 2). It includes 11 municipalities (from north to south: Sorsele, Storuman, Vilhelmina, Dorotea, Strömsund, Krokom, Åre, Berg, Härjedalen, Malung-Sälen), all bordering the Scandinavian Mountain range. The majority of the land is covered by forest (5.1 million ha) followed by non-forest alpine land (1.9 million ha) in the western part and wetlands (1.4 million ha**;** Riksskogstaxeringen SLU 2021). The forestland is mainly dominated by two coniferous tree species, Norway spruce (*Picea abies*; 47.8 %) and Scots Pine (*Pinus sylvestris*; 34.6 %), followed by birch species (*Betula pubescens* and *B. pendula*; 13.6 %). Other deciduous tree species such as Alder (*Alnus incana*), Aspen (*Populus tremula*), Goat willow (*Salix caprea*) and Mountain ash (*Sorbus aucuparia*) only cover 1.3 % of the forestland (Riksskogstaxeringen SLU 2021). Pine is more frequently occurring in the north and south, and Spruce in the central parts (Mikusiński et al. 2021). In addition, there is subalpine mountain birch (*Betula pubescens ssp. Czerepanovii*) stretching along the Scandinavian Mountain range and forming the alpine forest line.

The productive forestland (tree growth >1 m3/ha/year as an average over the rotation period) corresponds to 75.1 % of the total forestland within the study area (Riksskogstaxeringen SLU 2021) and is equal to 16.1 % of the total productive forestland in Sweden (SLU 2020). The land within the study area is climatically constrained (longitudinal, latitudinal, and altitudinal) with implications such as lower forest site productivity towards the west and north parts (Svensson et al. 2020), which characterise the ecosystem and species diversity.

The MFB divides the study area in two segments that extends continuously south to north. The study area has a higher proportion of forests with high nature conservation values than has the rest of the country (Claesson 2018), where the amount of high or very high nature conservation values in addition is much higher above the MFB than below (Jonsson et al. 2019; Svensson et al. 2020). For this reason, I stratified my analyses according to this border to allow quantification of the areal and spatial differences. Note: the area termed *below the MFB* is not equal to all land in Sweden below the MFB, rather to the area below the MFB within the study area.

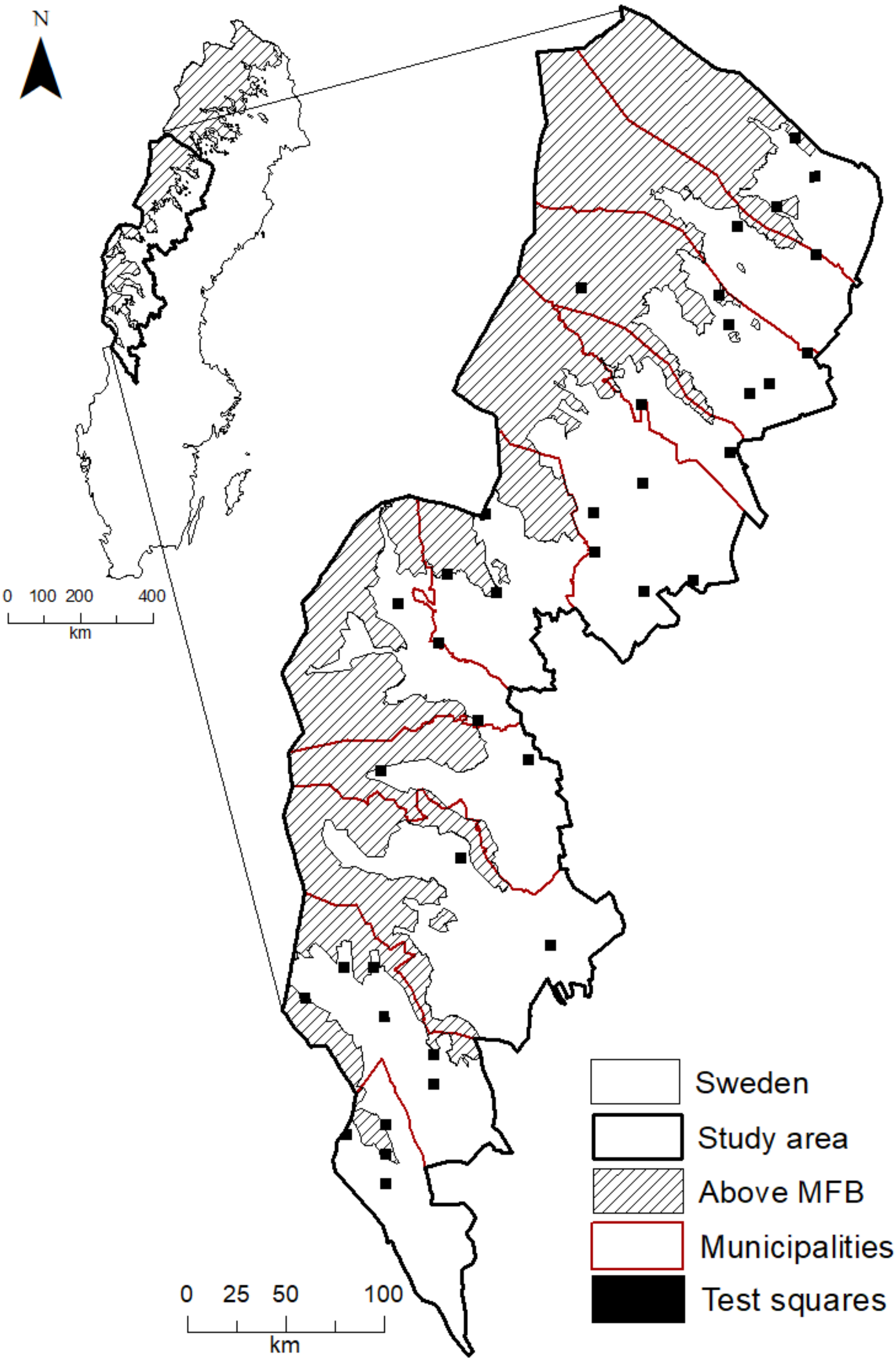


Figure 2. The study area in NW Sweden, including the region above the mountain forest border (MFB), 11 municipalities (from north to south: Sorsele, Storuman, Vilhelmina, Dorotea, Strömsund, Krokom, Åre, Berg, Härjedalen, Malung-Sälen), and 38 squares inventoried by the Swedish Forest Agency (SFA).

2.3. Input data

2.3.1. Data from the Swedish Forest Agency

The SFA provided spatially delineated field data from the 2018 inventory, which I used as a basis to construct and analyse different setups. One of the main objectives to perform the inventory was to practically test and evaluate the newly developed supporting method to identify and delineate WKHs in NW Sweden (Wester et al. 2019). Specifically, 69 test squares (hereafter squares) covering 5 x 5 km were randomly distributed in NW Sweden. Prior to the field inventory, all squares were digitally analysed to identify areas within proxy Continuity forests (pCF) potentially containing high nature conservation values (Wester et al. 2019). The pCF is a mapping of Swedish boreal forests that has not been clear-cut since the 1960s (Ahlkrona et al. 2017). In addition, areas that showed clear signs of human impact, thus expected to contain low nature conservation values, were excluded from the following field inventory. Within the areas identified to be of interest for the field inventory, several systematically distributed square areas (radius 25 m) were placed in a 200 x 200 m grid. The SFA performed the field inventory in 53 out of the 69 squares, supported by checklists developed for the new WKH-inventory method in NW Sweden. The checklists were designed to capture the core of the overall assessment associated with the WKH inventory, i.e. forest history, specifically valuable forest elements, the physical environment, and the presence of species of conservation concern (i.e. signal species and red-listed species). The checklists also constituted the decision basis for the area assignment into three categories *i*) high WKH quality, *ii*) semi-high ONV quality or *iii*) no documented conservation values. The SFA re-inventoried previously registered WKHs and ONVs, but did not inventory any formally protected areas. One important data limitation is the defaulted inventory in some of the digitally identified areas of interest within the 53 inventoried squares, which might underestimate the area containing high or semi-high nature conservation values. Due to insufficient data quality in the county of Norrbotten (Wester et al. 2019), I excluded all squares in Norrbotten in my analyses, leaving 38 squares for my study.

2.3.2. National landcover data

To identify areas of different forest types and connected wetlands, I used the open-source national landcover data (hereafter NMD; Naturvårdsverket 2019; accessed 2021-03-23), which provided high-resolution (10 x 10 m) information about different types of land coverage in Sweden (Appendix 2). In NMD, forestland was defined according to the FAO forest definition "Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.” (FAO 2010; Naturvårdsverket 2019). Forestland was classified into seven main forest types (Appendix 3), and in addition whether they were located on wet organic soil or on mineral soil. Since the study area is located along the Scandinavian Mountain range, where the subalpine mountain birch has its main distribution, I complemented the main raster with a data layer providing information on land covered by mountain woodland (10 x 10 m; Naturvårdsverket 2019). Mountain woodland was defined as tree-covered areas above the MFB with a tree height of 2-5 m and a tree crown cover of > 10 % (Naturvårdsverket 2020a) and included both coniferous and deciduous tree species. The addition of spatially defined data on mountain woodland contributed to a more comprehensive description of the land coverage within the study area, as well as it decreased the underestimation of deciduous forests.

2.3.3. High conservation value forest data

To add information on areas within nature reserves that by default are considered to contain high nature conservation values, I used the high conservation values forests data set (HCVF; Naturvårdsverket & Skogsstyrelsen (2017)**;** accessed 2021-03-23), which provided information on known forests containing high nature conservation values, covering both productive and unproductive forestland. This dataset was based on nationally unified and open-source material from 2016 on various formally and not formally protected areas (Appendix 2). However, it is important to note that the dataset only provided information on previously known high conservation value forests and might thus underestimate the real area of HCVF.

2.4. Data preparations

2.4.1. Set arrangements

To prepare the different datasets for the forthcoming connectivity analyses, I merged data on previously registered WKHs, on newly identified WKHs and ONVs, on HCVFs within formally protected nature reserves, and on all forestland according to NMD in four different sets (A, AB, ABC, and ABCD; Fig. 3), as described in detail below. This approach (i.e. set A-ABCD) allowed me to quantify the areal increase of core and corridor when forests with different levels of nature conservation values were added to forests with higher nature conservation values. In addition, I analysed data separately for three different biotope types in line with the classification of WKHs given by the SFA (i.e. *natural coniferous forest* (consisting of *coniferous forest* and *natural coniferous forest*), *broadleaf-rich natural coniferous forest,* and *wetland-forest mosaic)*. These three WKH-types are the most common and define the largest WKHs in NW Sweden (Roberge 2018) and were therefore of primary interest for this study. In total, I had 12 combinations to analyse (four sets times three WKH-types).

First, set A was based on data on previously registered WKHs only. Since each registered WKH was classified according to one to three pre-defined WKH-types, single WKHs could be classified as having one primary, one secondary, and one tertiary WKH-type, i.e. with one type dominating and placed first in the WKH-typing standard classification. In this study, consideration was taken to each WKH's primary and secondary WKH-type classification when I selected the WKHs classified as *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic* from the whole WKH dataset. Additionally, I investigated whether some of the selected WKHs had been clear-felled after the field inventory. I used the NMD class temporarily non-forest to represent potential clear-cuts (until 2019) and erased them from the selected WKHs. This action, though, might have erased other temporarily open areas such as storm-fellings or recently burnt areas, which could be seen as important structures for nature conservation.

Second, the sub-sets B and C were based on spatially defined objects classified as WKH or ONV, respectively. Data were originally separated by forest type (pine, spruce, or broadleaf-rich coniferous forest) and in order to fit the WKH-types used in set A, I reclassified them using the NMD base layer and the complementary NMD mountain woodland layer. All objects in which one WKH-type (i.e. defined by its corresponding NMD classes; Appendix 4) was dominating (> 70 %; Naturvårdsverket 2019) were classified according to that dominating WKH-type (n=498). The remaining objects were thereafter classified according to the WKH-type that exceeded 50 % (n=74). A few objects (n=18) remained un-classified, of which some had a nearly dominating (close to 50 %) WKH-type and some had no dominating nature type. These 18 polygons were all classified manually as belonging to the *wetland-forest mosaic* WKH-type, since the two other types naturally may be included in its mosaic. Formally protected areas were not included in the SFA inventory data, although parts of nature reserves were located within the 38 squares. To achieve more comprehensive results in the connectivity analyses, I included HCVFs within nature reserves in sub-set B (i.e. treated as containing habitats of WKH quality). The HCVFs within the nature reserves were assigned to the three focal WKH-types based on the same method and criteria as mentioned above (> 70 % n=256 and > 50 % n=58). The HCVFs within nature reserves that remained un-classified (n=10) were not located within the squares and thus were not included in the analyses. I thereafter merged sub-sets B (including HCVFs within nature reserves) and C to set A, which created sets AB and ABC.

Third, sub-set D was based on all remaining forestland in the 38 squares, separated on the three focal WKH-types, and was created by the extraction of the

NMD classes that corresponded to those WKH-types (Appendix 4). In other words, sub-set D consisted of forests with no documented conservation values. However, these forests could potentially harbour not documented or develop nature conservation values naturally over time or assisted by restoration actions, or contribute to increase connectivity between areas already containing high nature conservation values. I prepared set ABCD by adding sub-set D to set ABC, which formed a forestland baseline.

In summary, the four sets (A, AB, ABC, and ABCD) were prepared for the connectivity analyses, separated in three different focal WKH-types *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic*. In addition, I also created the four sets A up to ABCD for all three focal WKH-types merged. I converted all set layers to raster files (10 x 10m) and reclassified all area of interest within the study area as foreground and the remaining landcover as background to prepare for the following Morphological Spatial Pattern Analysis (MSPA; Vogt & Riitters 2017; European Commission 2021a).

2.4.2. Complications in data preparations

While I arranged the four sets (A-ABCD) for the forthcoming analyses, some data dilemmas needed to be solved. To begin with, I considered each WKH's two first WKH-type classifications (i.e. the primary and the secondary) when the WKHs classified as *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic* were selected from the full WKH dataset. This approach facilitated to include WKHs secondarily classified as one of the three focal WKH-types, but resulted in a few WKHs that were included twice, but separately, in the upcoming analyses. Specifically, three polygons were classified as both *wetland-forest mosaic* and *natural coniferous forest* (totally about 77 ha) and seven polygons were classified as both *broadleaf-rich natural coniferous forest* and *natural coniferous forest* (totally about 300 ha). However, this should not impact the analyses considerably, since the three focal WKH-types were not compared to each other in exact absolute areal.

Moreover, it is important to mention that a few polygons (n=19) were classified twice by the SFA during the inventory in 2018, and thus needed manipulation to fit the analyses. Some were defined to contain the same nature conservation value, but different tree species, of which one of the overlapping polygons simply was removed. Some were defined as containing both WKH and ONV quality. Following a conservative approach and to avoid overestimations of nature conservation values, I used the lower quality. For small "islands" defined as containing high nature conservation values within larger polygons defined as containing lower nature conservation values (or vice versa), I erased the shape of the "island". After the modification, the data consisted of 820 non-overlapping polygons.

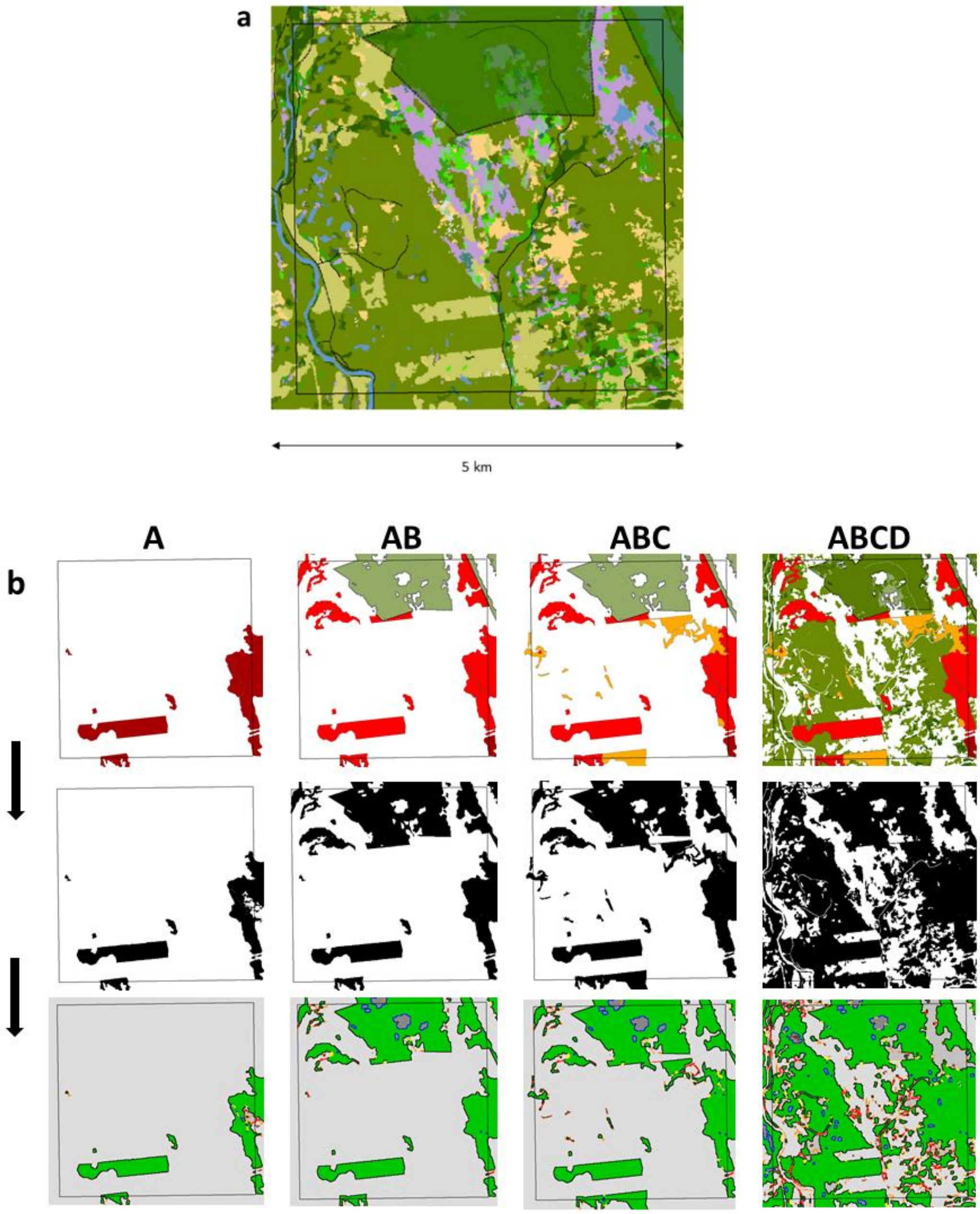


Figure 3. a) One of the 38 squares as an example, showing the landcover data (NMD) classes forest (green), wetland (purple), and temporarily open areas (khaki; see full legend in Appendix 3). b) In the same square, the four sets A, AB, ABC, and ABCD, illustrated by the polygons of which they are constructed. The polygons in the first row represents the various nature conservation values, i.e. previously registered WKHs (dark red) in set A, newly identified WKHs (red) added to create AB, newly identified ONVs (orange) added to create ABC, and all remaining forestland (green) added to create the forestland baseline ABCD. Note, a formally protected nature reserve is located partly within the square (dark green in the upper part), which has been included in set AB, i.e. as containing WKH quality. The second row represents the transformation of the different polygons in all four sets to a MSPA compatible binary raster file assigned as containing only foreground (black) and background (white) area. The third row represents the MSPA output, where the raster pixels are divided into a few generic non-overlapping classes which of some represent core (green), edge (black and blue), and corridor (red, orange and yellow; Appendix 4).

2.5. Analyses

2.5.1. Distribution of previously registered WKHs

To display an overview of the occurrence and size distribution of previously registered WKHs, I tabulated their total area, mean size, total number, largest WKH area, and smallest WKH area, separated on above and below the MFB. This was made for all existing WKH-types together as well as separately for the three focal WKH-types *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic*. Some WKHs were located partly above and partly below the MFB, and due to technical separating issues all WKHs placed with any part below the MFB were assigned to below the MFB. This created a small overestimation of the occurrence of WKHs below the MFB and hence a small underestimation above the MFB.

I compiled the secondary WKH-types classified by the SFA that corresponded to the WKHs that were primarily classified as *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, or *wetland-forest mosaic* and tabulated their total number and area. In contrast to the selection of WKHs for the creation of set A (i.e. where the selection was based on a WKH's primary and secondary biotope type; see 2.4.1), this tabulation was based only on the primary WKH-type to minimise potential overlaps between the WKHs. Moreover, data did not specify the areas of the different WKH-types within one individual WKH. This approach, however, failed to include areas secondarily classified as *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic* and thus underestimated their actual area.

2.5.2. Connectivity analyses

For each set (A-ABCD), I applied connectivity analyses using Morphological Spatial Pattern Analysis (MSPA; European Commission 2021a), which provided a variety of generic raster image processing tools. MSPA is targeted to describe the pixel-level geometry and connectivity of the components in an image (European Commission 2021a). In this study, the objects in set A-ABCD constituted the foreground area, which MSPA divided into a few generic mutually exclusive classes to describe its composition and spatial arrangement (Fig. 3; Appendix 5a). Next, I grouped the MSPA classes into four categories: core, edge, and corridor (including stretched forest occurrence and smaller islets of forest; Appendix 5b) as well as total foreground (i.e. consisting of the other three categories). All parameters except edge width were set to default prior to the MSPA. In natural and non-natural fragmented landscapes, the ecological effects of patch edges can be large (Aune et al. 2005; Timonen et al. 2010). Here, the edge effect was defined to occur in the outer 20 m of the patches, (i.e. corresponding to a pixel width of 2;

Svensson et al 2019). For each square, I calculated the percentage occurrence of the four MSPA categories and summarised their corresponding absolute area as preparation for the analyses. I further calculated the edge/core-ratio (i.e. the proportion of edge in relation to core) for *natural coniferous forest* in all squares. Moreover, I computed the proportion of total foreground and core area, separately, for sub-sets A, B, and C in relation to the forestland baseline ABCD for each square, to investigate whether they coincided with the Aichi target #11 of 17 % (CBD 2021) or not.

2.5.3. Statistical analyses

To test for differences in absolute area for the MSPA categories foreground, core, edge, and corridor among the four sets A, AB, ABC, and ABCD, I applied a simple linear regression, separately for each MSPA category assigning the four sets as predictor and area as response variable. I log-transformed area to ensure normally distributed data. Since the first model only tested set A in relation to the three other sets, I used 'contrasts' (R package contrast (O'Callaghan et al. 2020) and lsmeans (V. Lenth 2016)) to test for the differences between AB and ABC, AB and ABCD, and ABC and ABCD.

To analyse whether there was a difference in the continuous response variables absolute core area or the edge/core-ratio between the two categorical predictor groups above and below the MFB, I used a Mann Whitney U test. All squares partly or fully above the MFB were assigned to the group above (n=13) and the rest were assigned to the group below (n=25). The Mann Whitney U test is a non-parametric test without requirements of normally distributed input data and therefore transformations were not necessary.

These statistical tests were performed on the WKH-type *natural coniferous forest* alone since the amount of data related to *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* were not sufficient for the analyses (Appendix 6). The patterns of the merged data on all three focal WKH-types were very similar to data in the dominating *natural coniferous forest*, wherefore those data were not separately statistically analysed. Consequently, most results are available only for *natural coniferous forest*.

For the spatial analysis, I used the GIS software ArcMap (ArcGIS 10.8; ESRI, Redlands, CA, USA). For Morphological Spatial Pattern Analysis (MSPA) I used the Guidos Toolbox software (version 3.0; Soille & Vogt 2009; Vogt & Riitters 2017). I performed all statistical analyses in R software i386 4.0.2 (R Core Team 2020) using a significance level of $\alpha < 0.05$. Boxplots were created using the package *ggplot2* (Wickham 2016).

3. Results

3.1. Overview of previously registered WKHs

I found that out of the total area of all previously registered WKHs above the MFB, 81.8 % were *natural coniferous forest*, 3.1 % were *broadleaf-rich natural coniferous forest*, and 0.7 % were *wetland-forest mosaic* (Table 1). Below the MFB, the shares were 67.9 % of *natural coniferous forest*, 2.9 % of *broadleaf-rich natural coniferous forest*, and 1.8 % of *wetland-forest mosaic* (Table 2). Further, there was a large difference in absolute size and number of the WKHs between above and below the MFB, with a larger number and total area below the MFB (n=3,322; 23,781 ha) than above (n=641; 10,638 ha), which was also true for the three focal WKH-types separately. In contrast, the mean size of the WKHs was larger above the MFB than below, 17 ha vs. 7 ha, for all WKH-types together and the three focal WKH-types followed the same pattern.

Within the study area, 2,222 previously registered WKHs were primarily classified by the SFA as the WKH-type *natural coniferous forest* (corresponding to 24,864 ha; Appendix 7a). These WKHs were in turn secondarily classified according to 31 other WKH-types, with *spruce forest on wet soil* (Sw: *gransumpskog*; 4.4 %), *scree slope* (Sw: *bergbrant*; 4.4 %), and *natural forest creek* (Sw: *naturlig skogsbäck*; 3.4 %) as dominating types and *small canyon* (Sw: *liten sprickdal*; 0 %) as the least dominating. Fewer WKHs (n=118; 1036 ha) were primarily classified as *broadleaf-rich natural coniferous forest,* with 18 secondary types (Appendix 7b), namely *wetland-forest mosaic* (13.7 %), *natural coniferous forest* (13.5 %), and *surface spring outflow* (Sw: *källpåverkad mark*; 7.3 %) as the most common and *bank slope* (Sw: *brink*; 0.1 %) as the least. Even fewer WKHs (n=31; 509 ha) were primarily classified by the SFA as *wetland-forest mosaic* and had only 9 secondary types (Appendix 7c). The three most common were *forest on rocky ground* (Sw: *hällmarkskog*; 21.7 %), *spruce forest on wet soil* (Sw: *gransumpskog*; 18.4 %), and *small ponds* (Sw: *småvatten*; 7.9 %) and the least was *pine forest on wet soil* (Sw: *tallsumpskog*; 0.3 %).

Tabel 1: Total area, mean size, total number, largest area and smallest area of all previously registered WKHs for natural coniferous forest, broadleaf-rich natural coniferous forest, *and* wetland-forest mosaic, *separately, above the mountain forest border (MFB)*

WKHs above the MFB

	Total area (ha)	Mean size (ha)	Total number	Largest WKH (ha)	Smallest WKH (ha)
All WKH-types	10,638	17	641	513	0*
Natural coniferous forest	8,700	19	461	513	0*
Broadleaf-rich natural coniferous forest	330	21	16	142	0*
Wetland-forest mosaic	70	70	1	70	70

Tabel 2: Total area, mean size, total number, largest area and smallest area of all previously registered WKHs for natural coniferous forest, broadleaf-rich natural coniferous forest, *and* wetland-forest mosaic, *separately, below the mountain forest border (MFB)*

WKHs below the MFB

	Total area (ha)	Mean size (ha)	Total number	Largest WKH (ha)	Smallest WKH (ha)
All WKH-types	23,781	7	3,322	265	0*
Natural coniferous forest	16,164	9	1761	265	0*
Broadleaf-rich natural coniferous forest	706	7	102	79	0*
Wetland-forest mosaic	439	15	30	110	0*

** The smallest WKH area equals to 0 (zero) due to WKH-types represented by point objects such as one single, very large and old tree.*

3.2. Dominance of *natural coniferous forest*

With the focus on the three focal WKH-types *natural coniferous forest*, *broadleaf-rich natural coniferous forest*, and *wetland-forest mosaic*, the results showed that the former type strongly dominate by area (Fig. 4). The two latter WKH-types consisted only of few polygons and occurred only in few squares (Appendix 6), wherefore they were excluded from the statistical analyses. The summarised foreground area of all three focal WKH-types was highly influenced by the pattern of *natural coniferous forest*.

The *natural coniferous forest* absolute core, edge and corridor area increased in general from set A through AB and ABC to ABCD. The area increased most between set ABC and ABCD, whereas it increased less and with larger variation among the other sets (i.e. A to AB to ABC; Fig. 5). Apart from between set AB and ABC, there was a difference in absolute area among all sets (i.e. between A and AB, A and ABC, A and ABCD, AB and ABCD, ABC and ABCD; Appendix 8) for core as well as for edge and corridor. The corridor area was very small in the three sets containing nature conservation values (i.e. sets A-ABC), whereas the potential corridor area considering the forestland baseline (i.e. set ABCD) was considerably larger.

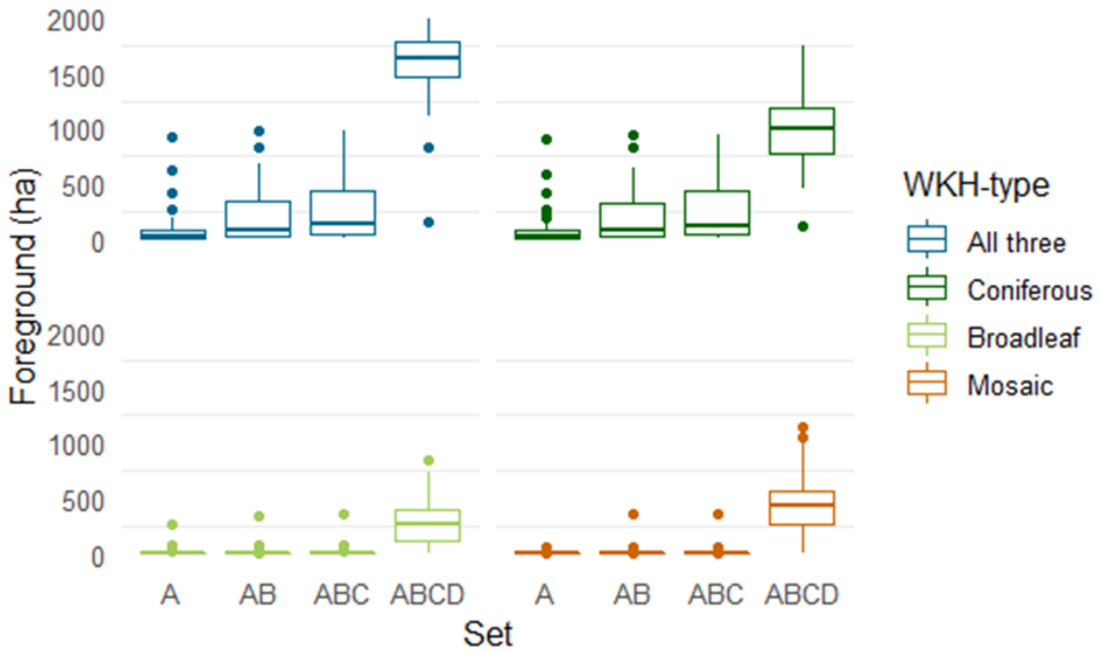


Figure 4. Foreground area (ha), i.e. the combined area of core, edge and corridor, per set summarised for all three focal WKH-types (All three) and separately for each type, i.e. for natural coniferous forest *(Coniferous),* broadleaf-rich natural coniferous forest *(Broadleaf) and* wetland-forest mosaic *(Mosaic). The midline represents the median value, and the dots represent outliers.*

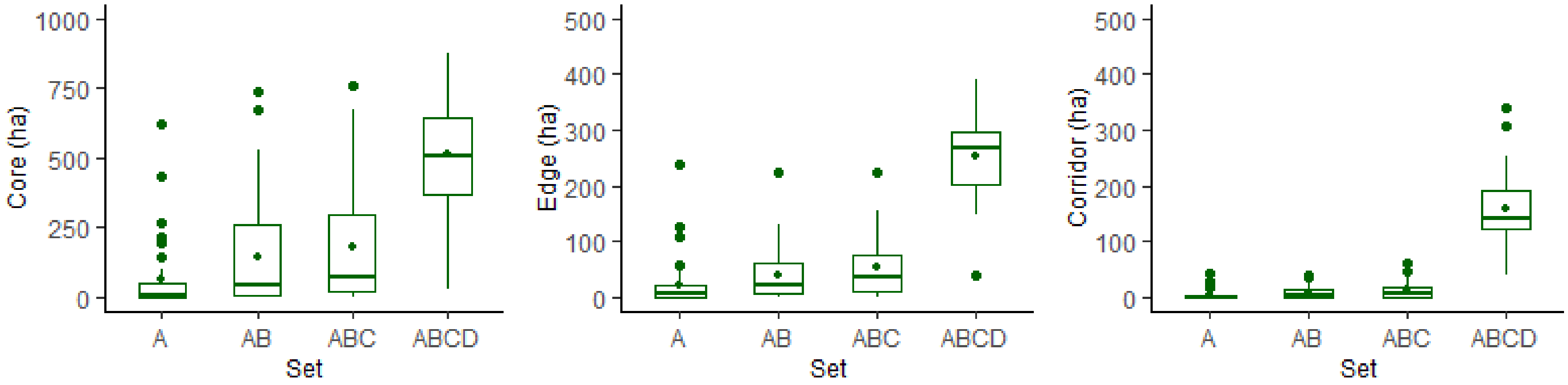


Figure 5. Area (ha) distribution between the sets (A, AB, ABC, and ABCD) in natural coniferous forest *core, edge, and corridor, separately. The midline within each box represents the median, the internal dots represent the mean values, and the external dots represent outliers. Note; the left diagram y-axis has a different scale.*

3.3. *Natural coniferous forest* core area and edge/core-ratio differ above and below the MFB

The *natural coniferous forest* core area differed according to the Mann Whitney U test between above and below the MFB for all sets (A: *W* = 71, *p* = 0.005; AB: *W* = 43, *p* = 0.000; ABC: *W* = 44, *p* = 0.000; ABCD: *W* = 76, *p* = 0.008; Fig. 6). In particular, the core area was much larger above than below the MFB for sets AB and ABC. The lowest core area was found in set A below the MFB (median = 1 ha), while the largest was found in set ABCD above the MFB (median = 717 ha). There was a larger variation in area size above the MFB. The edge/core-ratio (i.e. the proportion of edge in relation to core) for *natural coniferous forest* was significantly higher below the MFB than above for set AB, ABC, and ABCD (AB: *W* = 194, *p* = 0.007; ABC: *W* = 241, *p* = 0.000; ABCD: *W* = 252, *p* = 0.006; Fig. 7). Above the MFB, the edge proportion decreased when sub-sets B, C and D were added to the previously registered WKHs in set A, which was not the case below the MFB. The highest edge proportions were found in set A and ABC below the MFB (median (%) = 58.8 and 59.9, respectively) and the lowest in set AB and ABC above the MFB (median (%) = 31.1 and 29.1, respectively).

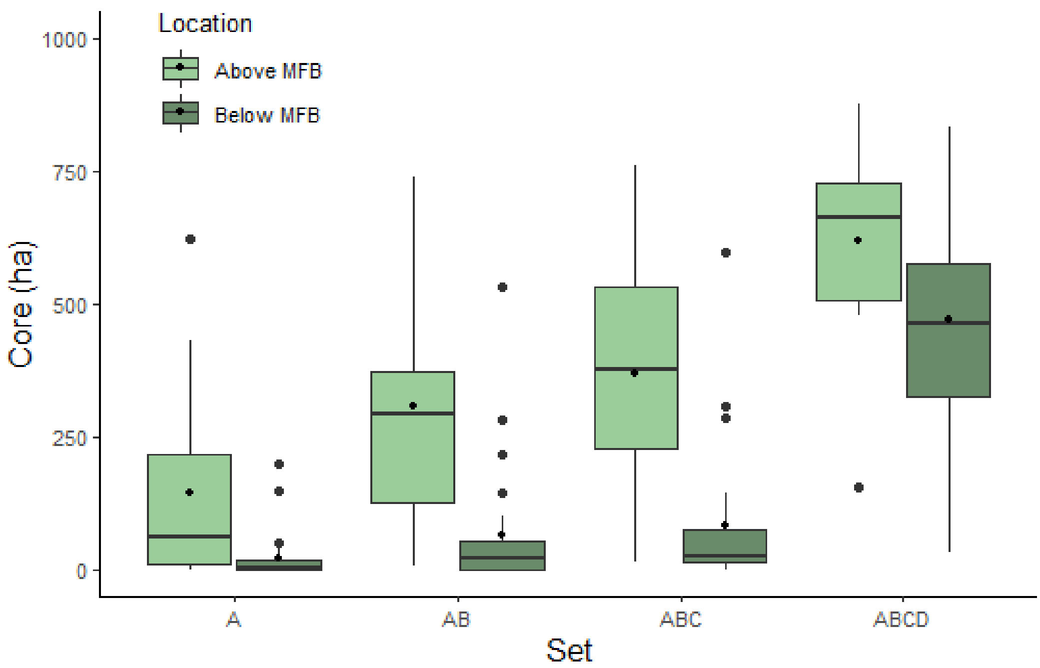


Figure 6. The difference in natural coniferous forest *core area between above and below the mountain forest border (MFB) for the four sets A, AB, ABC, and ABCD. The midline within each box represents the median, the internal dots represent the mean values and the external dots represent outliers.*

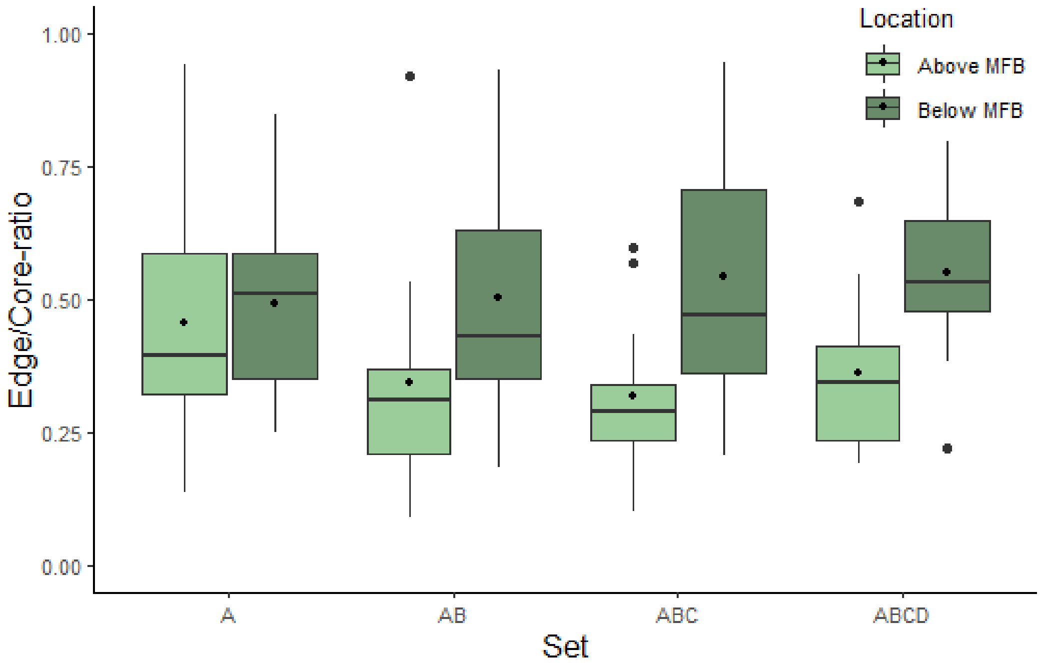


Figure 7. The difference in edge/core-ratio (i.e. the proportion of edge in relation to core) for natural coniferous forest *between above and below the mountain forest border (MFB) for the four sets A, AB, ABC, and ABCD. The midline within each box represents the median, the internal dots represent the mean values and the external dots represent outliers.*

3.4. *Natural coniferous forest* areas in relation to the international Aichi target #11

For *natural coniferous forest*, the proportion of areas containing high or semi-high nature conservation values (i.e. set ABC) in relation to the forestland baseline (i.e. set ABCD) per square was in general much higher above the MFB than below (Fig. 8). For total foreground area above the MFB, the proportion of set ABC exceeded the target of 17 % protected areas important for biodiversity required by the Aichi target #11 (CBD 2021) in 10 of 13 squares (77 %). Four out of these 10 squares exceeded the target with previously registered WKHs alone (i.e. set A), five with the addition of newly identified WKHs (i.e. set AB) and one by the addition of newly identified ONVs (i.e. set ABC). In contrast, only seven out of 25 squares (28 %) held a proportion of foreground in ABC that exceeded 17 % below the MFB. One of these seven squares exceeded the target with previously registered WKHs alone (i.e. set A), four with the addition of newly identified WKHs (i.e. set AB) and one by the addition of newly identified ONVs (i.e. set ABC). The remaining 18 squares (72 %) below the MFB, did not contain high or semi-high nature conservation values to meet the target of 17 %.

For the core proportion above the MFB, nine out of 13 squares (69 %) exceeded 17 %, of which four by previously registered WKHs alone, four with the addition of newly identified WKHs, and one with the addition of newly identified ONVs. On the contrary, for core proportion, only four out of 25 squares (16 %) exceeded 17 % below the MFB, of which one with previously registered WKHs, two with the addition of newly identified WKHs and one with the addition of newly identified ONVs. With the focus on core proportion, four squares (31 %) contained less than 17 % of high or semi-high nature conservation values above the MFB, compared with 21 squares (84 %) below the MFB.

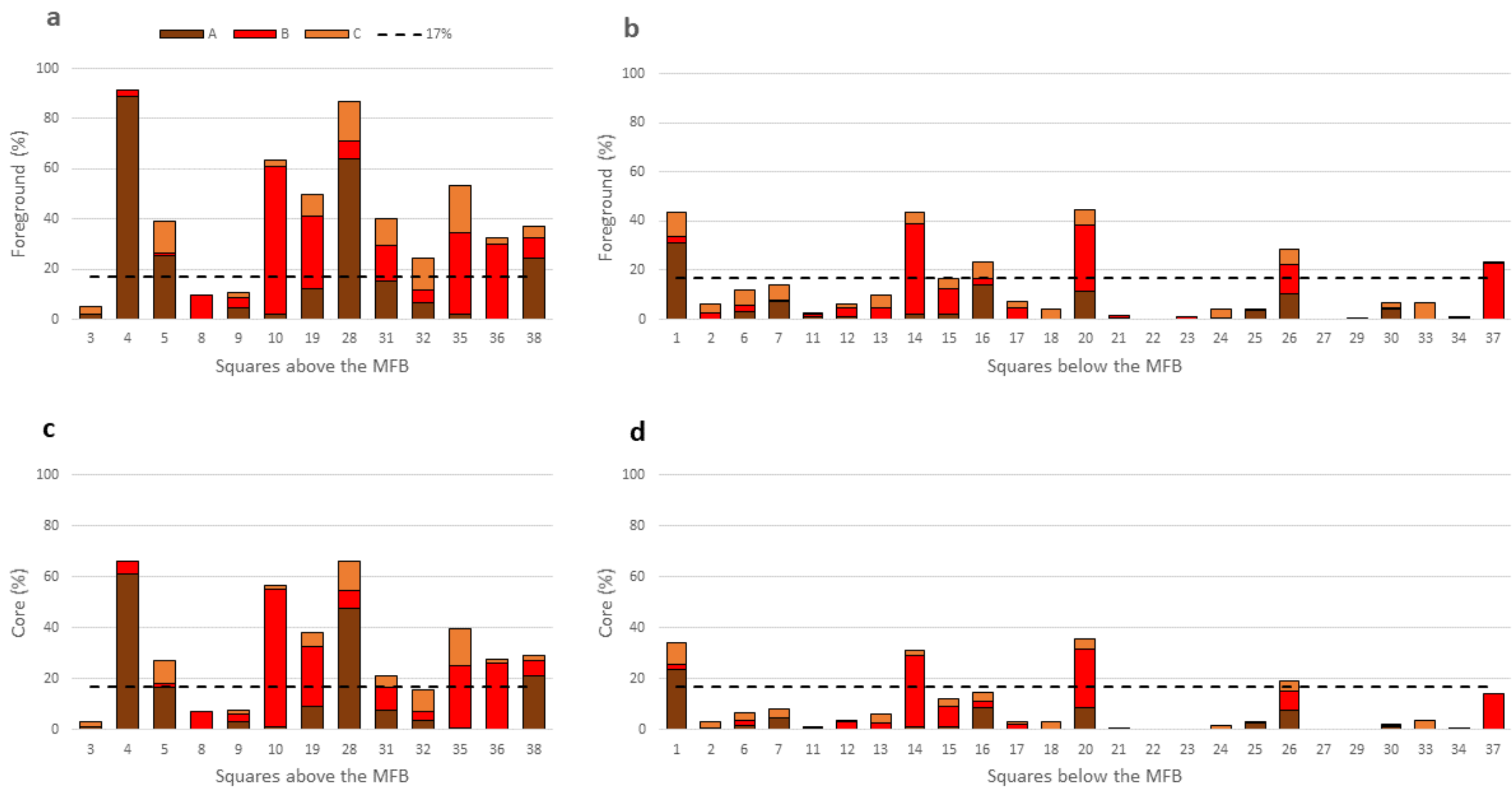


Figure 8. Proportion of natural coniferous forest *foreground (i.e. core, edge and corridor) and core for sub-sets A (previously registered WKHs; dark red), B (newly identified WKHs; light red), and C (newly identified ONVs; orange) in relation to the forestland baseline (ABCD) for each individual square, separated on above (left) and below (right) the mountain forest border (MFB). The dashed line represents the 17 % protected areas important for biodiversity required by the Aichi target #11* (CBD 2021).

3.5. *Small broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* core areas

Overall, areas of *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* with high or semi-high nature conservation values (i.e. set A, AB, and ABC) were rare (Fig. 9). For both WKH-types, the area increase among the sets A, AB, and ABC was minor, whereas the area increase in set ABCD was high, but showed a large variation among the squares. The *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* with additional high or semi-high nature conservation values (i.e. set AB and ABC) occurred to a slightly larger extent above the MFB than below. This result should be interpreted with care, however, due to the low sample size (Appendix 6).

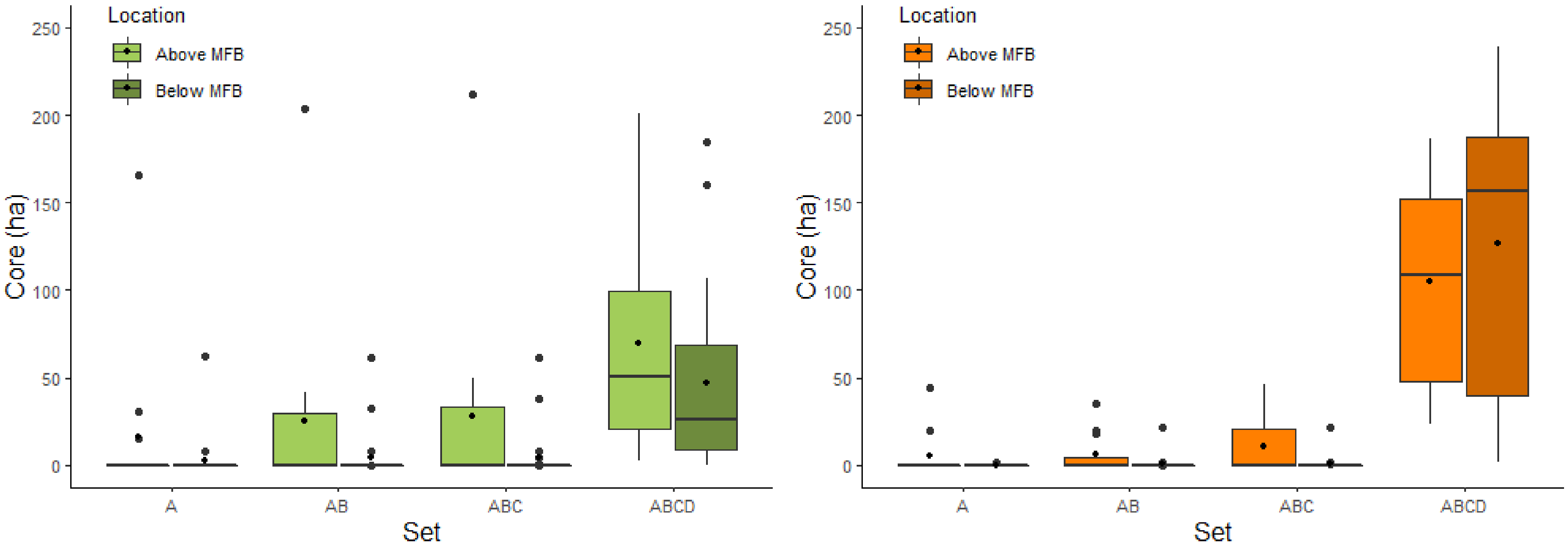


Figure 9. The difference in broadleaf-rich natural coniferous forest *(left) and* wetland-forest mosaic *(right) core area (ha) between above and below the mountain forest border (MFB) for the four sets A, AB, ABC, and ABCD.*

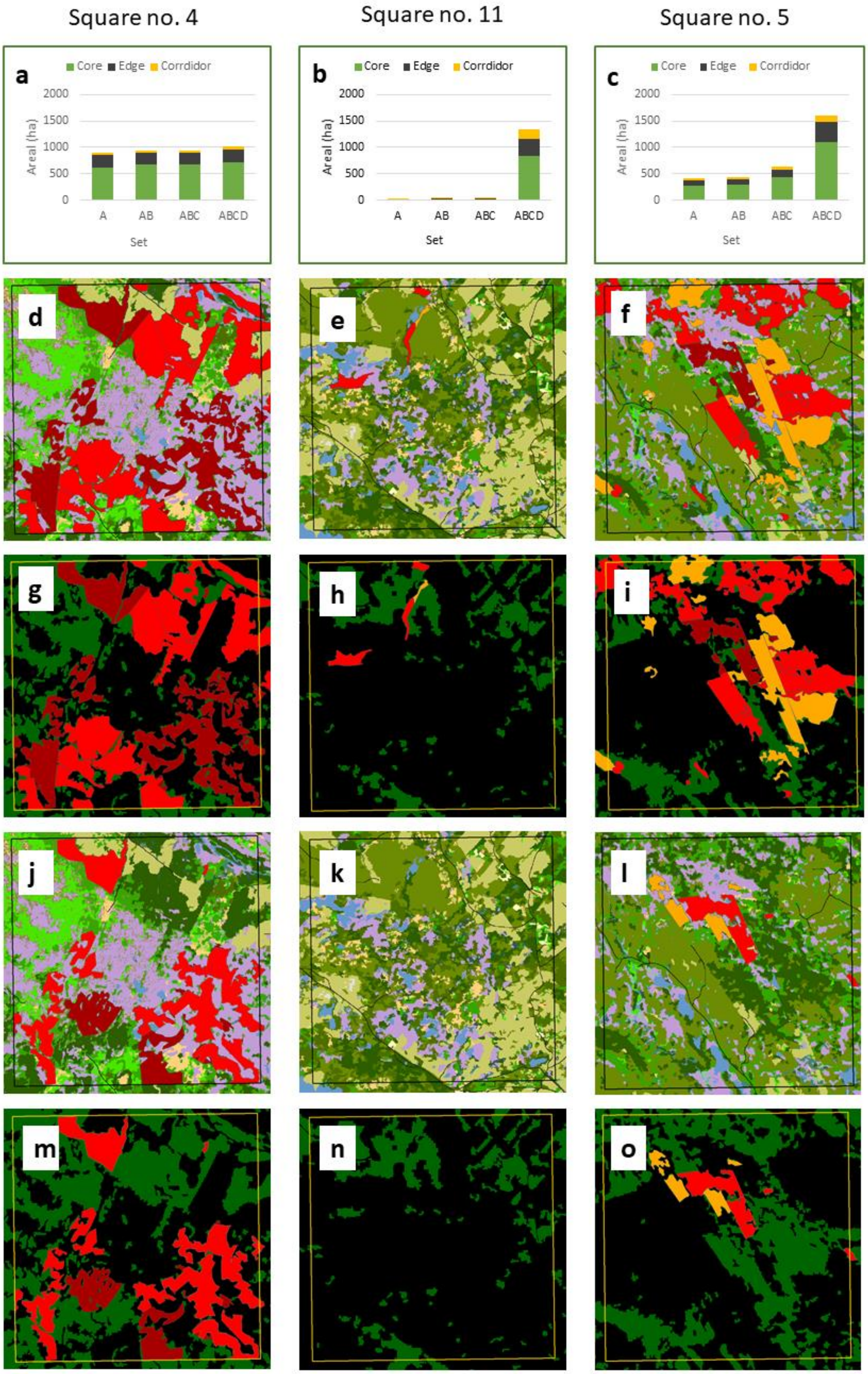
3.6. Various conditions for nature conservation among squares

I found a large variation in how local connectivity can be strengthened by the area additions among the 38 squares. More specifically, the absolute area and share of core, edge, and corridor as well as the area increment between the sets (A-ABCD) varied largely (Fig. 10). In general, for *natural coniferous forest*, the share of core area was larger than the shares of edge and corridor. However, in some squares and sets (n=16), the share of edge was larger than the share of core (A: n=7; AB: n=4; ABC: n=3; ABCD: n=2), mostly occurring below the MFB (n=13). Regarding the core area increase between the sets, some squares showed examples of extreme increases, especially between set ABC and the baseline ABCD. The largest *natural coniferous forest* core area increase equalled 177 times from 3 ha to 531 ha, whereas the comparable increase was 690 times for *broadleaf-rich natural coniferous forest* from 0.1 ha to 69 ha, and 14,325 times for *wetland-forest mosaic* from 0.04 ha to 573 ha. These large increases occurred when only small areas containing high or semi-high nature conservation values existed (or rather, were identified) in a square with high abundance of baseline forest.

To illustrate the substantial variability between the sample of squares, figure 10 shows no. 4, 5, and 11. Square no. 4 represents a situation with a marginal area increase between the sets for *natural coniferous forest* core, edge, and corridor, which is related to the already large area of previously registered WKHs within the square. The square is located in the municipality of Krokom (Appendix 9), partly above the MFB, and shows a typical landscape mosaic of wetlands and forest patches. Almost all newly identified WKHs (sub-set B) overlap spatially with previously registered ones (sub-set A), and the area of ONVs (sub-set C) does not contribute to any extent, for neither of the three focal WKH-types. The NMD- and pCF-maps suggest a marginal area increase in the baseline ABCD for *natural coniferous forest*, which represents an outlier situation in the sample. Here, most of the remaining unprotected pCF constitutes of deciduous forest and not of coniferous forest. Many previously registered WKHs are classified as both *natural coniferous forest* and *broadleaf-rich natural coniferous forest* within this square. Moreover, temporarily open areas (i.e. clear-cuts) can be detected close to the WKHs in the upper part of the map.

Square no. 11 represents a more common pattern among the squares, namely that sets A, AB, and ABC constitute only a small area in comparison to the forestland baseline. Thus, the area increase between set ABC and ABCD is very high. The square is located in the municipality of Storuman (Appendix 9) below the MFB. The NMD- and pCF-maps show a highly fragmented landscape, naturally through wetlands, as well as anthropogenically through many temporarily open areas (i.e. clear-cuts). For *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic*, neither previously registered WKHs nor newly identified WKHs or ONVs are present.

Square no. 5 is characterised by the abundance of ONV areas. It is located in the municipality of Berg (Appendix 9), partly above the MFB. Whereas almost all newly inventoried WKHs (sub-set B) are overlapping with previously registered WKHs, the SFA inventory performed in 2018 added large numbers and areas containing ONV qualities, especially for *natural coniferous forest*. For instance, a small WKH island (in the upper right corner) became contained in a large ONV object, and another small WKH (in the lower right corner) became linked to larger WKHs by the newly identified ONV patches. Some previously registered WKHs were classified as more than one WKH-type within this square. The pCF-map illustrates only small areas of continuity forest outside areas containing already known high nature conservation values.



Square no. 4
Square no. 11
Square no. 5
a
b
c
Core
Edge
Corrdidor
Areal (ha)
2000
1500
1000
500
0
A
AB
ABC
ABCD
Set
d
e
f
g
h
i
j
k
l
m
n
o

Figure 10. Three examples of SFA squares (no. 4, 11, and 5), representing three different area increase scenarios and prerequisites for nature conservation. The bar charts in the first panel (a-c) illustrate absolute area and proportion of core, edge and corridor for the four sets A, AB, ABC, and ABCD for natural coniferous forest. *The second panel and the fourth panel maps illustrate polygons representing previously registered WKHs (in dark red; sub-set A) newly identified WKHs (in light red; sub-set B) and ONVs (in orange; sub-set C) of* natural coniferous forest *(d-f) and* broadleaf-rich natural coniferous forest *together* with wetland-forest mosaic *(j-l), respectively. The background shows the national landcover data (NMD), where forest (green), wetland (purple), and temporarily open areas (khaki) are interesting landcover classes (see full legend in Appendix 3). The third panel and the fifth panel maps show the same polygons for* natural coniferous forest *(g-i) and* broadleaf-rich natural coniferous forest *together with* wetland-forest mosaic *(m-o), respectively, but at a background map of proxy-Continuity forest (pCF).*

4. Discussion

4.1. Overview of results

The forests and forest landscapes along the Scandinavian Mountain range are naturally heterogenous and diverse. Still, my results clearly show that *natural coniferous forest* is a strongly dominating WKH-type. Although this biotope type is intrinsically variable and more a type of a complex then a specific biotope, this implies an unbalanced distribution of documented conservational values among biotope types. The absolute areas containing high or semi-high nature conservation values of *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* are very small in comparison, and the majority of WKH-types are documented at low frequency and areal cover.

I found a larger absolute WKH area below the MFB than above, which can be explained by both the method I used to separate WKHs in above and below the border and by the existence of non-registered WKHs within already formally protected areas (Wester & Engström 2016), which largely are located above the MFB. However, I only investigated the absolute WKH area, but did not calculate it in relation to for example total forestland above and below the MFB. The mean size of the WKHs was larger above the MFB than below for all WKH-types, in line with observations by Wijk (2017b) and Roberge (2018). This can be explained by the in general larger areas containing high nature conservation values above the MFB (Angelstam et al. 2020; Svensson et al. 2020).

I further found a general significant increase in natural coniferous forest core, edge, and corridor absolute area when sets with areas of various nature conservation values were added, representing a potential increase in connectivity. In addition, I found a notable larger *natural coniferous forest* core area above the border and a higher *natural coniferous forest* edge/core-ratio below. Importantly, my results highlight a larger potential to meet the Aichi target #11 of 17 % of protected area (CBD 2021) above the MFB, while substantially larger areas and functionality have to be added for conservational purposes below. I found a large variation among the 38 squares, which further emphasises the intrinsic structural variability in the forest landscapes along the Scandinavian Mountain range.

4.2. *Natural coniferous forest* green infrastructure potential

My results suggest a general significant increase in *natural coniferous forest* core, edge, and corridor absolute area from previously registered WKHs by adding areas of varying conservational value, indicating a potential for improved connectivity. This is not unexpected, since overall connectivity increases by area increase (e.g. Mikusiński et al. 2021). Yet, it is important to note that connectivity increased the most between set ABC and ABCD, which may question how much real conservational value is added, since the latter mostly constitutes of forests with no documented nature conservation values. However, the forestland baseline may provide suitable habitat for some specific species, but does in general only provide a green infrastructure potential that is dependent on connectivity and habitat improvement as part of the forest management profile (Felton et al. 2020).

Corridor areas are important to connect different core areas as they facilitate species dispersal and enhance connectivity between isolated core areas (Ye et al. 2020). Therefore, the small corridor areas found in the sets with high or semi-high nature conservation values in this study might indicate low connectivity, with potential negative implications for biodiversity (Aune et al. 2005). In contrast, in the forestland baseline, the corridor area was significantly higher, potentially explained by the inclusion of fragmented forests, i.e. some of the forest fragments created corridors between other forest fragments. However, the quality of these corridor forests determines whether they contribute to species migration or not, which in addition largely is species-specific.

It is important to note, however, that I defined increased connectivity as increased core and corridor area in this study. This is in line with the island biogeography theory (Helmus & Behm 2020) that stresses the importance of large coherent suitable habitat areas and reasonable dispersal distances for species persistence and migration ability. Connectivity, especially ecological functional connectivity, can be assessed in numerous ways, with far more spatial, habitat, and species complexity than performed in this study. Additionally, connectivity within the squares was investigated without any attention to their spatial configuration or their surrounding environment. This may lead to over- or underestimations of individual areas' importance for nature conservation or green infrastructure.

The lack of significant increase in absolute core, edge and corridor area between set AB and ABC indicate an in general low contribution of the ONVs to increase the area with nature conservation values. Overall, the occurrence of ONVs in Sweden might be underestimated since their identification has not been prioritised and has varied regionally (Wester & Engström 2016), but in this study data were collected in the squares by the SFA aiming at including ONVs, which should minimise such a general underestimation. The ONV concept is not as complete as is the WKH concept, and the value of ONVs can vary depending on their assigned WKH-type and location (Kretz, E. pers. comment). Hence, there is a need for a national definition to achieve a uniform application and understanding of the ONV registration (Wester et al. 2019).

4.3. Larger *natural coniferous forest* green infrastructure potential above the MFB

The MFB clearly has had practical implications for the maintenance of WKHs, ONVs, and intact forests (Jonsson et al. 2019), as shown by the considerable larger *natural coniferous forest* core areas above the border. This is in line with earlier studies, that for example found Sweden's largest HCVF patches (> 10,000 ha, some exceeding 100,000 ha) to be located above the MFB, whereas most HCVF patches below are smaller than 1000 ha (Angelstam et al. 2020). Overall, the forest belt along the Scandinavian Mountain range is a green infrastructure hotspot (Svensson et al. 2020).

Sweden has a long history of intensive forestry that has transformed the forest landscape (Ericsson & Östlund 2000; Ecke et al. 2013). The exploitation of forestland in northern Sweden started at the Bothnian coast and progressed via the inland towards the mountain region where it gradually ceased (Linder & Östlund 1992). This timeline, and the establishment of the MFB (von Sydow 1988) largely explain the difference in amount of intact forest core area that I found between above and below the MFB. My results do contribute to the view that there is a larger potential to realise a functional forest green infrastructure above the MFB than below (Svensson et al. 2020), but that the in general high nature conservation values rather are associated with a limited habitat type (i.e. *natural coniferous forest*) than with overall habitat diversity. However, as discussed above, *natural coniferous forest* is a broad WKH-type and include a continuum of more specific habitat types.

Moreover, I found a notable core area increase between previously registered WKHs and newly identified WKHs above the MFB, which marks the inclusion of HCVFs within existing nature reserves. In this study, formally protected forests were treated as containing WKH quality and do constitute relatively large areas within some squares. About 75 % of the total area of Sweden's over 5,000 nature reserves are located in the mountain region (Naturvårdsverket 2021), which therefore affects the core area above the MFB to a larger extent than below.

My results further showed significant higher *natural coniferous forest* edge/core-ratio below the MFB than above. This suggests that the core areas below the MFB are smaller and more fragmented than the core areas above, which again can be explained by the differences in forestry intensity (e.g. Linder & Östlund 1992; Jonsson et al. 2019). Moreover, below the MFB, the edge/core-ratio became slightly higher as more areas were added. Hence, despite the additional areas, the forest landscapes still contained a large proportion of edge in relation to core, which suggests that the additional areas constituted of small forest fragments. In contrast, above the MFB the edge/core-ratio decreased from the previously registered WKHs as more areas were added, indicating that the additional areas contributed to create larger coherent core areas (i.e. with smaller shares of edge areas), and not to more patches of small, isolated core areas. Thus, my results indicate contrasting patterns above and below the MFB, which even further emphasize a stratification of the Swedish mountain region forest landscape, but in a wider context also point at substantially different forest landscapes above the MFB than elsewhere in Sweden. The area below the MFB, but within NW Sweden, is intermediate, and the future governance direction will determine whether this area will add to the intact values above the MFB or to the forest production landscapes below.

In this study, I defined the edge effect as the outer 20 meters of a forest patch. However, the edge effect is probably larger and more varied, following the 'rule-of-thumb' saying edge effects extend two to three tree lengths into forests (Aune et al. 2005). Consequently, this may lead to a potential underestimate of the absolute edge area and a potential overestimate of the absolute core area throughout my results. As an effect, the edge/core-ratio could have been higher, with increased forest patch exposure to negative biotic and abiotic edge effects (Aune et al. 2005) and with smaller functional core areas (Svensson et al. 2019a).

All types of forest edges do not necessarily need to be negative, given the species-specific sensitivity to edge effects (Aune et al. 2005) and the differences between natural and anthropogenic edges (Harper et al. 2015). Natural edges (e.g. between forests and wetlands, or shaped by natural disturbances) are a natural part of the boreal forest biome, while anthropogenic edges are a result of human activity such as timber harvesting (Harper et al. 2015). In this context, one can expect a larger share of natural edges above the MFB and a larger share of anthropogenic edges below the border (Esseen et al. 2016), with varied effects on biodiversity in the affected core areas.

4.4. WKHs for fulfilment of international targets

The Convention on Biological Diversity's Aichi target #11 (CBD 2021) states that 17 % of a country's terrestrial land area important for biodiversity should be protected by 2020. I found that more squares (69 %) above than below (16 %) the MFB contained areas with high or semi-high nature conservation values that exceed 17 %, and thus represent a larger potential to meet the Aichi target #11. There was a general surplus above the MFB that could compensate for the few squares (i.e. 4 out of 13) not exceeding 17 %. In contrast, below the MFB, I found a general shortage that could not compensate for the many squares (i.e. 21 out of 25) not exceeding 17 %. Consequently, this again supports the conservational hotspot status of the forests along the Scandinavian Mountain range. My results highlight single areas of high conservational value below the MFB as well, but also reveal the large lack of it in most squares, which emphasises the need for more conservational effort (Svensson et al. 2020; Mikusiński et al. 2021).

All individual squares, however, do not necessarily need to exceed 17 % for Sweden to meet the Aichi target #11 nationally, but my results strengthen the view of the uneven distribution of high nature conservation value forests in the Swedish boreal biome (e.g. Svensson et al. 2019a; Angelstam et al. 2020). Above the MFB, 57 % of all forestland is formally protected, in contrast to only up to 4 % in the rest of the country (SCB 2021). With regards to the criteria on ecological representativeness and connectivity according to the Aichi target #11 (CBD 2021), one can question whether Sweden's nature conservation work is successful or not, as discussed in Angelstam et al. (2020). This question is further supported by the failure in meeting the national Environmental Quality Objective *Sustainable forests* (Skogsstyrelsen 2021a).

WKHs are recognised as being important for biodiversity conservation and are furthermore acknowledged as key in meeting the *Sustainable forests* target (Wester & Engström 2016; Wijk 2017a). Unfortunately, there is no national systematic WKH-inventory at present (Wester & Engström 2016), and the identification of WKHs in association with harvest notification administration ceased in 2021 (Skogsstyrelsen 2021b), probably resulting in large areas of future WKHs to remain unidentified in Sweden. My results clearly show that especially the newly identified WKHs, but to some extent also the newly identified ONVs, are key elements in reaching the international Aichi target #11 of 17 %, which I think emphasise the importance to continue the WKH-inventory to identify and map areas containing high or semi-high nature conservation values to meet other national and international biodiversity targets.

Biodiversity is lost in a rapid rate globally and many species are red listed as threatened, a pattern apparent in Sweden as well (IPBES 2019; SLU Artdatabanken 2020; IUCN 2021). My results and previous research (e.g. Potapov et al. 2017; Watson et al. 2018; Jonsson et al. 2019; Svensson et al. 2020) highlight the very high conservational values of the intact forest landscapes above the MFB. Unfortunately, intact forests are currently under high pressure globally, due to their potential high-value timber resources (Potapov et al. 2017; Watson et al. 2018). In Sweden, only around 300 000 ha are available for forest harvesting above the MFB, which represents 1.3 % of its productive forestland (Jonsson et al. 2019). Apart from timber harvesting, the intact boreal forests above the MFB hold multifunctional values for recreation, tourism, and climate change resilience (Pohjanmies et al. 2017), for biodiversity (Esseen et al. 1997), for the indigenous Sámi culture and reindeer husbandry as well as for rural development and livelihood (Jonsson et al. 2019). Thus, one can question whether it is defensible to manage these 1.3 % of productive forestland for wood production or if it is more relevant to promote a holistic and sustainable perspective.

The Aichi target #11 was to be achieved by 2020, a target that was not met in Sweden. The next possibility for Sweden to meet an international target and to enhance and secure biodiversity is until 2030, concerning the EU's biodiversity strategy, in which one key commitment is to legally protect a minimum of 30 % of the EU's land area (European Commission 2020). To achieve this, including sufficient habitat representation and functional connectivity, strong political incentives are required nationally. In addition, priorities need to be considered in policy making on whether it is more suitable to protect remaining forests with high nature conservation values, or to perform restoration and connectivity improvement actions in degraded forest landscapes. The new EU Biodiversity Strategy stresses the importance of mapping and strictly protecting all the remaining primary and old-growth forests in the EU (European Commission 2020), which clearly will affect the high nature conservation value forest landscapes along the Scandinavian Mountain range.

4.5. *Broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* green infrastructure potential

In contrast to my results on *natural coniferous forest,* the absolute areas containing high nature conservation values of *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic* were very small. However, the area increase to the forestland baseline was relatively large, which indicates a theoretical potential to increase connectivity for these two WKH-types by restoration efforts or other management actions. However, due to the very small sample size, and no statistical analyses performed on these data, it is not possible to draw any general conclusions. Moreover, even if the area increase between the objects with high or semi-high nature conservation values and the forestland baseline was large for both *broadleaf-rich natural coniferous forest* and *wetland-forest mosaic*, the absolute area itself in the forestland baseline likely is too small to potentially achieve a functional green infrastructure.

The lack of deciduous forests, especially below the MFB, is partly explained by earlier forest management where deciduous tree species were removed by cleaning and herbicide spraying in favour of coniferous wood production (Axelsson et al. 2002). In addition, deciduous forests are associated with post-fire successional stages in naturally dynamic boreal forest landscapes, which were more common prior to fire suppression (Esseen et al. 1997). The contribution of the subalpine mountain birch forest to provide area of deciduous forest for both high and low demanding broadleaf-dwelling species largely is unquestionable (Mikusiński et al. 2021). However, the subalpine mountain birch forest is low-productive and located close to the Scandinavian Mountain range with harsh climate conditions, and thus is not suitable for all deciduous forest depending species. Therefore, besides restoration, there is a need for enhanced inventory efforts to identify and protect deciduous forest habitats that still exist to secure biodiversity and a functional green infrastructure, which calls for an improved and continued WKH inventory.

One of the largest challenges with performing the WKH-inventory in vast areas with *wetland-forest mosaic* is the delimitation of the WKHs, since the whole landscape consists of a mosaic of different forest types, wetlands, and other neighbouring land covers (Wester & Engström 2016; Fig. 11). Therefore, as for *broadleaf-rich natural coniferous forest*, an improved WKH-inventory is important to secure the various elements of this WKH-type. The reason to the small area of *wetland-forest mosaic* with high or semi-high nature conservation values in my results may have more than one explanation. First, only few previously registered WKHs within the study area are classified as the WKH-type *wetland-forest mosaic* by the SFA (Appendix 7c). Second, in sub-set B I included the HCVFs within nature reserves, which consist of forestland and not of wetland (Naturvårdsverket & Skogsstyrelsen 2017), why I probably underestimated the real wetland area. In the forestland baseline, though, all wetlands were included, which explains part of the large area increase.

Figure 11. Wetland-forest mosaic in Lina fjällurskog nature reserve - a landscape consisting of a mosaic of different forest types, wetlands, water bodies, and other land covers.

4.6. Various conditions for nature conservation among local landscapes

There is a large variation in absolute core, edge, and corridor area, as well as in their areal increase and share among the squares, which reflects a naturally large ecological variation and the extent of human impact on nature (Roberge 2018). In some squares, the area increase between the objects with high or semi-high nature conservation values (i.e. set ABC) and the forestland baseline (i.e. set ABCD) was extremely large, as a consequence of few and small identified and demarked areas containing high or semi-high nature conservation values in a landscape mostly covered by forest. In theory, these extreme area increases correspond to a large potential to increase connectivity within the square, but reality is far more complex. The potential to increase connectivity based on the baseline forests is very much dependent on the quality of those forests, including e.g. age distribution, tree species composition, content and variability of dead wood, and other structures important for biodiversity (Halme et al. 2013). Due to the previous and current extensive forestry in NW Sweden, many forests are left fragmented and degraded (e.g. Jonsson et al. 2019; Angelstam et al. 2020) and hence lack such natural values that maintain biodiversity (Esseen et al. 1997; Halme et al. 2013; Mikusiński et al. 2021). Those values, however, can probably develop naturally over time if forests are set aside from commercial forestry or assisted by restoration actions (Halme et al. 2013). Still, the development of forest structures that are associated with natural and old growth forests is a slow process (Svensson et al. 2020) and the success of restoration can be challenged by unwanted and unpredictable side effects associated with restoration actions (Halme et al. 2013). In other words, the extreme area increases in the forestland baseline in some squares do not by default mean there is a large potential to increase connectivity, but rather demonstrate how limited nature conservation conditions currently are. However, the forestland baseline may contain areas with high or semi-high nature conservation values that yet are not identified and mapped, which readily can contribute to realise a functional green infrastructure, which again calls for an improved and continued WKH inventory.

4.7. Future research

My study focused on the current research gap concerning the importance of specific biotope and forest types for a functional green infrastructure in NW Sweden. By including different biotope types and various nature conservation values (i.e. previously registered WKHs, newly identified WKHs and ONVs, and baseline forests with no documented conservation values) I evaluated the current green infrastructure potential of the multifunctional landscape in NW Sweden. However, my study could be improved further, for instance by analysing a larger sample (>

38 squares) and by including the county of Norrbotten - a geographically large part of NW Sweden acknowledged to contain large areas with high nature conservation values (Wester et al. 2019). To achieve an ecologically functional green infrastructure in the landscape, representation of different biotope and forest types need to be considered (Pimm et al. 2014; Angelstam et al. 2020). My results showed a clear dominance of *natural coniferous forest* whereas most WKH-types are documented at low frequency and areal cover, suggesting that further research is needed to analyse their contribution to and importance for a functional green infrastructure. Moreover, species with various habitat requirements and valuable forest structures (e.g. dead wood) need to be included in research to achieve an ecological functional green infrastructure on an even narrower and deeper scale. Finally, my results support a continued WKH-inventory to secure biodiversity and habitat connectivity on different scales. The improved WKH-inventory method developed for NW Sweden and tested in 2018 used digital identification of areas potentially containing nature conservation values prior to the field inventory. This is a cost-efficient way to perform an inventory scheme and thus it is motivated to improve that two-step method if the WKH-inventory is to be continued in Sweden.

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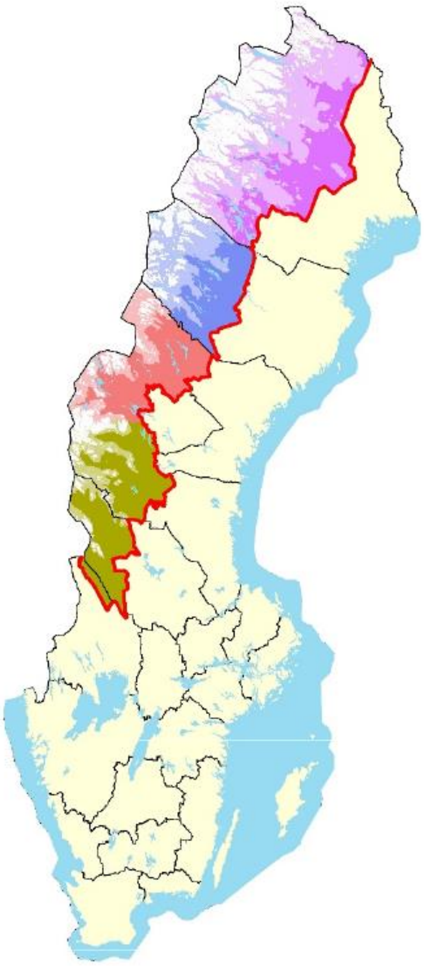
Acknowledgements

I would like to express my appreciation to my main supervisor Johan Svensson for his patience when we designed and developed this thesis work. Thank you for all your good project ideas, for listening to my thoughts, and for taking the time to support and improve my work. I would also like to thank my assistant supervisor Wiebke Neumann, especially for all your valuable support during the data analyses process, but also for helping me express the method I used and its outcome in an understandable language in this report. I would also like to thank my second assistant supervisor Bengt-Gunnar Jonsson for critically providing input and new perspectives throughout my thesis work. Additionally, I want to thank Erik Kretz at the Swedish Forest Agency for data provision and for giving me information on the newly developed WKH-inventory method.

Britta Sterner

Appendix 1: Delimitation of NW Sweden



Appendix 1. Delimitation of northwest Sweden (NW Sweden) according to Roberge (2018). The red line shows NW Sweden's south eastern border.

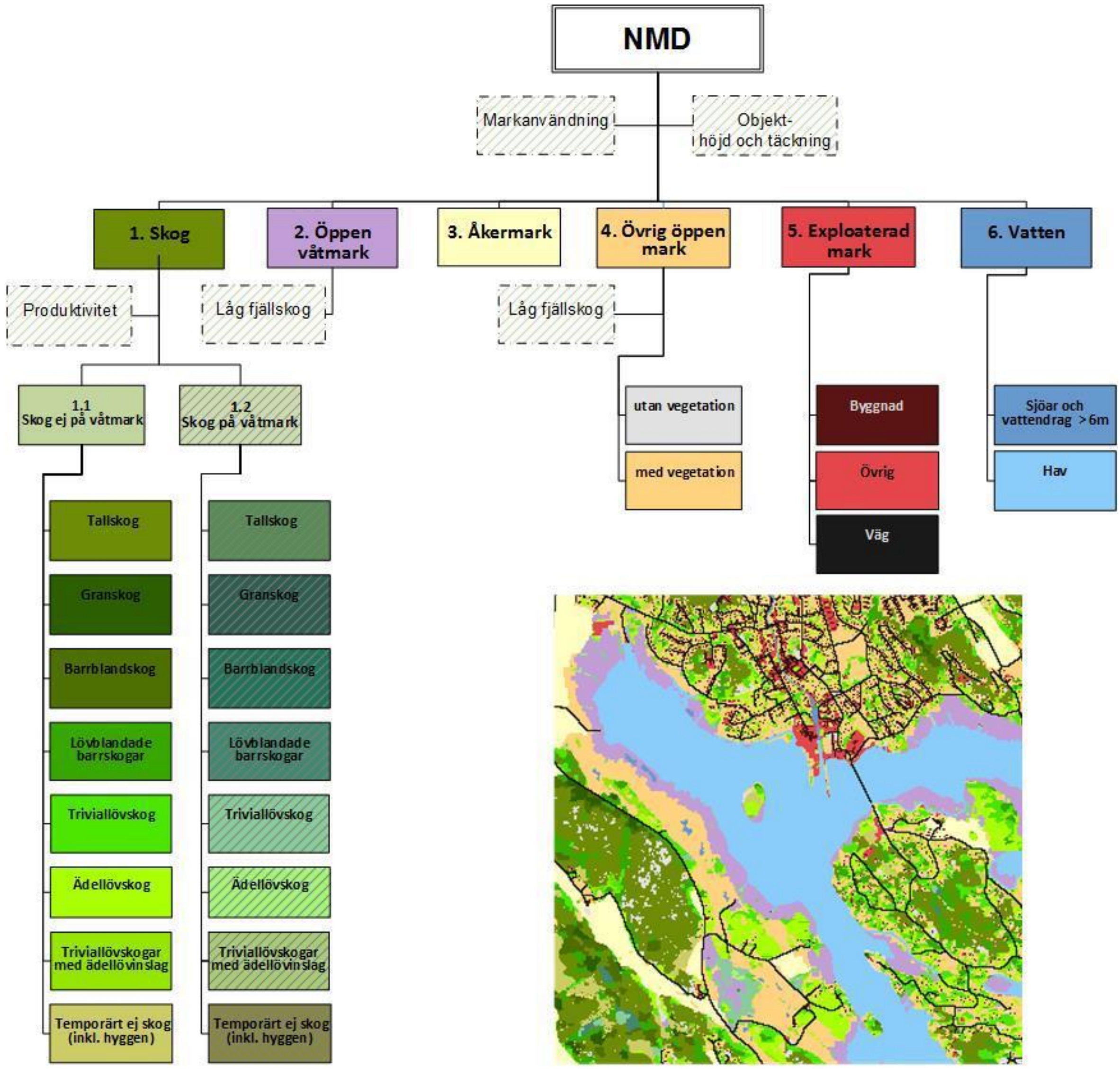
Appendix 2: Metadata associated with input data

Appendix 2. Metadata associated with this study's input data, specifically showing data source, data set name, latest update, data type, data solution, and coordinate system

Variable	**Source**	**Data set name**	**Updated**	**Type**	**Solution (m)**	**Coordinate system**
National landcover data Mountain woodland data	SEPA*	nmd2018bas_ generaliserad _v1_0.tif nmd_lag_fjallskog_v1_1.t if	2019	Raster	10*10	SWEREF 99 TM
Previously registered WKHs Newly identified WKHs & ONVs**	SFA	sksNyckelbiotoper.shp	2021	Vektor		SWEREF 99 TM
Nature reservs	SEPA	nr_polygon.shp	Daily	Vektor		SWEREF 99 TM
HCVF	SEPA SFA	skogliga_vardekarnor	2016	Vektor		SWEREF 99 TM
pCF***	SEPA	kskog_boreal_raster.img	2017	Raster	10*10	

**Swedish Environmental Protection Agency. **Non-public data provided by the SFA for my analyses. ***This data set was not used in my analyses, but was included in the SFA field inventory preparations that generated data for my analyses.*

Appendix 3: NMD landcover data classes



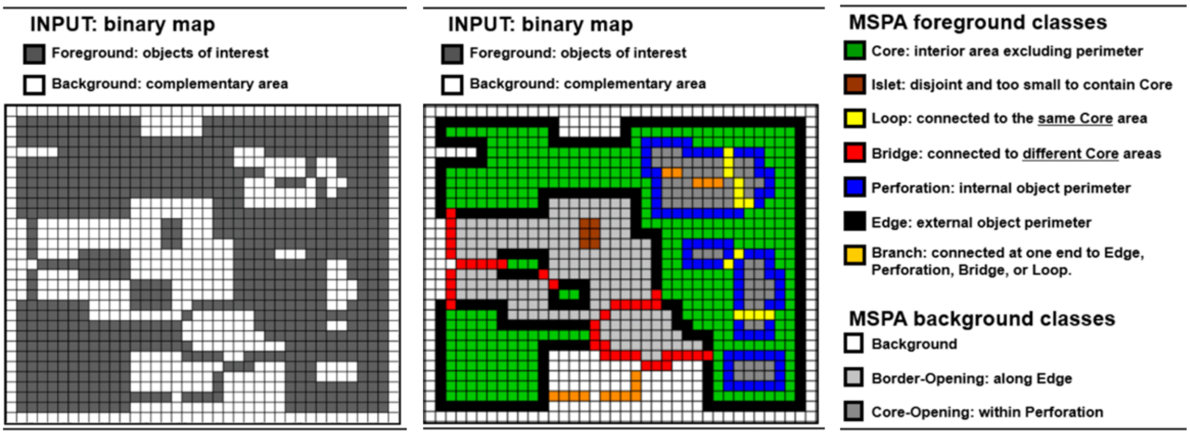
Appendix 3. Hierarchical visualisation of the NMD landcover data classes (Naturvårdsverket 2019).

Appendix 4: Nature types included in the three focal WKH-types based on NMD

Appendix 4. National landcover data (NMD) main raster and complementary mountain woodland raster classes that constitute the basis for the three focal WKH-types in this study (Naturvårdsverket 2019, 2020a)

WKH-type	**NMD main raster & complementary mountain woodland raster**
Natural coniferous forest	Pine forest not on wetland Spruce forest not on wetland Mixed coniferous not on wetland
Broadleaf-rich natural coniferous forest	Mixed forest not on wetland Non-vegetated other open land + mountain woodland Vegetated other open land + mountain woodland Pine forest not on wetland + mountain woodland Spruce forest not on wetland + mountain woodland Mixed coniferous forest not on wetland + mountain woodland
Wetland-forest mosaic	Open wetland Pine forest on wetland Spruce forest on wetland Mixed coniferous on wetland Mixed forest on wetland Deciduous forest on wetland Open wetland + mountain woodland Pine forest on wetland + mountain woodland Spruce forest on wetland + mountain woodland Mixed coniferous on wetland + mountain woodland Mixed forest on wetland + mountain woodland Deciduous forest on wetland + mountain woodland

Appendix 5: MSPA category arrangement



Appendix 5a. A binary map consisting of foreground and background area is the input (left map) for the Morphological Spatial Pattern Analysis (MSPA; European Commission (2021a)). The output (right map) is a separation of the foreground area in a few generic mutually exclusive classes to describe its composition and spatial arrangement. The figure is modified from European Commission (2021a).

Appendix 5b. Arrangement of the MSPA generic mutually exclusive classes and corresponding MSPA values in categories for this study's analyses; namely in background, core, edge, and corridor (Vogt n.d.)

MSPA categories	MSPA classes	MSPA Values
Background	Background	0
	Border-Opening	220
	Core-Opening	100
Core	Core	17, 117
Edge	Edge	3, 103
	Perforation	5, 105
Corridor	Loop	65, 165
	Loop in edge	67, 167
	Loop in perforation	69, 169
	Bridge	33, 133
	Bridge in edge	35, 135
	Bridge in perforation	37, 137
	Branch	1, 101
	Islet	9, 109

Appendix 6: Sample size per WKH-type and analyse set

Appendix 6. Number of squares that contain at least one polygon of previously registered WKHs (i.e. sub-set A) or newly inventoried WKHs (i.e. sub-set B) or ONVs (i.e. sub-set C), separated on the three WKH-types natural coniferous forest, broadleaf-rich natural coniferous forest, *and* wetland-forest mosaic*, as well as for all three together*

WKH-type	Set A	Set AB	Set ABC	Set ABCD
Natural coniferous forest	27	32	35	38
Broadleaf-rich natural coniferous forest	5	10	13	38
Wetland-forest mosaic	3	10	14	38
All three together	27	33	37	38

Appendix 7: Previously registered WKHs' primary and secondary WKH-types

Appendix 7a. The secondary WKH-type, its total area and number, and its areal share of the primary WKH-type natural coniferous forest*, as classified by the Swedish Forest Agency (SFA). Note: the WKH-types are only provided in Swedish*

Natural coniferous forest

Total area (ha): 24863.6
Number: 2222

Secondary WKH-type	**Total area** (ha)	**Number**	**Area share** (%)
Gransumpskog	1088.4	96	4.37
Bergbrant	1081.6	65	4.35
Naturlig skogsbäck	850.8	73	3.42
Myr- och skogsmosaik	677	16	2.72
Lövrik barrnaturskog	464.8	15	1.87
Källpåverkad mark	314.9	26	1.27
Hällmarkskog	244.1	24	0.98
Örtrika bäckdråg	220.8	28	0.89
Blandsumpskog	189.2	12	0.76
Bäckdal	180.3	14	0.73
Småvatten	172.4	17	0.69
Löväng	133	1	0.53
Övriga lövträd	93.6	10	0.38
Kalkbarrskog	76.9	13	0.31
Ravin	70.7	5	0.28
Åsgranskog	55.5	2	0.22
Tallsumpskog	42.4	7	0.17
Strandskog	40	7	0.16
Rasbrant	39.9	8	0.16
Lövbränna	39.6	3	0.16
Betad skog	30.6	2	0.12
Vattenfallsskog	29.5	3	0.12
Lövsumpskog	18	3	0.07
Brandfält	17.4	4	0.07
Barrträd	16.5	2	0.07
Sandbarrskog	14	1	0.06
Kanjondal	10.8	1	0.04
Rikkärr eller kalkkärr	9.9	3	0.04
Lövrik barrskog	7.5	1	0.03
Aspskog	5.1	1	0.02
Liten sprickdal	1.2	1	0.005

Appendix 7b. The secondary WKH-type, its total area and number, and its areal share of the primary WKH-type broadleaf-rich natural coniferous forest*, as classified by the Swedish Forest Agency (SFA). Note: the WKH-types are only provided in Swedish*

<u>Broadleaf-rich natural coniferous forest</u>

Total area (ha):	1035.5
Number:	118

Secondary WKH-type	**Total area** (ha)	**Number**	**Area share** (%)
Myr- och skogsmosaik	142.1	1	13.72
Barrnaturskog	139.6	5	13.48
Källpåverkad mark	75.1	4	7.25
Lövbränna	56	5	5.41
Örtrika bäckfråg	33.4	4	3.23
Hällmarkskog	23.3	1	2.25
Barrskog	20	3	1.93
Bergbrant	15.9	3	1.54
Kalkbarrskog	12.4	1	1.20
Ravin	12.2	1	1.18
Blandsumpskog	10.8	3	1.04
Gransumpskog	10.4	2	1.00
Småvatten	9.9	4	0.96
Lövsumpskog	5.8	1	0.56
Bäckdal	3.4	1	0.33
Sekundär lövnaturskog	2.6	1	0.25
Lövträdsrika skogsbryn	2.2	1	0.21
Brink	1.5	1	0.14

Appendix 7c. The secondary WKH-type, its total area and number, and its areal share of the primary WKH-type wetland-forest mosaic, *as classified by the Swedish Forest Agency (SFA). Note: the WKH-types are only provided in Swedish*

<u>Wetland-forest mosaic</u>

Total area (ha)	508.6
Number	31

Secondary WKH-type	**Total area** (ha)	**Number**	**Area share** (%)
Hällmarkskog	110.2	1	21.67
Gransumpskog	93.4	3	18.36
Småvatten	40.2	1	7.90
Naturlig skogsbäck	24.8	2	4.88
Barrnaturskog	13.1	2	2.58
Barrskog	8.5	2	1.67
Rikkärr eller kalkkärr	8	1	1.57
Bergbrant	2	1	0.39
Tallsumpskog	1.3	1	0.26

Appendix 8: Test statistics for *natural coniferous forest* core, edge, and corridor area between sets

Appendix 8. Test statistics for natural coniferous forest *core, edge, and corridor area between sets (i.e. A, AB, ABC, and ABCD)*

Core

Set	**A**	**AB**	**ABC**
AB	*t-value* = 2.92 *p* = 0.00402		
ABC	*t-value* = 4.09 *p* = 7.11e-05	*t-ratio* = -1.17 *P* = 0.2457	
ABCD	*t-value* = 9.27 *p* < 2e-16	*t-ratio* = -6.35 *p* <.0001	*t-ratio* = -5.18 *p* <.0001

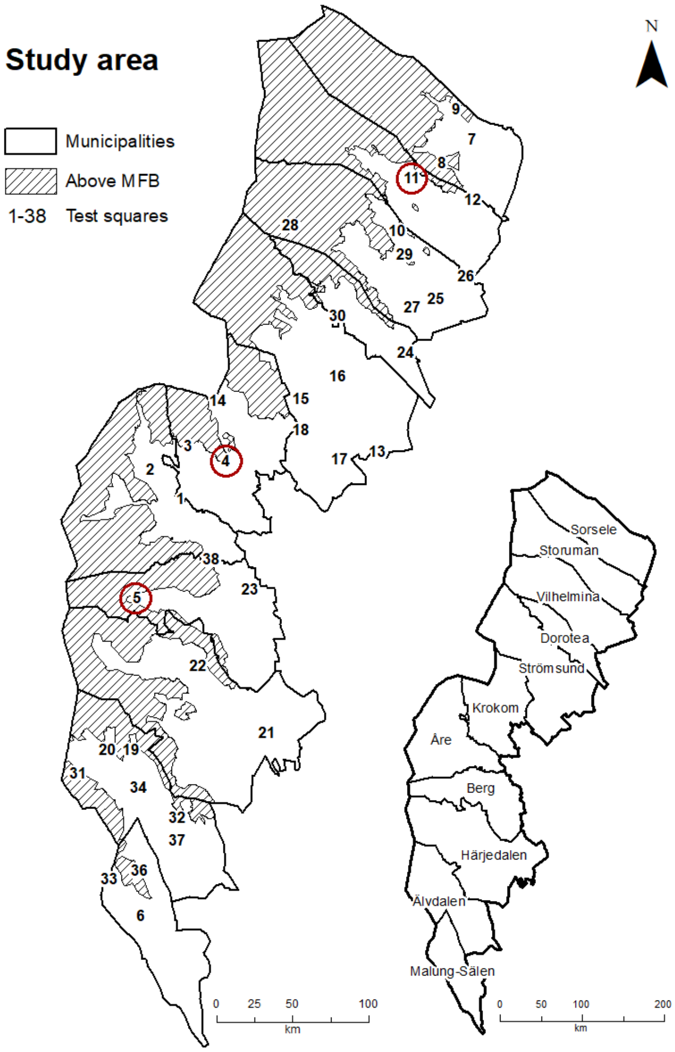
Edge

Set	**A**	**AB**	**ABC**
AB	*t-value* = 2.96 *p* = 5.46e-15		
ABC	*t-value* = 4.30 *p* = 3.16e-05	*t-ratio* = -1.34 *p* = 0.1830	
ABCD	*t-value* = 11.18 *p* < 2e-16	*t-ratio* = -8.23 *p* <.0001	*t-ratio* = -6.89 *p* <.0001

Corridor

Set	**A**	**AB**	**ABC**
AB	*t-value* = 2.69 *p* = 0.00807		
ABC	*t-value* = 4.44 *p* = 1.74e-05	*t-ratio* = -1.76 *p* = 0.0811	
ABCD	*t-value* = 17.08 *p* < 2e-16	*t-ratio* = -14.40 *p* <.0001	*t-ratio* = -12.64 *p* <.0001

Appendix 9: Study area including names of municipalities and locations of squares



Appendix 9. Study area displaying borders and names of the included municipalities, location of the 38 test squares, as well as the border between above (dashed) and below the MFB.