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Identification of restoration hotspots in landscape-scale green infrastructure planning based on model-predicted connectivity forest

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Abstract

Boreal forest landscapes have undergone severe anthropogenic fragmentation and their enormous values concerning, e.g., ecosystem service, biodiversity and culture are hazarded. Maintenance of the remaining intact boreal forest landscapes and restoring the structural and functional connectivity among these remnants are essential for boreal forest conservation. In Sweden, such conservation tasks are highlighted in planning and implementing green infrastructure (GI). At the national level, the GI is established upon a network of high conservation value forests (HCVF). However, HCVF are insufficient to guarantee a functional GI and thereby cannot effectively halt boreal forest degradation. Forest restoration is urgently needed.

This study explored a restoration approach based on connectivity forest (CF), i.e., forest areas with intermediate to high conservation likelihood prescribed by a new GIS-empowered artificial intelligence model. By step-wisely inserting the CF into the current GI, represented by the HCVF, this study assessed how the GI was reconfigured and strengthened over 1.3 million hectares of boreal landscapes in northern Sweden.

First, this study demonstrated good restoration potential in all three subregions of the study area (Mountainous, Inland, Coastal), since the total area of CF within a subregion accounted for at least 11% of the corresponding subregional forest area. Second, by evaluating the GI-area increase and the GI-density variation, this study showed the inland and coastal subregions, much underrepresented in the current GI configuration, might have a higher sensitivity to the CF-insertions than the mountainous subregion. By adding the CF, the GI-area was increased by over 400% in both the inland and coastal subregions versus 60% in the mountainous subregions. The GI-density increase, achieved per unit CF area input, was higher in the inland and coastal than in the mountainous subregion. However, with the proposed insertion of CF, the GI-patches in these two subregions were still scarce, disconnected and poorly functioned as habitats to support biodiversity, compared with those in the mountainous subregion. Third, by assessing the GI of different forest types, this study found that the GI maintained by pine forests, much lacking in current GI, was improved but still incomparable with those maintained by broadleaved or spruce forests. Finally, this study pinpointed restoration hotspots from the CF-areas, which could be incorporated into the conservation practices and GI-planning.

This study suggested that a restoration regime centred on passive area-preserves has limited effectiveness for constructing a functional GI, especially in the heavily transformed landscapes over the inland and coastal areas. An urgent task in GI-planning is to rebalance the representativeness of different forest types and different landscapes with contrasting biogeological properties and human impact gradients.

Keywords: boreal forest, conservation, restoration, connectivity, green infrastructure, GIS, Sweden

Sammanfattning

Det boreala skogslandskapet har allvarligt fragmenterats på grund av mänsklig exploatering, vilket har lett till en nedsättning av deras omfattande värde i, bland annat, ekosystemtjänster, biologisk mångfald, och kultur. För att bevara det boreala skogslandskapet är det avgörande att skydda de kvarvarande fragmenten av landskapet samtidigt som att återställa den strukturella och funktionella anslutningen mellan dessa fragment.

I Sverige har bevarandet av det boreala skogslandskapet betonats och genomförts genom planering och etablering av grön infrastruktur (GI). I nuvarande läget på nationell nivå byggs GI upp som ett nätverk av skogliga värdekännor, dvs skogar med bekräftade höga bevarandevärden. Dock är dessa skogliga värdekännor otillräckliga för att etablera en väl fungerande GI där det boreala skogslandskapet effektivt bevaras. För att utveckla en bättre fungerande GI behöver bevarandevärdena i många skogsområden höjas genom skogsrestaurering.

I denna studie utforskades en restaureringsmetod som är baserade på anslutningsskogar ("connectivity forest" på engelska), vilket är skogsområden med mellan-höga till höga restaureringsvärden som bedöms av en ny GIS-baserad artificiell intelligensmodell. Genom att gradvis restaurera dessa anslutningsskogar och inkludera dem i den befintliga gröna infrastrukturen, undersöker denna studie hur den nuvarande gröna infrastrukturen kan omformas och förbättras över ett borealt skogslandskap på 1,3 miljoner hektar i norra Sverige.

Resultaten visar att alla tre subregioner i studieområdet (bergiga, inland och kust) har en betydande potential för restaurering, förutsatt att minst 11% av den totala skogsarealen inom en subregion utgörs av anslutningsskogar.

Denna studie indikerar att inland- och kustsubregionerna, som är underrepresenterade i den nuvarande gröna infrastrukturen, har högre restaureringseffektivitet än bergiga subregionen. Genom att restaurera anslutningsskogar kunde GI-arealen ökas med över 400% i både inland- och kustsubregionerna, jämfört med 60% i bergiga subregionen. Dessutom har det visat sig att restaurering av anslutningsskogar per hektar kan leda till en större ökning av GI-tätheten i både inland- och kustsubregionerna än i bergiga subregionen. Trots detta var den totala mängden och storleken av GI-ytor inom dessa två subregioner fortfarande färre och mindre än i bergiga subregionen, och anslutningen mellan GI-ytorna var svagare. Även efter att alla anslutningsskogar hade restaurerats fungerade GI i dessa subregioner sämre som habitat för att bevara biologisk mångfald jämfört med bergiga subregionen.

Ytterligare visar denna studie att andelen tallskogar, som är underrepresenterade i den nuvarande gröna infrastrukturen, ökade genom restaurering av anslutningsskogar, men är fortfarande betydligt lägre än andelen löv- eller granskogar. Slutligen lokaliserade studien också potentiala heta punkter för restaurering av anslutningsskogar, vilka kan användas i praktiskt naturvårdsarbete och GI-planering.

Studien föreslår att enbart att satsa på att öka arealen av restaurerade skogsområden inte räcker för att skapa en fungerande GI, särskilt i kraftigt fragmenterade landskap såsom inland- och kustsubregionerna i denna studie. En brådskande uppgift inom GI-planering är att åter balansera företrädet för olika skogstyper och skogsområden med hänsyn till deras biogeologiska egenskaper och mänskliga påverkansintensitet.

Nyckelord: boreal skog, naturvård, restaurering, anslutning, grön infrastruktur, GIS, Sverige

Table of Contents

List of Figures

List of Tables

Terminologies and abbreviations

The major terminologies used in this study are briefly defined in this sheet, sequenced by order of appearance in the main text and further explained in the main text.

Intact Forest Landscape, IFL

Potapov et al. (2008, 2017) defines IFL as "a seamless mosaic of forests and associated natural treeless ecosystems that exhibit no remotely detected (by satellite imagery) signs of human activity or habitat fragmentation and are large enough to represent all native biological diversity".

Structural connectivity

Structural connectivity and functional connectivity are two metrics of ecological connectivity. Ecological connectivity measures "the degree to which the landscape facilitates or impedes movements among resource patches" (Taylor et al., 1993). Functional connectivity concerns how a featured species or species group responses to the physical environment of a featured landscape (Auffret et al., 2015; Heino et al., 2019). Structural connectivity measures the physical properties of the landscape (Auffret et al., 2015; Mikusinski et al., 2021), such as the amount, size and configuration of habitat patches maintained within this featured landscape (Auffret et al., 2015; Mikusinski et al., 2021). This study features the structural connectivity among a GI, proxied by, mainly, the density of GI-patches (in %).

Green Infrastructure, GI

GI is "a strategically planned network of natural and semi-natural areas with other environmental features" aiming to "maintain biodiversity, species viability and ecosystem services" (EC, n.d.-c)

High Conservation Value Forest, HCVF

HCVF refers to all the forest areas with field-confirmed high conservation value in Sweden; the HCVF is documented in the HCVF-dataset (Skogliga värdekärnor) (Naturvårdsverket & Skogsstyrelsen, 2017), a publicly available geospatial dataset produced by the Swedish County Administration (download: https://geodata.naturvardsverket.se/nedladdning/tathetsanalys.zip).

Correspondingly, the non-HCVF refers to the forest areas not included in the HCVF-dataset.

Connectivity Forest, CF

CF is not a formally defined term. Here, the term is applied as the non-HCVF forest areas that have intermediate to high model-predicted conservation likelihood values. With respect to connectivity, it is assumed that CF, with active or passive restoration applied, will increase its conservation value and improve the spatial connectivity among a concerned GI. In this study, the likelihood value range specifying CF was set to 0.4-1, through comparing the value distribution over the HCVF versus non-HCVF areas across the study area.

High Conservation Value Forest Tracts, HCVF-tracts:

HCVF-tracts are the forest landscape subsections with higher concentration of HCVF-patches and larger areal size, and therefore considered as prioritized areas in practical conservation works (Bovin et al., 2017; Friesen & Uppsäll, 2016). The HCVF-tracts are delineated by different sets of criteria, adapting to specific forest and nature-geographical conditions at different spatial extents (e.g., national or regional).

1. Introduction

1.1 Background

Anthropogenic fragmentation of boreal forest landscapes

Covering vast landscapes over the northern latitudes (~45-70°N), boreal forest compromises ~29% of the global forest area (UNECE, 2021). As the second largest terrestrial biome (Kayes & Mallik, 2020), boreal forest is one of the most significant ecosystem services providers on Earth (Frelich, 2020). It is a crucial carbon sink, storing vast amounts of carbon in both the soil and vegetation. According to estimates, it contains approximately 272 billion tons of carbon, which accounts for 32% of global forest carbon stocks (Pan et al., 2011). As such, it has a substantial impact on local, regional, and global climate. It provides habitats for a large number of plant and animal populations and conserves a distinctive biodiversity (Venier et al., 2018); it is also the largest living biomass pool on land (DeAngelis, 2008). Boreal forest is also the cradle of many indigenous cultures and communities (UNECE, 2021). As an example, the Sami people, native to the rural regions in Fennoscandia (i.e., Norway, Sweden, Finland, and Russian Federation), have lived in the boreal forests for millennia and used them as their main sources for livelihood, such as reindeer husbandry (Moen & Keskitalo, 2010).

During the past 70 years, boreal forests have been severely disturbed by human activities (Svensson et al., 2019b). Industrial forestry, characterised by intensive timber extraction and systematically clear-cut, is the most predominant impact factor (e.g., Mikusinski et al., 2021; Svensson et al., 2019a). In Sweden, a country with forestry playing a fundamental socioeconomic role (Schlyter et al., 2006), the boreal forest landscapes have been continuously and substantially reconfigured by large-scale clear-cut that can be traced back to the 1950s, or even earlier (Lundmark et al., 2021; Svensson et al., 2019b), and still dominates the present forest management (Sterner, 2022). Loss of the landscape intactness and connectivity are some most direct consequences caused by the anthropocentric reconfiguration of the boreal forest landscapes. Given the profound significance of boreal forests in ecological processes, services and forest biodiversity, such reconfiguration is increasingly concerned over the boreal, as well as in other forest regions globally (Svensson et al., 2020).

Maintenance of intact forest landscape (IFL)

As a key metric of forest conservation (Venier et al., 2018), IFL is commonly used in forest management, certification and spatial planning; it is also a key theme in boreal forest conservation and studies.

The concept of IFL is rooted in the concept of primary forest (Venier et al., 2018). While primary forest includes only the “natural-regenerated forests of native species” without “clearly visible indications of human activities” (FAO, 2015; Venier et al., 2018), IFL acknowledges the heterogeneity of landscapes and features simultaneously the non-forest elements (Potapov et al., 2017; Venier et al., 2018). Conceptually, IFL refers to “a seamless mosaic of forests and associated natural treeless ecosystems that exhibit no remotely detected (by satellite imagery) signs of human activity or habitat fragmentation and are large enough to represent all native biological diversity” (Potapov et al., 2008; 2017). However, in practical operations such as forest certification, the more operational concept of IFL is the so-called "frontier forest" proposed by Bryant et al. (1997) (Venier et al., 2018). According to this concept, IFL is "on the whole, relatively undisturbed and big enough to maintain all of their biodiversity, including viable populations of the wide-ranging species associated with each forest type" (Bryant et al., 1997). This concept suggests that IFL should be “relatively unmanaged” (Venier et al., 2018) and large enough to provide sufficient habitat and resources to naturally occurring species.

Indeed, sufficient spatial size is critical in IFL. This is because ecological processes are spatial-scale dependent (Felton et al., 2020) and certain processes can only fully operate at large spatial scales (Laestadius, 2001; Laestadius et al., 2003; Venier et al., 2018). A typical example of such ecological processes is natural wildfire, a major driving force of boreal landscape dynamics and succession (Axelsson & Östlund, 2001; Jönsson et al., 2009; Kuuluvainen et al., 2017), which may require IFLs of 200 000 to 1 million ha in natural conditions (Laestadius et al., 2003). A ”large enough” IFL ensures, intrinsically, sufficient habitat sizes and resources to support the viability of all the species native to the concerned landscape (Venier et al., 2018). This is especially important for maintaining populations of wide-ranging animals, such as the boreal forest caribou (*Rangifer tarandus caribou*) (Venier et al., 2014). As a conventional operating standard, the minimum size of an IFL is set to 50 000 ha (Venier et al., 2018). However, flexible size criteria should be explored and applied adapting to e.g., specific ecoregion, climatic zone, forest type, featured species and conservation goals (Angelstam et al., 2004; Laestadius et al., 2003; Mackey et al., 2014; Potapov et al., 2008; Venier et al., 2018). Indeed, some regional studies have used much smaller threshold of IFL, e.g., > 500 ha in Cheng et al. (2010). Recently, forest areas < 3 500 ha are proposed as the global biodiversity conservation frontiers (Brennan et al., 2022; Riva et al., 2022), based on the findings that in heavily human-impacted landscapes, smaller, rather than bigger, forest patches display higher potentials in maintaining biodiversity and ecosystem services (Riva et al., 2022; Valdés et al., 2020).

High degree of ecological connectivity is another inherent property of IFLs. Ecological connectivity measures “the degree to which the landscape facilitates or impedes movements among resource patches” (Taylor et al., 1993), where the “movements” represent natural flows of a complex composite of organism, gene, energy, matter, and nutrients, etc., as well as various other natural processes (Heino et al., 2019). In a fragmented forest landscape, the remaining IFL fragments are isolated in the matrix of heavily managed or disturbed areas (Heino et al., 2019; Svensson et al., 2020), and thus their connectivity is hazarded. These remaining patches can be e.g., old-growth forest patches (Öhman & Eriksson, 1998),or larger protected areas (Heino et al., 2019).

Ecological connectivity can be described from structural and functional perspectives. Structural connectivity concerns the physical properties of a landscape (Auffret et al., 2015;

Mikusinski et al., 2021), such as the amount, size and configuration of habitat patches maintained within a featured landscape (Auffret et al., 2015; Mikusinski et al., 2021). Functional connectivity, on the other hand, measures how a featured species or species group moves between these existed habitat patches or responses to the physical environment of this particular landscape (Auffret et al., 2015; Heino et al., 2019).

Globally, the distribution of the boreal IFLs is extremely uneven. The boreal regions over northern Eurasia and North America still maintain a relatively high level of intactness, due to large areas of unlogged primeval forests; whereas the intact boreal forests have nearly disappeared from the European map (Frelich, 2020; Lundmark et al., 2021; Potapov et al., 2008). The forest belt, stretching north to south in the mountainous region in north-western Sweden, preserves the last IFLs in the European continent (Jonsson et al., 2019; Svensson et al., 2020). Within this forest belt ("Scandinavian Mountains Green Belt"; Svensson et al. 2020), approx. 60% of the forestland remains intact with overall high connectivity, and the contiguous areas dominated by primary forests can sometimes reach 10 000 ha or larger (Angelstam et al., 2020; Svensson et al., 2020).

However, outside this narrow forest belt, the forest landscapes across the boreal regions in Sweden are severely fragmented with barely remained spatial connectivity, especially over the inland and coastal ecoregions (Angelstam et al., 2020; Jonsson et al., 2019). This is not surprising since these regions have a long history of heavily industrialised forest use (Mikusinski et al., 2021; Potapov et al., 2017; Svensson et al., 2020); in addition, manmade suppression of wildfire, a critical natural disturbance driving power, also hinders the natural processes over these forest landscapes (Mikusinski et al., 2021). According to a recent assessment, the old, previously non-clearcut forests in the Swedish boreal biome have been logged at an annual rate of about 1.4% since 2003 (Ahlström et al., 2022). If such anthropogenic pressure continues and even intensifies, the old-growth boreal forest of this region will disappear within four decades. Therefore, the maintenance and protection of the remaining intact forests are of great importance to the sustainable management of the boreal forest landscapes (Eriksson et al., 2018; Svensson et al., 2022).

Strategic green infrastructure (GI) planning

The conservation of ecological integrity and connectivity in the boreal forest landscapes is addressed in strategic spatial planning on various spatial scales, where the maintenance and establishment of functional GI play an essential role (Mikusinski et al., 2021; Svensson et al., 2020). GI is "a strategically planned network of natural and semi-natural areas with other environmental features" aiming to "maintain biodiversity, species viability and ecosystem services" (EC, n.d.-c), which has been endorsed and highlighted in various domestic and EU-level policies and legislations (Mikusinski et al., 2021). For example, the Swedish Environmental Quality Objectives (EQOs) (Miljökvalitetsmål), established by the Swedish Parliament in 1999 (bet. 1998/99:MJU6), features environmental concerns in the society development and thus set the framework and foundation for promoting GI.

A functional GI is based on protecting areas with identified high conservation values and ensuring their connectivity across spatial scales (Hermoso et al., 2020). The quantitative goals concerning the areas that should be put under protection are specified: Sweden conforms to the criteria set in the Aichi target #11 established by the United Nation Conservation on Biological Diversity (CBD), i.e., at least 17% of terrestrial areas with well-functioned connectivity shall be protected (Angelstam et al., 2020; CBD, 2020); meanwhile, the Swedish national forest and environment policies set up a target of 20% protected areas across the country’s forestlands (Angelstam et al., 2020).

The forest areas with confirmed high conservation value at the Swedish national level, under or outside formal protection, are referred to as High Conservation Value Forests (HCVF) (Naturvårdsverket & Skogsstyrelsen, 2017). All the known HCVF, up to 2016, were documented in the HCVF-dataset, produced by the Swedish County Administration, and updated in 2019 and 2020. The HCVF-dataset has become a core source of information in the GI-planning. In compiling this dataset, the conservation values were field-identified by standard protocol (mainly woodland key habitat protocols) procedures, e.g., “deadwood in different stages of decay, multi-layered old-growth forest and presence of indicator species” (Angelstam et al., 2020). The HVCF-dataset includes areas 1) under legal protection during long- or short-terms, typically as national parks, nature reserves, biotopes, nature conservation agreements on forest land (“naturvårdsavtal”) and forest habitats within the Natura 2000 areas, etc.; 2) voluntarily set-aside, if a continuous productive forest area above 0.5 ha and containing high natural, cultural or recreational values (Biodiversity Information system for Europe, n.d.) and 3) unprotected, such as woodland key habitats (WKH, “nyckelbiotoper”) (Angelstam et al., 2020; Mattsson, 2022). Up to 2020, the total area documented in the HCVF-dataset, i.e., all the formally protected, voluntarily set-aside and unprotected areas accumulated, has exceeded 26% of all the forest lands in Sweden, and 20% in its northern boreal region.

Compared with the target of 17-20% protected areas, these numbers seem to depict a satisfying current image and a promising future of the GI in Sweden. However, as Angelstam et al. (2020) pointed out, one “pitfall” with these numbers is that they focused solely on size but ignored the spatial connectivity that must be simultaneously ensured to establish a long-term functional GI. Revealed by the same study (Angelstam et al., 2020), only approx. 12% of the HCVF areas are functionally connected.

Indeed, escalating the protection of the isolated remnants of IFL alone cannot effectively and sustainably support a functional GI (Angelstam et al., 2020; Estreguil et al., 2013; Heino et al., 2019); restoring the forested areas potentially significant for re-establishing the spatial connectivity across multiple spatial scales should be equally addressed in the strategic GI-planning. Featuring the boreal Sweden, the effect of the latter work has been theoretically evaluated, which confirmed that adding the “proxy Continuity Forests”, i.e., forests have not been clearcut since the mid-1900s, into the current GI represented by the HCVF areas, can substantially increase the connectivity among the GI holistically (Mikusinski et al., 2021). However, though critical for setting the conceptual framework of the future GI-planning, such evaluation based on restoring all the proxy Continuity Forests, is not only likely to overestimate the actual restorable forest resources (Mikusinski et al., 2021), but also less indicative in supporting the decision makings in the daily forest conservation and managements aiming for GI promotion. Therefore, to further identify and assess the forest areas that should be emphasized or prioritized in restoration has become a critical task. Typically, major knowledge gaps are found in “how much” and “where”, addressing the spatial size and allocation of the areas with high restoration value, and how the GI can be strengthened by restoring the targeted areas. The answers to these questions can more directly assist decision making in the operational practices and strengthen the fundamental support for Sweden to achieve its GI commitment.

Conservation likelihood prediction by a new artificial intelligence (AI) model

The AI model, recently developed by Bubnicki et al. (2022)(in rev.), enables a spatially explicit identification of forest areas with potentially high conservation values. Assessing the size and distribution of these areas, as well as their effect on the GI-construction, could provide new information that can potentially facilitate the GI-planning. This new AI model is unofficially named “KubAI ” by its authors (“Kub” tributes to its main developer, Jakub “Kuba” Bubnicki) and referred to as KubAI in this study.

KubAI predicts the conservation values through modelling the forest naturalness. The extent of naturalness measures how much a forest has been degraded relative to its natural status (Winter, 2012). Taking the currently known HCVF as the main information source for “nature status”, KubAI catches the inherent properties of the HCVF in terms of a comprehensive collection of spatial variables and uses these variables to jointly quantify the naturalness or the conservation value of a forest landscape (Bubnicki et al., 2022)(in rev.). The prediction by KubAI has been validated against two independent datasets and both validations showed that, overall, the forest areas with documented high naturalness (e.g., areas displaying Natura 2000 habitat qualities) and/or under various forms of conservation considerations (e.g., voluntarily set-aside areas in forest management) are associated with significantly higher predicted conservation values than the rest forest areas.

However, the prediction given by KubAI is interpreted as a “relative likelihood of HCVF occurrence”, rather than an “actual probability of occurrence” (Bubnicki et al., 2022)(in rev.). Because the HCVF-dataset, fundamental to the model prediction, is “presence-only” (Barbet-Massin et al., 2012; Guillera-Arroita et al., 2015), meaning it contains no information about the non-HCVF areas, and thus could introduce unknown extent of bias to the spatial sampling of forest with HCVF-properties. Nevertheless, due to the following two features, the prediction by KubAI has the potential to effectively support the identification of forest areas critical to the GI development.

- The prediction by KubAI covers all the areas dominated by forest in Sweden with a pixel size of 1 ha (forest dominance identified as forest area > 0.5 ha per pixel). This feature ensures the prediction could be tailored to various spatial scales according to the specific goal of a GI-planning, at a spatial resolution of 1 ha. Similar level of spatial coverage and resolution are, however, rarely achieved simultaneously by previous mappings targeting forest conservation (Bubnicki et al., 2022)(in rev.). As an example, the map of European primary forests (Sabatini et al., 2018), features the whole Europe at a much coarser spatial resolution (1km).

- The predicted relative likelihood of HCVF occurrence varies continuously along a gradient from 0 to 1, where 1 indicates the highest likelihood and 0 the lowest. In contrast, the mainstream datasets featuring forest conservation in the boreal Sweden, i.e., the HCVF and the proxy Continuity Forest dataset, represent the forest landscapes in a binary form (i.e., 1 or 0, where 1 represents the HCVF and 0 the non-HCVF). In this sense, the prediction by KubAI, to certain extent, transparentises the variability among the vast non-HCVF forest areas in terms of their conservation/restoration values, and thus could effectively assist the identification of the forest areas that should be prioritized in the future restoration or conservation works.

A brief summary of KubAI's constitution of variables and data sources is provided in Appendix 1. However, as the model and its associated work are not yet publicly available, more detailed information can be obtained by contacting the author team, as specified in Appendix 1. It should be noted that the quality of the model prediction was not explicitly assessed for forested areas with different forest compositions, nor on finer spatial scales (e.g., subregional or local).

Connectivity forest, CF

The non-HCVF areas (i.e., forest areas outside the HCVF-dataset) with KubAI-predicted intermediate to high relative likelihood of HCVF occurrence (e.g., 0.5-1) could imply the potential restoration frontiers. These areas are loosely defined as CF by this study. With respect to connectivity, it is assumed that the CF, with active or passive restoration applied, could increase its conservation value and improve the spatial connectivity among a concerned GI. The value range specifying “intermediate to high” relative likelihood is identified through comparing the value distribution over the HCVF and non-HCVF areas.

1.2. Study Objective

The overall objective of this study is to explore the new opportunities, provided by the model-prediction, for further identification and assessment of forest areas potentially significant to the strategic GI-planning over a boreal forest landscape of 1.3 million ha in northern Sweden. More specifically, this study targets the CF and aims to 1) understand how a stepwise restoration of these CF areas will reconfigure and impact the GI over the featured landscape, and 2) identify restoration hotspots, i.e., a subset of the CF-areas that could be prioritized in the restoration practices in the short and/or long run.

1.3 Research questions

This study focuses on the following three questions:

1. Based on the model prediction, how much CF-areas could be identified and how are these areas spatially distributed?

2. What effect could be achieved on the GI over the studied landscapes, through stepwise insertion of CF?

3. How and where the restoration hotspots could be detected? Compared with CF-areas, these hotspots are supposed more effectively incorporated into the operational practices since they are a subsection of CF.

2. Materials and Methods

2.1 Study Area

This study is performed over the Vindelälven-Juhttátahkka (V-J), one of the UNESCO World Network of Biosphere Reserves in Sweden (Fig. 1). The following study area description refers to the report by Gardeström et al. (2016) that formed the formal document for inclusion into this network. V-J has a total area of over 1.3 million ha, stretching 450km from west to east through two biogeographical regions: the alpine region originated from the Scandinavian Mountain range and the boreal region extending to the Gulf of Bothnia coastlines. V-J encloses the whole drainage basin for the Vindeläven-Umeälven river system which are amongst the "last few free-flowing major rivers" in Europe. The mountain and forest landscapes mosaiced with waters and wetlands, characteristic to V-J, supports a rich diversity of ecosystem services of local, regional, and global significance, and fostered unique and magnificent natural and cultural values. The Sami, Sweden's indigenous community, have been migrating seasonally through or within the boreal landscapes of this region for reindeer herding for thousand years.

More than 1/3 of the total area of V-J is legally protected or voluntarily set-aside, constituted by bundle of nature reserves, Natura 2000 sites, biotope protections and more, including the largest nature reserve in northern Europe, the Vindelfjällen nature reserve (565 000 ha). A distinctive array of biodiversity is preserved here, and nearly five hundred of red-listed species may find their last chance to survive or thrive here.

Forest- and shrublands cover more than half of the total area of the V-J, and most of them are productive forests (530 683 ha) with on-going forestry practices aiming for timber production. The productive forest areas are dominated by pine (346 810 ha, ca. 65.5%), followed by spruce (97 889 ha, 18.5%), coniferous mixed (80 475 ha, 15%), mixed (37 690 ha, 7%) and deciduous forests (27 103 ha, 5%). 12% (64 042 ha) of the productive forestland is old-growth forest (>140 years), abundant of deciduous trees. Two forest companies, Holmen and SCA, are the major forest landowners in the V-J.

The forest landscapes over the V-J have evidenced a long history of intensive forest use. The industrialised forestry has already begun by the 1750s in this region and has been continuously intensified through the following centuries. The landscapes are inevitably impacted and altered by, amongst others, forestry harvesting and reforestation. While the mountain forests, formed mainly by birch and conifers, remain largely undisturbed, remaining forest landscapes of the V-J, especially over the coastal boreal region, are heavily affected, which has caused severe forest landscape fragmentation. The remaining intact landscapes or landscape patches are likely to be further threatened, considering the forest production over this region continues running intensively, with a yearly felling rate estimated to about 1%.

V-J places a strong emphasis on protecting its natural and cultural environments, particularly through regional and national investment in establishing long-term and sustainable GI. The maintenance of IFL is a fundamental component of this approach. Increasing priority has been given to those areas outside the already conserved areas and their buffer zones, since they are critical in promoting the landscape connectivity. V-J is also a demo site of the Horizon 2020 project SUPERB which aims to "create transformative change toward large-scale restoration" (SUPERB: Upscaling Forest Restoration, n.d.) https://forest-restoration.eu/). The findings of this study will be incorporated into forest and landscape restoration efforts in the V-J and the wider study area. These efforts are also aligned with ongoing regional green infrastructure approaches led by the County Administrative Board of Västerbotten.

To address the contrasting biogeographical properties and the gradient of human disturbance from the western alpines to the eastern seashores, the V-J is further divided into three subregions, namely the mountainous, inland, and costal subregions (Fig. 1). The subregion-specific analyses also enable an inter-subregion comparison. The border between the inland and coastal subregions is merged from the border pieces of two municipalities in adjacency of the Gulf of Bothnia (i.e., Umeå and Vännäs), and the border between the mountainous and inland subregions is a subsection of the border of the municipality Sorsele.

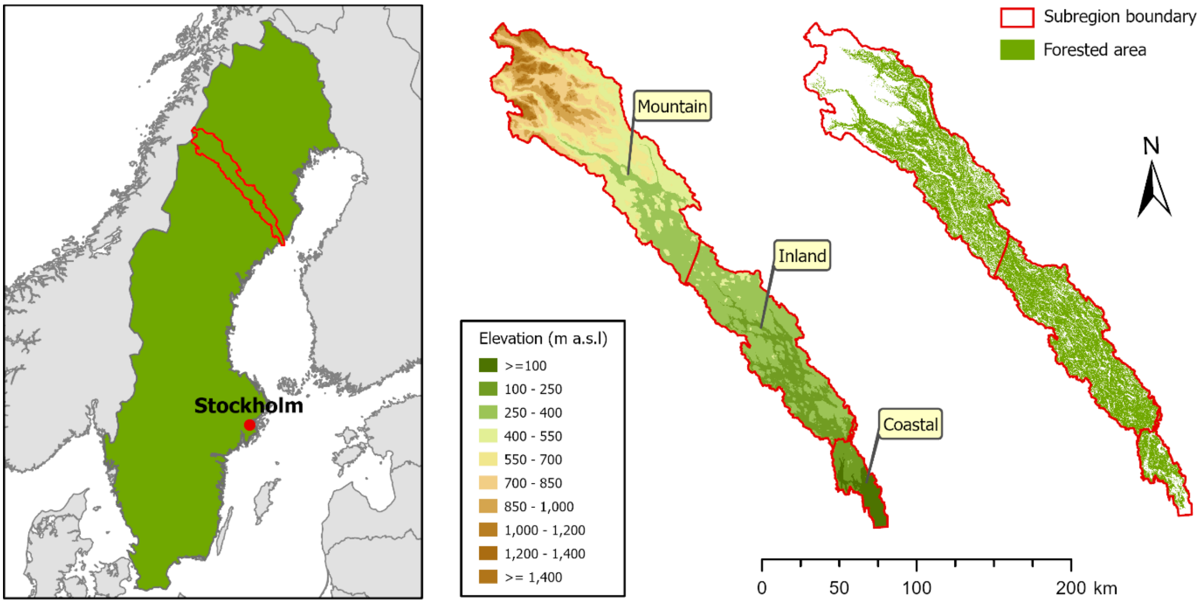

Figure 1. **Left**: location of the study region, the Vindelälven-Juhttátahkka Biosphere, in Sweden. **Mid**: division of the three subregions (mountainous, inland, and coastal, in red line) and elevation (m a.s.l) over the whole study region. **Right**: total forested areas over the study region.

2.2 Data

This study used three sets of spatial data. First, the Swedish national HCVF dataset (Skogliga värdekärnor, download: https://geodata.naturvardsverket.se/nedladdning/tathetsanalys.zip) (Naturvårdsverket & Skogsstyrelsen, 2017) was used for extracting the currently known HCVF areas. The HCVF-dataset is a shapefile storing all the forests with field-survey confirmed high conservation values up to 2016 (updated in 2019 and 2020), including formally protected, voluntarily set aside and unprotected areas. More information about the HCVF-dataset can be found in the Introduction section.

The HCVF area found within the mountainous subregion accounted for 16.8% of the total area of the forestlands in V-J, whereas the total HCVF area, accumulated over the inland and coastal subregions, was only 1.5% of the total forestland area in V-J ("forestland" is specified in the description of the Swedish national landcover dataset in below) (Fig. 2). The HCVF over the study area can be found in Fig. 4.

Second, to identify the CF, the relative likelihood of HCVF occurrence map (RL-map), generated by KubAI as a raster of 1 ha resolution (Bubnicki et al., 2022)(in rev.), was used (Supplementary Fig. A1).

Third, the forest type information was extracted from the Swedish national landcover data (Nationella Marktäckedata, NMD, download: https://www.naturvardsverket.se/verktyg-och-tjanster/kartor-och-karttjanster/nationella-marktackedata) (Naturvårdsverket, 2019), which is a raster with a pixel size of 10m. In NMD, forestland is defined following FAO's standard, i.e., "land spanning more than 0.5 ha 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, 2015; Sterner, 2022).

In NMD, forestlands are classified into seven major types, based on dominant tree species in combination with the site productivity. A tree species is dominant when its canopy cover is ≥ 70% of the total canopy cover of a 0.01 ha forestland (i.e., per pixel of NMD, 10m x 10 m) (Naturvårdsverket, 2020). Site productivity is divided based on whether a given site supports tree growth of $\geq 1 m^3 ha^{-1} year^{-1}$ over a rotation cycle (Svensson, 2022). The major forest types are further divided by whether they are situated on wet organic soil or mineral soil (Sterner, 2022). The full list of the forest types involved in NMD can be found in Olsson & Ledwith (2020).

To facilitate the analyses in this study, the forestlands in the study area were reclassified into six categories (Table 1). Certain forest types (e.g., Deciduous hardwood forest on wetland, Code 126) do not exist over V-J and thus were excluded from the reclassification. Over the study area, the forest composition contrasts across the subregions: the mountainous subregion is dominated by broadleaved and spruce forest, whereas the inland and coastal subregions are dominated by pine (Fig. 2 (right)).

Table 1. Forest type reclassification, based on the forest type categories given in Swedish national landcover data (NMD).

Forest types used in this study	Corresponding forest types in NMD	
	Code	Forest type
Pine forest	111	Pine forest not on wetland
	121	Pine forest on wetland
Spruce forest	112	Spruce forest not on wetland
	122	Spruce forest on wetland
Mixed coniferous	113	Mixed coniferous not on wetland
	123	Mixed coniferous on wetland
Broadleaved-coniferous mixed	114	Mixed forest not on wetland
	124	Mixed forest on wetland
Broadleaved forest	115	Deciduous not on wetland
	125	Deciduous on wetland
Temporarily not forested	118	Temporarily non-forest not on wetland
	128	Temporarily non-forest on wetland

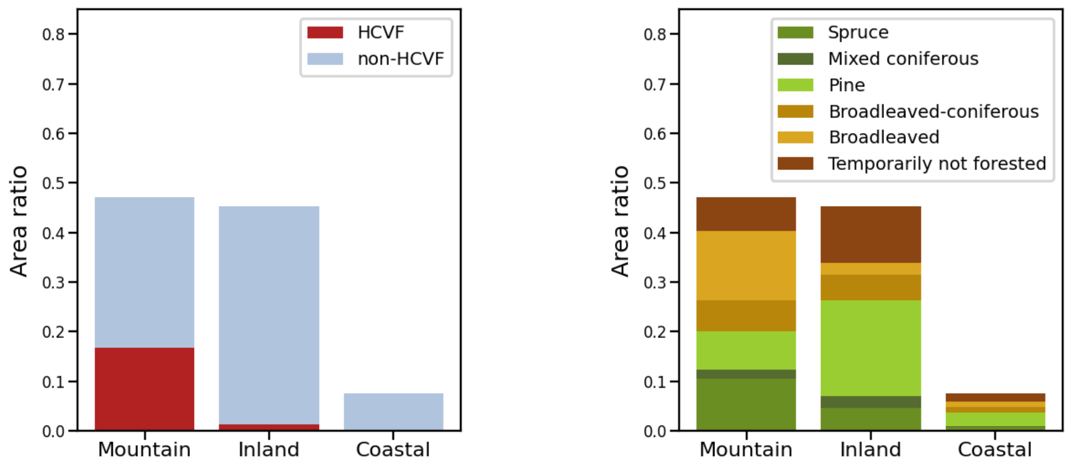

Figure 2. Area distribution of the HCVF versus non-HCVF in each subregion, calculated as ratios relative to the total area of the forestlands in the whole study area (**left**) and forest composition (**right**) over the forestlands in the three subregions. The three columns together sum up to 100%, i.e., all forest area in the study region.

2.3 Analyses

The overall workflow of this study is shown in Fig. 3.

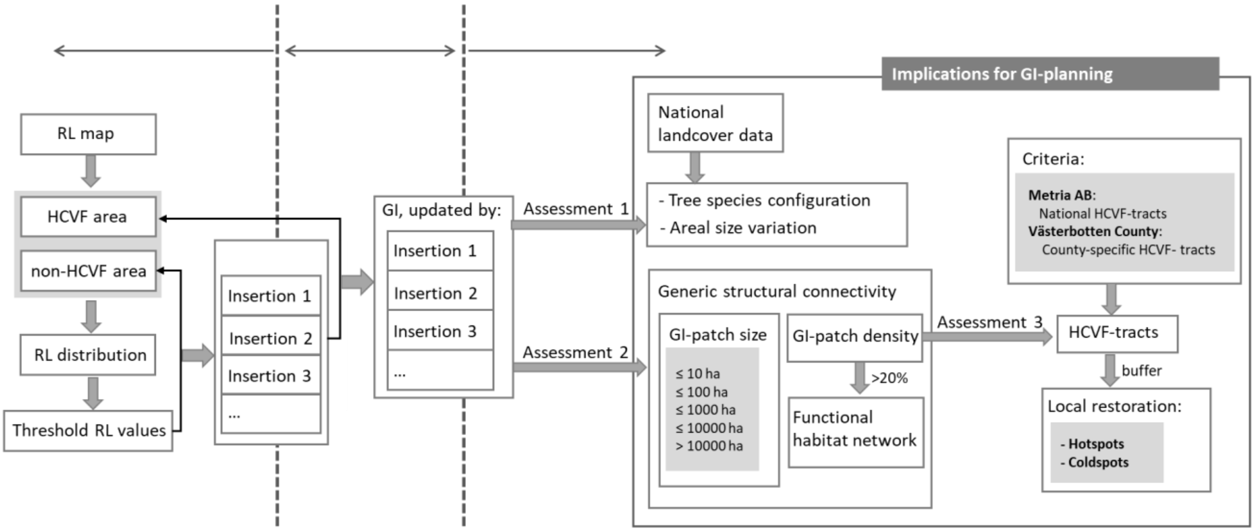

Figure 3. Overall workflow of the analysing processes.

First, the connectivity forest (CF) was identified. The high conservation value forest (HCVF) map and the model-predicted relative likelihood (RL) of HCVF occurrence map were overlaid to compare the RL distribution over the HCVF and non-HCVF areas, and a threshold RL was specified through the comparison. The CF was then extracted as the forests with an RL no less than this threshold from the non-HCVF areas. Second, the CF was step-wisely inserted into the current HCVF areas, at an RL interval of 0.1, generating a series of updated green infrastructures (GIs). Third, the effect of the CF-insertions on the GI development over the study area was assessed from three main aspects. Assessment 1 featured the reconfiguration of the forest composition and the changes of the spatial size of the GIs. Assessment 2 featured the variations of the structural connectivity, proxied by density and size variations of GI-patches. Assessment 3 featured the projection of the HCVF-tracts (i.e., the forest landscape subsections with high concentration of the known HCVF and/or model-predicted CF), using two sets of criteria applied in the previous national and regional GI-plannings, respectively. Detailed descriptions of the above analysing processes found in Section 2.3.1 to 2.3.4.

2.3.1. Specification of the threshold RL and the CF areas

A threshold RL, indicating the minimum RL required for being CF, was specified by comparing the distribution of the KubAI-predicted relative likelihood (RL) values among the HCVF- and non-HCVF areas. First, the HCVF-map over the study area was converted into a raster layer using the "Feature to Raster" tool in ArcGIS pro 2.7 (ESRI, 2020). The Category attribute of the shapefile, which indicates whether a land surface area is under formal protection or not, was used to assign pixel values to the output raster. The resulting raster was aligned with the RL-map and re-sampled to a spatial resolution of 1 ha, consistent with that of the RL-map. Then, the RL values were extracted for the HCVF and non-HCVF areas through the following four steps:

1) By reclassifying all the pixels representing non-HCVF into no data pixels, all the pixels representing HCVF were separated and retained from this raster layer.

2) These pixels of HCVF were reassigned a common pixel value of 1, since this study did not differentiate the specific forms of HCVF (e.g., whether or not under official protection).

3) The value of each pixel representing HCVF (i.e., 1) was multiplied with the value of its corresponding pixel on the RL-map, and thus the RL values over the HCVF areas were extracted.

4) The resulted RL-submap over the HCVF areas was clipped to each subregion so that three subregional outputs were generated.

Similar processes were applied to extract the RL values over the non-HCVF areas, after reclassifying all the pixels representing non-HCVF into 1 and the rest into no data. The above spatial analyses were managed using ArcGIS Pro 2.7 (ESRI, 2020). The RL distribution over the HCVF versus non-HCVF areas was visualised (Supplementary Fig. A2) and the RL quantiles were calculated for each subregion, using the Python library Rasterio (MapBox, 2016). Revealed by the quantiles (Table 2), in all three subregions, more than 50% of the HCVF areas were associated with an RL above 0.4. Based on this observation, the non-HCVF areas with an RL ≥ 0.4 were assumed to have the properties more similar to the HCVF areas, compared with those with an RL < 0.4. Therefore, the threshold RL was set to 0.4.

Correspondingly, the CF was identified as all the non-HCVF areas with an RL-value ≥ 0.4 (Fig. 4). To enable the stepwise insertion of CF, the CF was separated into six RL-classes by an RL interval of 0.1 (i.e., 0.9-1, 0.8-0.9, …, 0.4-0.5) (Fig. 4). The CF of each discrete RL-class was, then, inserted into the baseline GI (i.e., the current HCVF) one by one, started from the CF of RL-class 0.9-1 and ended with the one of 0.4-0.5, resulting a series of updated GIs.

Table 2. Quantiles of the relative likelihood for the high conservation value forests (HCVF) and non-HCVF in the three subregions (Mountain, Inland, Coastal) and the whole study area.

	Quantile	Mountain	Inland	Coastal	Whole region
HCVF	1st (25%)	0.77	0.33	0.32	0.74
	2nd (50%)	0.88	0.49	0.42	0.86
	3rd (75%)	0.96	0.65	0.53	0.95
	4th (100%)	1	0.97	0.88	1
non-HCVF	1st (25%)	0.22	0.12	0.17	0.15
	2nd (50%)	0.44	0.22	0.25	0.27
	3rd (75%)	0.67	0.35	0.35	0.46
	4th (100%)	1	0.97	0.83	1

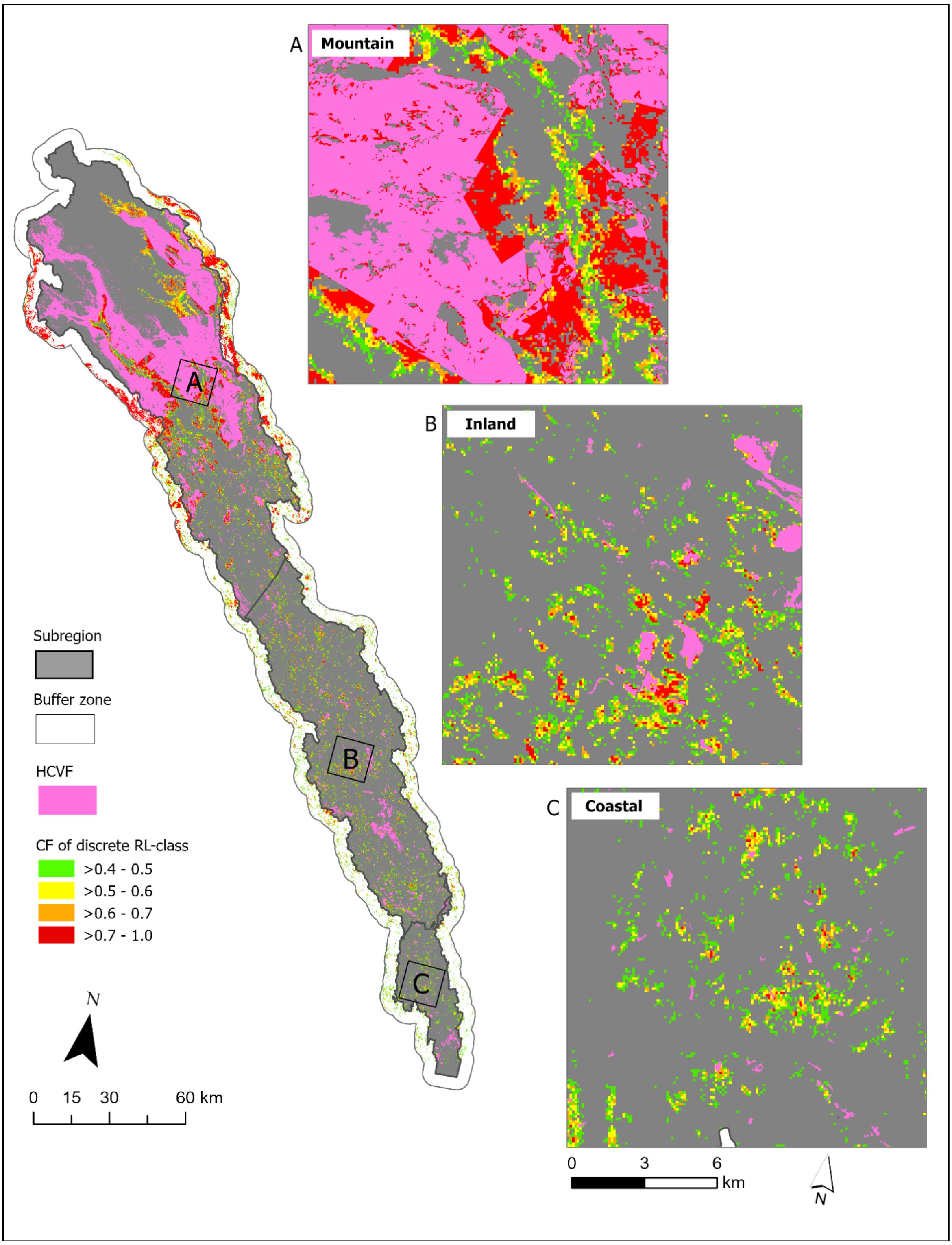

Figure 4. The high conservation value forest (HCVF) over the study region and the connectivity forest (CF), as all the non-HCVF areas with a model-predicted relative likelihood (RL) ≥ 0.4. A closer demonstration of the conceptual CF is shown, respectively, for three sample squares randomly placed in the three subregions (Mountain, Inland and Coastal); each sample square represents an area of 22 500 ha (15 × 15 km^2). For visualisation's purpose, the CF with an RL ≥ 0.7 is rendered in the same colour. A buffer zone of 5km-width, created to counterwork the spatial extent shrinkage due to the moving window analysis (specified in Subsection 2.3.3.2), is also visualized.

2.3.2. Area distribution of the CF

The CF area of nested RL-classes, i.e., the collectively involved RL-classes as the insertion step-wisely continued, was assessed.

Featuring all forest (i.e., without separation of forest types), the CF areas of nested RL-classes, found within each subregion, were calculated into ratios of the total forest area within 1) the whole study area and 2) the corresponding subregion.

Then, these area ratios were calculated for different forest types. Specifically, the CF areas per forest type per subregion, accumulated across nested RL-classes, were calculated into ratios of the total area of the corresponding forest type within 1) the whole study area and 2) the corresponding subregion. The forest type information was extracted by overlapping the reclassified NMD map (Table 1, Fig. 2 (right)) with the CF- or HCVF-maps of the discrete or nested RL-classes.

By intersecting with the original NMD map (i.e., NMD without reclassification), a minor proportion of the HCVF (31 072 ha) was found left over the non-forest land-use categories (represented by code 0 to 62 in the original NMD map, e.g., open wetland), and these areas were excluded from the area statistics where the HCVF was involved.

2.3.3. Effect-assessment of the stepwise insertion of CF

The effect was assessed through 1) how the baseline GI (i.e., the current HCVF) was re-configured, in terms of spatial size and forest composition and 2) how the structural connectivity varied across the baseline GI and each updated GI (i.e., the GI appeared after each CF-insertion).

2.3.3.1. GI reconfiguration

The effect of the stepwise CF-insertions was, first, assessed by the area increase across the baseline and each updated GI. The total area of each concerned GI (baseline or updated) was separated into the three subregions, and the area increase of an updated GI was calculated for each subregion, as a percentage relative to the subregional area of the baseline GI. In addition, the reconfiguration of the forest composition, from the baseline GI to each updated GI, was also compared.

2.3.3.2. Structural connectivity

The structural connectivity was proxied by GI-density, i.e., the concentration of GI-patches over a neighbourhood specified by the moving window method. The GI-density was chosen, over other more complex metrics of structural connectivity (e.g., the cumulative current density (CCD), see Koen et al. (2014); Mikusinski et al. (2021); Svensson et al. (2020)), because:

- A simple density analysis of GI-patches could provide a much less time- and computer-capacity-consuming, yet very relevant and indicative assessment of the structural connectivity (Auffret et al., 2015; Heino et al., 2019), which is important considering the rather restricted time frame for this thesis work.

- This study aims also for delineating the so-called high conservation value forest tracts (HCVF-tracts), i.e., the prioritized areas in practical GI-planning (see subsection 2.3.4, Bovin et al. (2017) and von Friesen & Uppsäll (2016) for more information); and GI-density, as computed in this study, is the major quantitative value supporting the delineation of the HCVF-tracts.

The density of the baseline and each updated GI, established over all forest and three separate forest types, was assessed.

Density and size of GI-patches over all forest

The density of GI-patches was calculated by moving window filtering, an approach commonly used in detecting the variations of GI-density (e.g., Angelstam et al., 2020; Bovin et al., 2017; Mikusinski et al., 2021). In this study, the moving window filtering was managed using the Focal Statistic tool by ArcGIS Pro 2.7 (ESRI, 2020), which summed up the total area of the GI-patches within a circular neighbourhood defined by a moving window. The total area of GI-patches was, then, divided by the area of the moving window to get the density of GI-patches (in percentage).

Two radii, 1km and 3km, were used for the circular moving window, respectively, to calculate the GI-density over a smaller or bigger neighbourhood (corresponding to a circular area of 314 ha and 2 827 ha, respectively). The 1 and 3km window sizes were identical to the ones used in the identification of the HCVF-tracts by the Swedish authorities to allow direct comparison (see Section 2.3.4 for more information concerning HCVF-tracts). Before applying the moving window, a buffer zone of 5km-width, enclosing the entire outer boundary of the study area, was created to counterwork the shrinkage of the spatial extent caused by the moving window scanning.

In addition to density, the changes of the structural connectivity were also assessed through the size variations of the GI-patches. More detailed description of the patch size analysis can be found in Appendix 4.

Density of GI-patches over separate forest types

To detect whether the effect of the CF-insertions on structural connectivity was specific to different forest types, the density analysis was further applied to GI-patches of three forest types.

The GI-density of each concerned forest type was analysed using the method by Mikusinski et al. (2021), targeting the density of habitat-patches maintained by different forest types. Specifically, each concerned GI (baseline or updated) was decomposed into three types of habitats maintained by, respectively, spruce, pine, and collective broadleaved species, three major components in the studied boreal forest. The density of the habitat-patches was then filtered by the moving windows identical to the ones used in the previous steps featuring GI-density of all forest.

The three types of habitats were extracted using the criteria by Mikusinski et al. (2021): the habitats maintained by spruce were considered as spruce forest and coniferous mixed forest, specified by the reclassified NMD dataset; by pine, as pine forest and coniferous mixed forest; and by broadleaved species, as broadleaved forest and broadleaved-coniferous mixed forest. As proposed by Mikusinski et al. (2021) and Edenius and Mikusinski (2006), the habitats maintained by mixed forest (i.e., coniferous mixed or broadleaved-coniferous mixed) might be less effective in sufficing the resources needed for its inhabitants, compared with the relevant pure stands. Therefore, the habitat area constituted by mixed forest was weighed by a factor of 0.5. With this weighing factor applied, the effective habitat area constituted by the mixed forest was only considered as half of their actual sizes.

Density median variation and the corresponding amount of inserted CF

The GI-density distribution was summarised by quantiles for each baseline and updated GI per forest type (including all forest as one type) per subregion. To assess whether the increase of GI-density was proportional to the corresponding CF-area inputs, the density medians were used to proxy the overall density variations and compared upon their corresponding amount of cumulatively inserted CF. Due to the time restriction of this thesis project, this assessment was only applied to the density filtered by the moving window of 3km radius.

GI-density variations filtered by a threshold density of 20%

Finally, on the density maps generated in the previous steps, the landscape subsections displaying a density value ≥ 20% were separated and the area percentages of these subsections was calculated (relative to the total area of the landscape subsections with a density value > 0). The analyses were applied to the GI-density results of all forest and the three forest types (spruce, pine, broadleaved species (co-)dominated), featuring both the whole study area and the subregions. The GI-density was filtered by the moving window of 3km and 1km radius, respectively.

The threshold of 20% was based on the findings that over a given forest landscape, the density of the remaining habitat-patches lower than 20% would lead to a severe species isolation and biodiversity degradation (Andrén, 1994; Bovin et al., 2017). Therefore, the minimum GI-density of 20% was a general indication of a functioning habitat (e.g., Angelstam et al., 2020; Bovin et al., 2017), which was also set as a quantitative goal of GI construction by the Swedish government (Angelstam & Manton, 2021).

2.3.4. Delineation of HCVF-tracts and identification of restoration hot- and coldspots

2.3.4.1 Delineation of HCVF-tracts

The effect of the stepwise insertion of CF, was translated into a series of HCVF-tracts, and these updated HCVF-tracts were compared with the current ones given by the Swedish authorities, based mainly on the current known HCVF-patches.

HCVF-tracts are the forest landscape subsections with higher concentration of GI-patches and larger areal size, and therefore should be prioritized in practical conservation works (Bovin et al., 2017; Friesen & Uppsäll, 2016). Exactly how “high” the density and how “large” the patch size should be, are specified by various sets of criteria, adapting to specific forest and nature-geographical conditions at different spatial extents (the whole country or different counties). Detailed information about HCVF-tracts can be found in e.g., Bovin et al. (2017).

In this study, the HCVF-tracts were, first, extracted from the baseline GI formed by the current HCVF, to represent the current HCVF-tracts. The delineation of the HCVF-tracts was following the criteria and procedures used by Metria AB (Bovin et al., 2017) on commission by the Swedish Environmental Protection Agency (SEPA). Therefore, the current HCVF-tracts, delineated in this study, were referred to as ***current HCVF-tracts (Metria)***. The major differences of the data, criteria/procedures used by Metria and by this study can be found in Appendix 4.

Then, two sets of updated HCVF-tracts were extracted based on the GI that appeared after inserting all the CF with an RL ≥ 0.7 and after the final insertion including all the CF with an RL ≥ 0.4, respectively. These two updated sets represented the intermediate versus the final status along the transitions of GI prescribed by this study, and thus were referred to as ***updated HCVF-tracts (intermediate)*** and ***updated HCVF-tracts (final)***.

The two sets of updated HCVF-tracts were then compared with 1) ***current HCVF-tracts (Metria)***, and 2) the HCVF-tracts delineated by the County Administrative Board (CAB) of Västerbotten, henceforth ***current HCVF-tracts (CAB Västerbotton)***. The latter (i.e., by the CAB Västerbotten) was identified based on similar fundamental criteria used by Metria but based on more county-specific and extensive data sources (details find in von Friesen & Uppsäll (2016)). A brief description of how the data sources and the criteria/procedures used by the CAB of Västerbotten were different from the ones by Metria AB is also found in Appendix 5.

2.3.4.2 Identification of the restoration hot- and coldspots

Finally, the HCVF-tracts were translated into restoration hot- and coldspots, to further support the decision makings in the daily forest management and conservation operations.

To localise the hotspots, a 3km-width buffer zone was created enclosing each identified HCVF-tract. Then, all the additionally inserted CF areas, found within either the HCVF-tracts or the 3km-width buffer zones, were identified as restoration hotspots. The inclusion of the 3km buffer was because the HCVF-tracts were identified based on GI-density filtered by the moving window of, maximum, 3km radius, and thus any input of CF within this 3km buffer could have impacted the appearance/distribution of the HCVF-tracts.

Over each updated HCVF-tracts, the total area of the identified hotspots was calculated within each subregion, respectively over the known HCVF and the newly appeared ones due to the insertions.

Starting from the outer boundary of the 3km buffer, additional buffers were consecutively created at a 5km-width interval, until the “blank” landscape subsections (i.e., the tracts outside the HCVF-tracts and the 3km buffers) were fully covered, and these areas were considered as restoration coldspots, or rather, cold-subsections: the further away from any HCVF-tract, the colder the subsection.

3. Results

3.1 Area distribution of the CF

Featuring all forest (i.e., irrespective of forest types), measured in hectares (ha), the CF accumulated across nested RL-classes, if any area, was much less in the inland or coastal subregion than in the mountainous subregion (80 981, 42 901 and 6 562 ha respectively in the mountainous, inland, and costal subregion, shown in Appendix 6). However, such comparatively much less amount (in ha) of CF accumulated to over 13% and 11% of the total forest area in the inland and coastal subregion, respectively (Fig. 5, Appendix 6). Similar pattern was found for the CF of separate forest types. In the inland and coastal subregions, the area of CF per forest type could eventually accumulate to about 7-23% of the total subregional area of the corresponding forest type (Fig. 5, Appendix 6). Among the three subregions, the inland subregion showed the highest total area of pine-dominated CF (in ha) (Appendix 6).

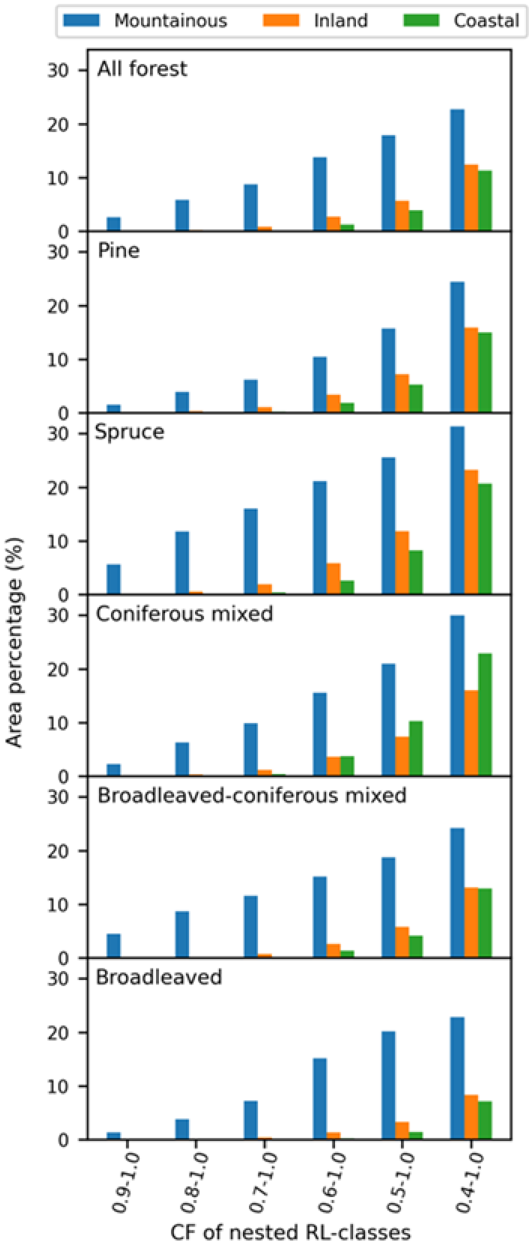

Figure 5. Area percentage (%) of connectivity forest (CF), of all forest (i.e., without separation of forest types) and per forest type, accumulated across nested relative likelihood classes (RL-classes) for each subregion of the study area. Percentages are calculated relative to the total subregional area of each forest type (including all forest as one type). The percentages are specified in Appendix 6.

3.2. Effect-assessment of the stepwise insertion of CF

3.2.1 Area increase and forest composition reconfiguration of the updated GIs

The CF-insertions caused higher extent of GI-area increase in the inland and coastal subregions than in the mountainous subregion (Fig. 6). In the mountainous subregion, the area increase was about 60% as a maximum; whereas in the inland and coastal subregions, the GI area was already doubled after inserting all the CF of an RL ≥ 0.6 and was eventually quadrupled at the end of the insertion.

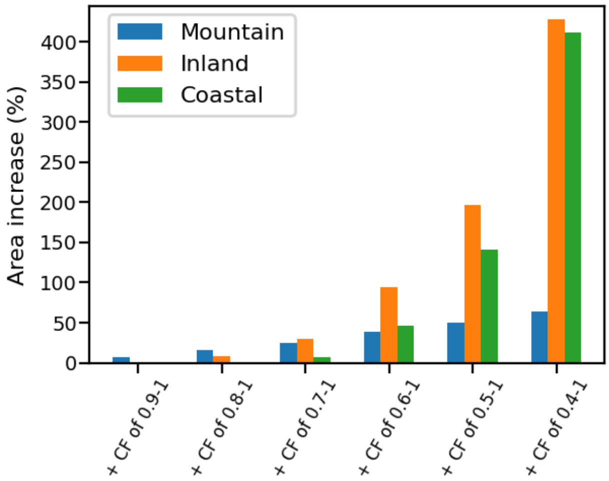

Figure 6. Area increase of green infrastructure (GI) by the stepwise insertion of connectivity forest (CF), relative to the total area of the current high conservation value forest (HCVF) per subregion.

The CF-insertions also caused the variation of the forest composition across the baseline and updated GIs (Fig. 7). In the mountainous subregion, the collective proportion of the broadleaved and broadleaved-coniferous mixed forest decreased slightly. In the inland subregion, the proportion of the spruce forest decreased, while the proportion of the pine and broadleaved forest increased marginally. In the coastal subregion, the proportion of spruce and broadleaved forest both decreased, and the proportion of the pine forest increased, especially after inserting all the CF-areas with an RL of 0.6-1

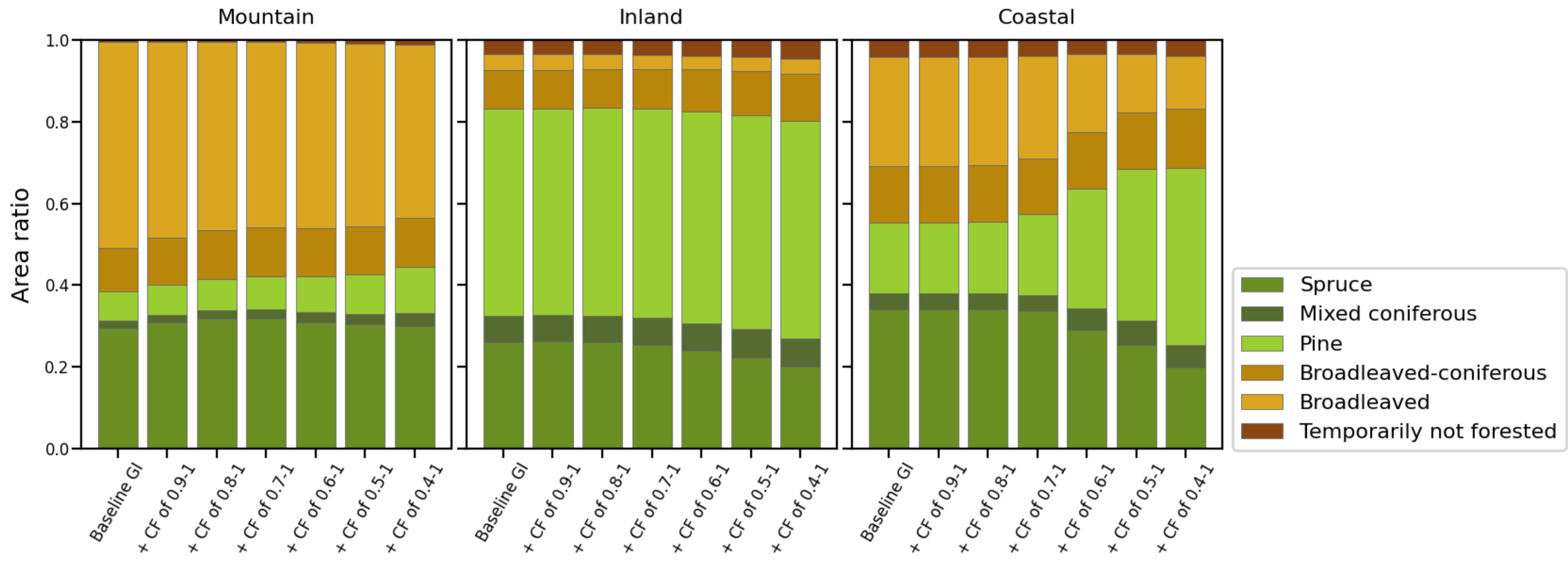

Figure 7. Variation of forest composition across the baseline green infrastructure* (GI) and the updated GIs* with the stepwise insertion of connectivity forest (CF), within each subregion (Mountain, Inland, Coastal).

*Baseline GI: represented by the high conservation value forests (HCVF); updated GI: formed jointly by a baseline GI and the CF of nested relative likelihood classes (RL-classes).

3.2.2. GI-density variation

Visual assessment of the density variation

The stepwise insertion of CF gradually increased the GI-density of all forest and each concerned forest type over the study area (Fig. 8-11).

Featuring all forest, after inserting all the CF with an RL ≥ 0.6, the GI-density, filtered by a moving window of 3km radius, became generally above 0 (Fig.8: upper panel). This means at least one GI-patch could be found within a searching radius of 3km from almost anywhere over the study region. After inserting all the CF with an RL ≥ 0.4, such GI-patches would most-likely be found within a searching radius of 1km (Fig.8: lower panel).

Featuring the spruce or broadleaved (co-)dominated forest (Fig. 9 and 10), the density-gaps (i.e., areas with a GI-density = 0) filtered by the moving window of 3km radius were basically eliminated after inserting all the CF of an RL ≥ 0.5 (Fig. 9 and 10: upper panel). When filtered by the moving window of 1km radius, however, the density-gaps were still quite visible even after inserting all the CF of 0.4-1 (Fig. 9 and 10: lower panel). In contrast, for the pine (co-)dominated forest, the density-gaps filtered by the moving window of 1km radius basically disappeared in the end of the insertions (Fig. 11: lower panel).

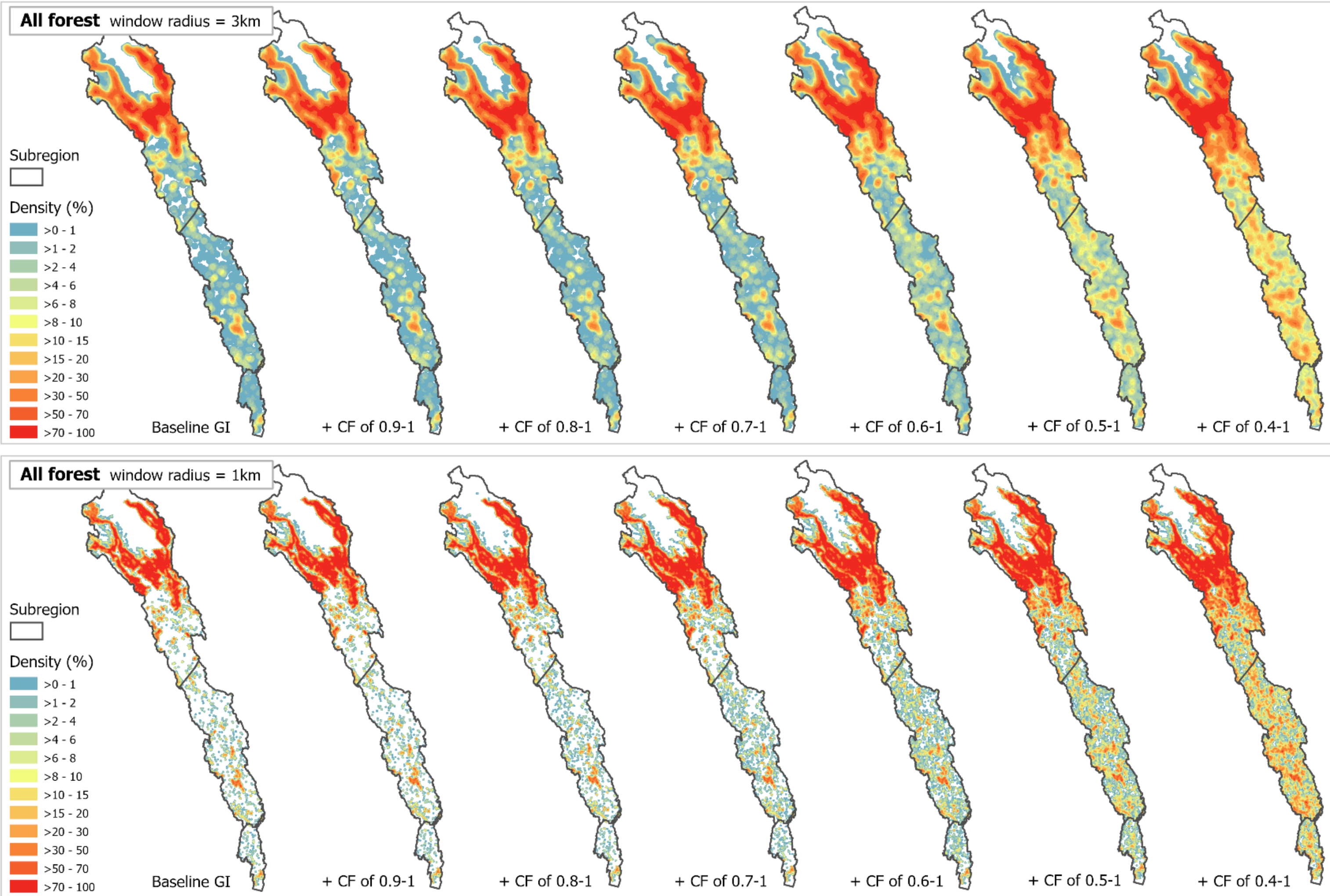

Figure 8. Green infrastructure (GI) density variation across baseline GI* and each updated GI*, of **all forest** (i.e., without separation of forest types), with the stepwise insertion of connectivity forest (CF). GI-density was filtered by a circular moving window of 3km radius (**upper panel**) and 1km radius (**lower panel**).

* Baseline GI: represented by the current high conservation value forest (HCVF); updated GI: formed jointly by a baseline GI and the CF of nested relative likelihood classes (RL-classes).

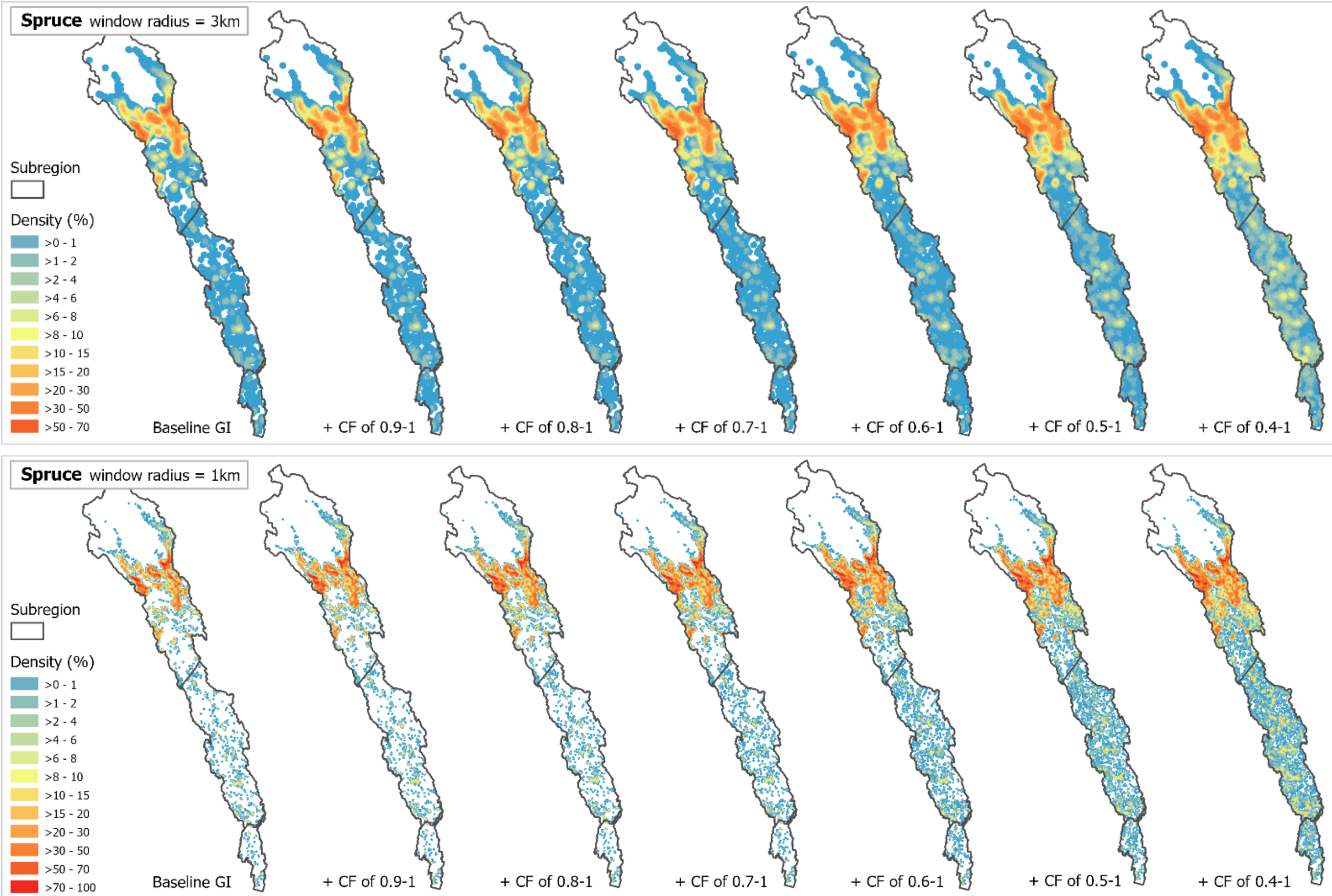

Figure 9. Green infrastructure (GI) density variation across baseline GI and each updated GI, established over **spruce** (co-)dominated forest*, with the stepwise insertion of connectivity forest (CF). GI-density was filtered by a circular moving window of 3km radius (**upper panel**) and 1km radius (**lower panel**).

* Spruce (co-)dominated forest: spruce forest plus mixed coniferous forest.

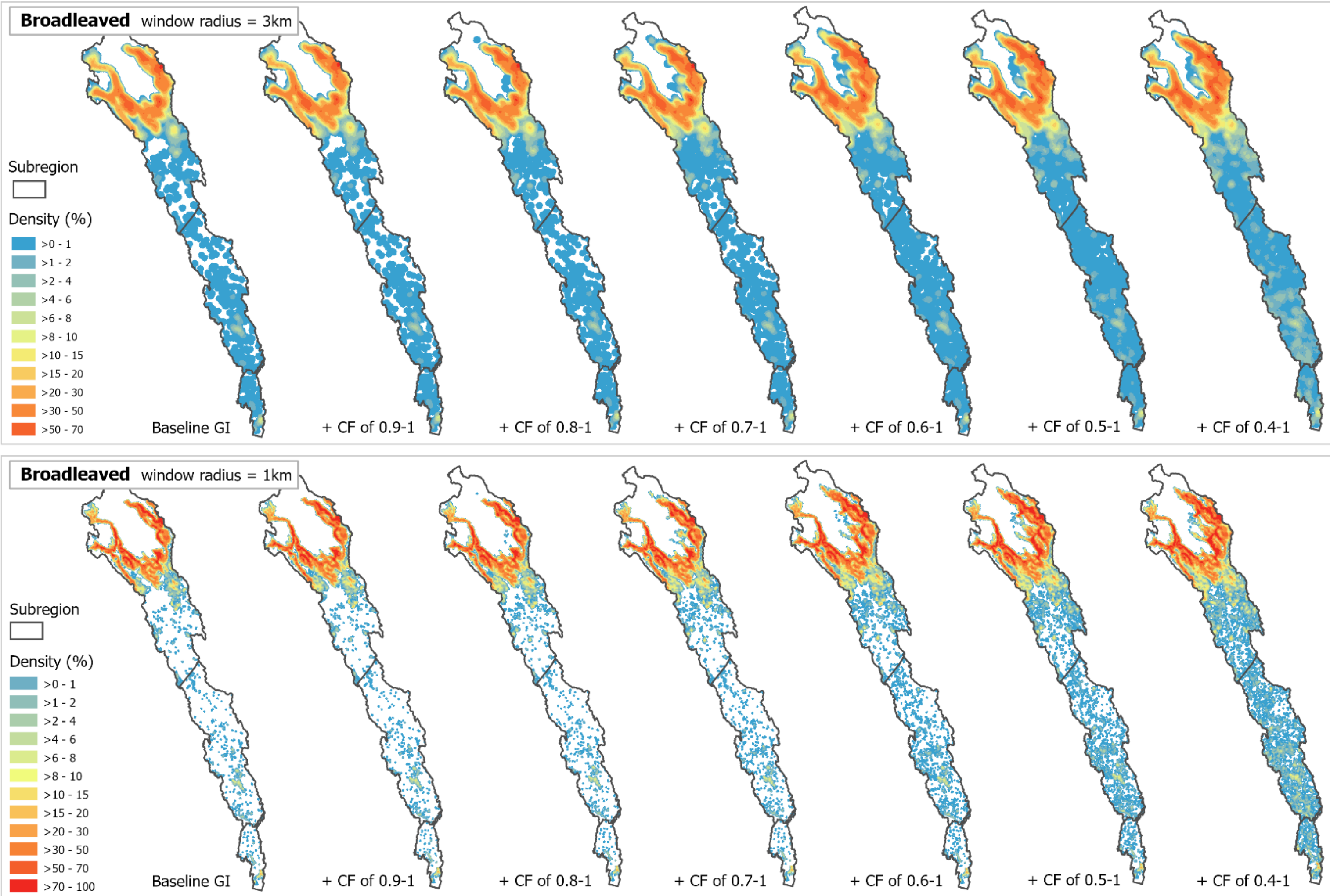

Figure 10. Green infrastructure (GI) density variation across baseline GI and each updated GI, established over **broadleaved** species (co-)dominated forest*, with the stepwise insertion of the connectivity forest (CF). GI-density was filtered by a circular moving window of 3km radius (**upper panel**) and 1km radius (**lower panel**).

* Broadleaved species (co-)dominated forest: broadleaved forest plus broadleaved-coniferous mixed forest.

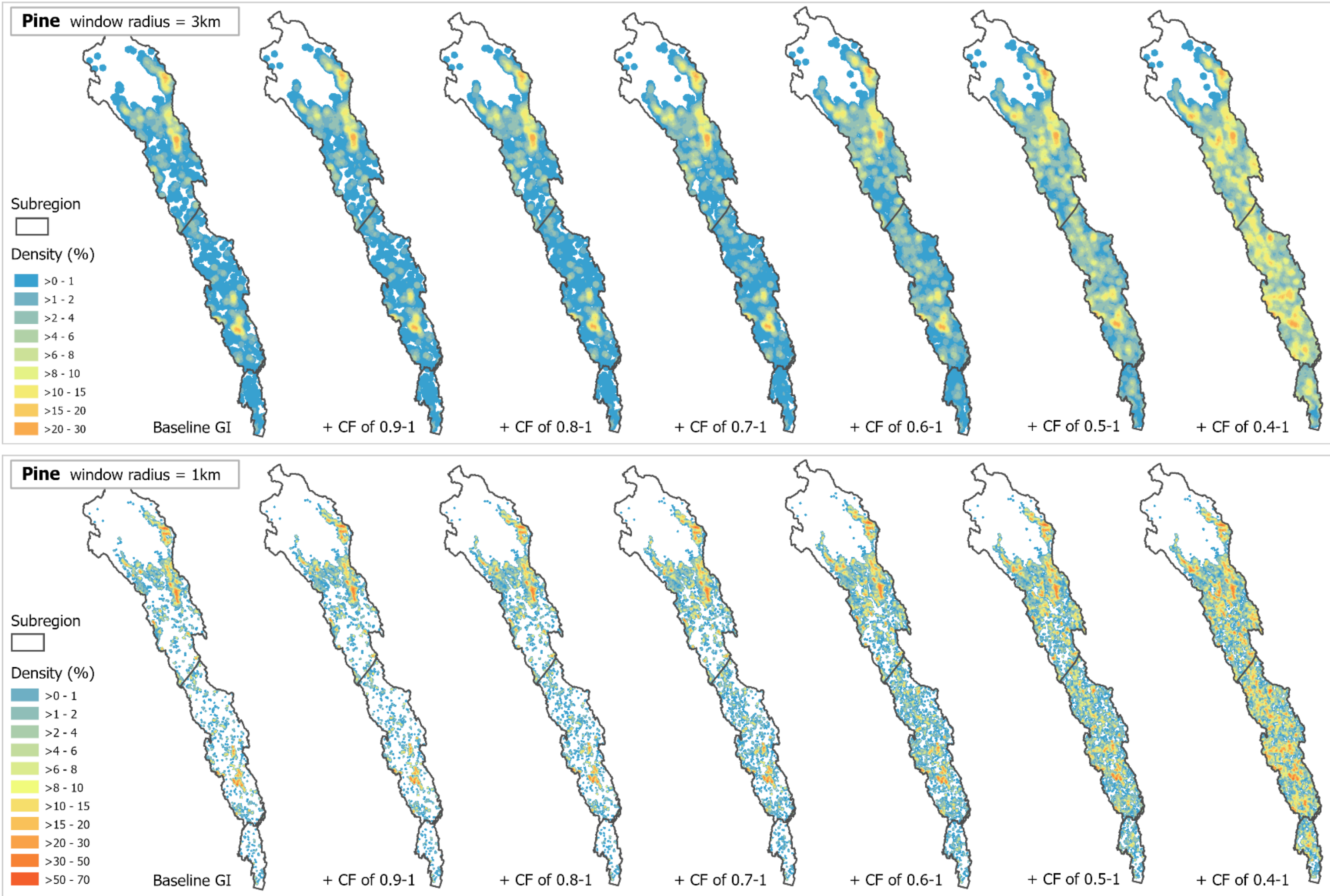

Figure 11. Green infrastructure (GI) density variation across baseline GI and each updated GI, established over **pine** (co-)dominated forest*, with the stepwise insertion of connectivity forest (CF). GI-density was filtered by a circular moving window of 3km radius (**upper panel**) and 1km radius (**lower panel**).

* Pine (co-)dominated forest: pine forest plus mixed coniferous forest.

Density median variation and the corresponding amount of inserted CF

The extents and patterns of GI-density increase varied among the GIs of different forest types (including all forest as one type) and in different subregions (Fig. 12).

For all forest, spruce and broadleaved (co-)dominated forest, the CF-insertions increased the density medians of these three forest types by a higher extent in the mountainous than in the rest two subregions (Table 3). However, the extent of density increase was disproportional to the corresponding amount of cumulatively inserted CF-areas, which was much larger in the mountainous than in the other two subregions (Table 3). As an example, after the final insertion in the mountainous subregion, the median increase for spruce (co-)dominated forest was about twice of that in the inland or coastal subregion (approx. 4%, 2% and 1.6%, respectively in the mountainous, inland and coastal subregions). The corresponding total amount of inserted CF in the mountainous subregion was more than twice of that in the inland or coastal subregion (3.8%, 1.5% and 0.2% of the total regional forest area, for mountainous, inland and coastal subregion, respectively)(Table 3).

The total density increases of pine (co-)dominated forest were almost the same in the mountainous and coastal subregions (both about 3.3%)(Table 3). However, the total inserted CF-areas accounting for such increase were much smaller in the coastal than in the mountainous subregion (i.e., 0.5% versus 2.5% of the total regional forest)(Table 3). In the inland subregion, the total density increase was about 1.5 times higher than that in the mountainous subregion (about 5.5% versus 3.3%). Yet again, the cumulatively inserted CF areas in the inland subregion was only 1% higher than that in the mountainous subregion (3.5% versus 2.5%).

Overall, the density median increase achieved upon per unit CF area input was higher in the inland and the highest in the costal subregion, compared with that in the mountainous subregion.

The results of the patch-size analyses are described in Appendix 9.

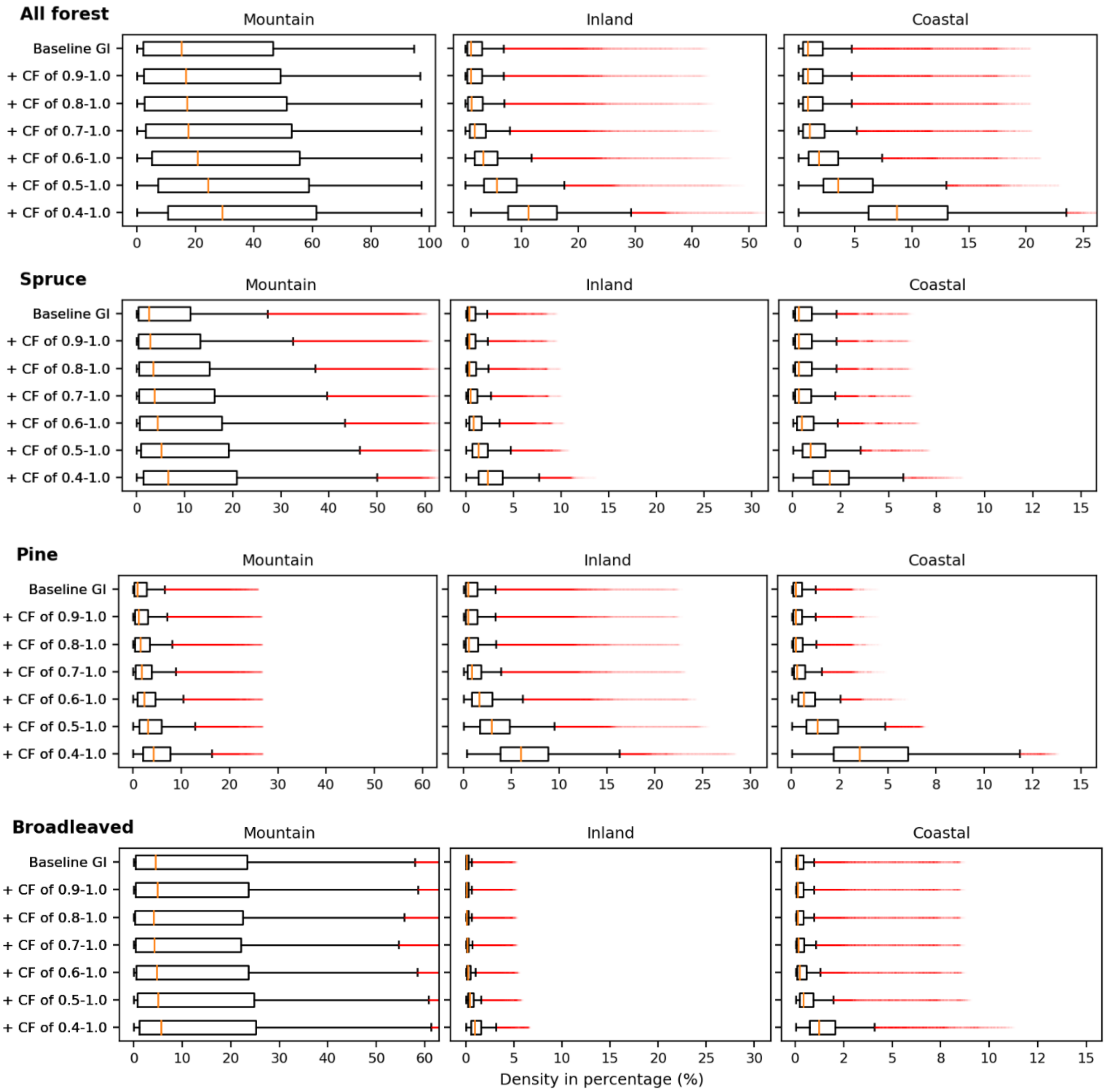

Figure 12. Summarization of green infrastructure density (GI-density) variations across baseline GI* and each updated GI*, per forest type* (including all forest as one type) and subregion. The boxplots visualize the minimum, median, first and third quartiles; the whiskers drawn within the 1.5 times inter-quartile range, and the outliers shown in red. The density was filtered by the moving window of 3km radius.

* Baseline GI: represented by the current high conservation value forest (HCVF); updated GI: formed jointly by a baseline GI and the CF of nested relative likelihood classes (RL-classes).

* Forest type includes:

1) spruce (co-)dominated forest: spruce forest plus mixed coniferous forest.

2) Pine (co-)dominated forest: pine forest plus mixed coniferous forest.

3) broadleaved species (co-)dominated forest: broadleaved forest plus broadleaved-coniferous mixed forest.

Table 3. Green infrastructure density (GI-density) median increase (%) and the corresponding total area of inserted connectivity forest (CF). CF areas are shown in percentage (%) of the total forest area in the study region (i.e., 756 831 ha) and in hectares (ha).

Forest type	GI	Mountain			Inland			Coastal		
		density increase (%)	Inserted CF areas		density increase (%)	Inserted CF areas		density increase (%)	Inserted CF areas	
			%	ha		%	ha		%	ha
All forest	+ CF of 0.9-1	1.52	1.23	9 318	0.04	0.01	42	0	0	0
	+ CF of 0.8-1	1.95	2.75	20 840	0.14	0.11	834	0	0	8
	+ CF of 0.7-1	2.37	4.13	31 298	0.64	0.39	2 962	0.18	0.01	106
	+ CF of 0.6-1	5.66	6.48	49 074	2.12	1.23	9 314	0.95	0.1	744
	+ CF of 0.5-1	9.09	8.43	63 851	4.6	2.6	19 704	2.65	0.3	2 256
	+ CF of 0.4-1	13.97	10.7	80 981	10.15	5.67	42 901	7.78	0.87	6 562
Spruce (co-)dominated (spruce forest + coniferous mixed forest)	+ CF of 0.9-1	0.25	0.64	4 809	0	0	24	0	0	0
	+ CF of 0.8-1	0.85	1.35	10 229	0.02	0.04	271	0	0	3
	+ CF of 0.7-1	1.17	1.86	14 086	0.11	0.12	921	0	0	31
	+ CF of 0.6-1	1.82	2.5	18 914	0.42	0.36	2 708	0.16	0.03	200
	+ CF of 0.5-1	2.6	3.06	23 146	0.96	0.72	5 465	0.62	0.08	601
	+ CF of 0.4-1	3.93	3.82	28 914	1.96	1.46	11 021	1.59	0.19	1 457
Pine (co-)dominated (pine forest + coniferous mixed forest)	+ CF of 0.9-1	0.19	0.16	1 230	0	0	17	0	0	0
	+ CF of 0.8-1	0.55	0.42	3 192	0.07	0.07	517	0.02	0	4
	+ CF of 0.7-1	0.81	0.67	5 049	0.35	0.25	1 870	0.07	0.01	66
	+ CF of 0.6-1	1.41	1.11	8 378	1.15	0.75	5 710	0.43	0.06	469
	+ CF of 0.5-1	2.1	1.62	12 228	2.48	1.58	11 976	1.13	0.18	1 326
	+ CF of 0.4-1	3.34	2.46	18 625	5.48	3.46	26 219	3.33	0.48	3 647
Broadleave (co-)dominated (broadleaved forest + broadleaved-coniferous mixed forest)	+ CF of 0.9-1	0.42	0.47	3 576	0	0	5	0	0	0
	+ CF of 0.8-1	-0.37	1.07	8 112	0	0.01	93	0	0	0
	+ CF of 0.7-1	-0.3	1.73	13 134	0.04	0.05	384	0.02	0	14
	+ CF of 0.6-1	0.27	3.05	23 127	0.12	0.17	1 286	0.09	0.02	124
	+ CF of 0.5-1	0.57	3.98	30 128	0.32	0.38	2 876	0.28	0.06	440
	+ CF of 0.4-1	1.2	4.69	35 507	0.8	0.89	6 720	1.1	0.21	1 596

3.2.3 GI-density variation filtered by the threshold of 20%

Over all forest

Featuring the whole study region (i.e., without separation of subregions), a large area already fulfilled the density requirement of a functioning habitat (i.e., ≥ 20%) under the baseline status, accounting for about 26% and 41% of the total area with an GI-density > 0, respectively under the window size of 3km and 1km (Fig. 13, Table 4). The stepwise insertion of CF gradually increased the area shares to 40% and 43%, respectively.

However, the areas fulfilled the density requirement of 20% were concentrated in the mountainous subregion (Fig. 13, Table 4). In the inland and costal subregions, the areas with an GI-density ≥ 20% were low in amount, small in size and highly disconnected (Fig. 13, Table 4).

Over separate forest types

The dominant component of these functioning habitat areas (i.e., areas with a GI-density ≥ 20%) was broadleaved (co-)dominated forest (Fig. 14, Supplementary Fig. A5). Across the updated GIs in the mountainous subregion, such functioning patches of broadleaved (co-)dominated forest remained above 24% of the total subregional areas with a GI-density > 0, under both window sizes (Table 4). Featuring the whole study area, this area share remained above 13% (Table 4).

There were also quite some functioning patches maintained by spruce (co-)dominated forest in the mountainous subregion (Fig. 14, Supplementary Fig. A3). With the CF-insertions, the area share of such patches in the mountainous subregion increased from 11% to 19% of the total subregional areas with a GI-density > 0, under the window size of 3km radius; and from 17% to 20% under that of 1km radius (Table 4).

The status across the GIs maintained by pine was very poor on either subregional or regional scale (Fig. 14, Table 4, Supplementary Fig. A4). With the CF-insertions, only some very small and scattered functioning patches appeared (Table 4, Supplementary Fig. A4).

Table 4. Percentage of the areas with a green infrastructure density (GI-density) ≥ 20%, of all forest and per forest type. Percentages were calculated based on the total area of GI-density > 0 specified by a baseline or updated GI in a subregion or the whole study area. Baseline GI was represented by the current high conservation value forest (HCVF); updated GI was formed jointly by a baseline GI and the connectivity forest (CF) of nested relative likelihood classes.

Forest type	GIs	Area (%) with GI-density ≥ 20%:							
		moving window radius = **3 km**				moving window radius = **1 km**			
		Mountain	Inland	Coastal	Whole area	Mountain	Inland	Coastal	Whole area
All forest	Baseline GI	45.49	1.85	0.04	25.99	56.88	8.79	6.52	40.72
	+ CF of 0.9-1	47.05	1.85	0.04	26.96	57.37	8.71	6.52	41.37
	+ CF of 0.8-1	47.47	1.82	0.04	27.28	57.13	7.52	6.50	40.02
	+ CF of 0.7-1	47.82	1.91	0.05	27.73	55.61	6.55	5.78	37.37
	+ CF of 0.6-1	50.79	2.32	0.12	29.78	56.01	6.57	4.52	35.55
	+ CF of 0.5-1	54.29	3.78	0.24	32.40	58.08	9.12	6.09	36.51
	+ CF of 0.4-1	60.89	14.16	5.62	40.27	61.44	21.64	15.99	43.19
Spruce (co-)dominated (spruce forest + coniferous mixed forest)	Baseline GI	10.86	-	-	6.05	16.96	0.33	0.02	11.40
	+ CF of 0.9-1	12.53	-	-	7.00	18.48	0.33	0.02	12.54
	+ CF of 0.8-1	14.30	-	-	8.02	19.54	0.28	0.02	12.91
	+ CF of 0.7-1	15.23	-	-	8.61	19.51	0.25	0.02	12.35
	+ CF of 0.6-1	16.36	-	-	9.32	19.19	0.24	0.04	11.38
	+ CF of 0.5-1	17.58	-	-	10.05	19.42	0.33	0.15	11.08
	+ CF of 0.4-1	19.27	-	-	11.02	19.90	0.72	0.31	11.28
Pine (co-)dominated (pine forest + coniderous mixed forest)	Baseline GI	0.29	0.22	-	0.25	2.12	3.15	-	2.28
	+ CF of 0.9-1	0.33	0.22	-	0.26	2.22	3.12	-	2.34
	+ CF of 0.8-1	0.33	0.23	-	0.27	2.17	2.70	-	2.22
	+ CF of 0.7-1	0.33	0.28	-	0.29	2.19	2.31	-	2.11
	+ CF of 0.6-1	0.36	0.37	-	0.34	2.33	2.10	-	2.11
	+ CF of 0.5-1	0.39	0.48	-	0.40	2.82	2.55	0.01	2.54
	+ CF of 0.4-1	0.48	0.91	-	0.60	4.06	5.92	1.70	4.59
Broadleaved species (co-)dominated (broadleaved forest + broadleaved-coniferous mixed forest)	Baseline GI	24.47	-	-	13.62	30.85	-	0.53	20.60
	+ CF of 0.9-1	24.74	-	-	13.82	30.50	-	0.53	20.57
	+ CF of 0.8-1	24.67	-	-	13.83	29.34	-	0.53	19.28
	+ CF of 0.7-1	24.74	-	-	13.99	28.00	-	0.47	17.63
	+ CF of 0.6-1	26.60	-	-	15.16	28.24	-	0.35	16.65
	+ CF of 0.5-1	27.68	-	-	15.82	28.20	-	0.33	15.91
	+ CF of 0.4-1	28.32	-	-	16.20	27.74	-	0.50	15.34

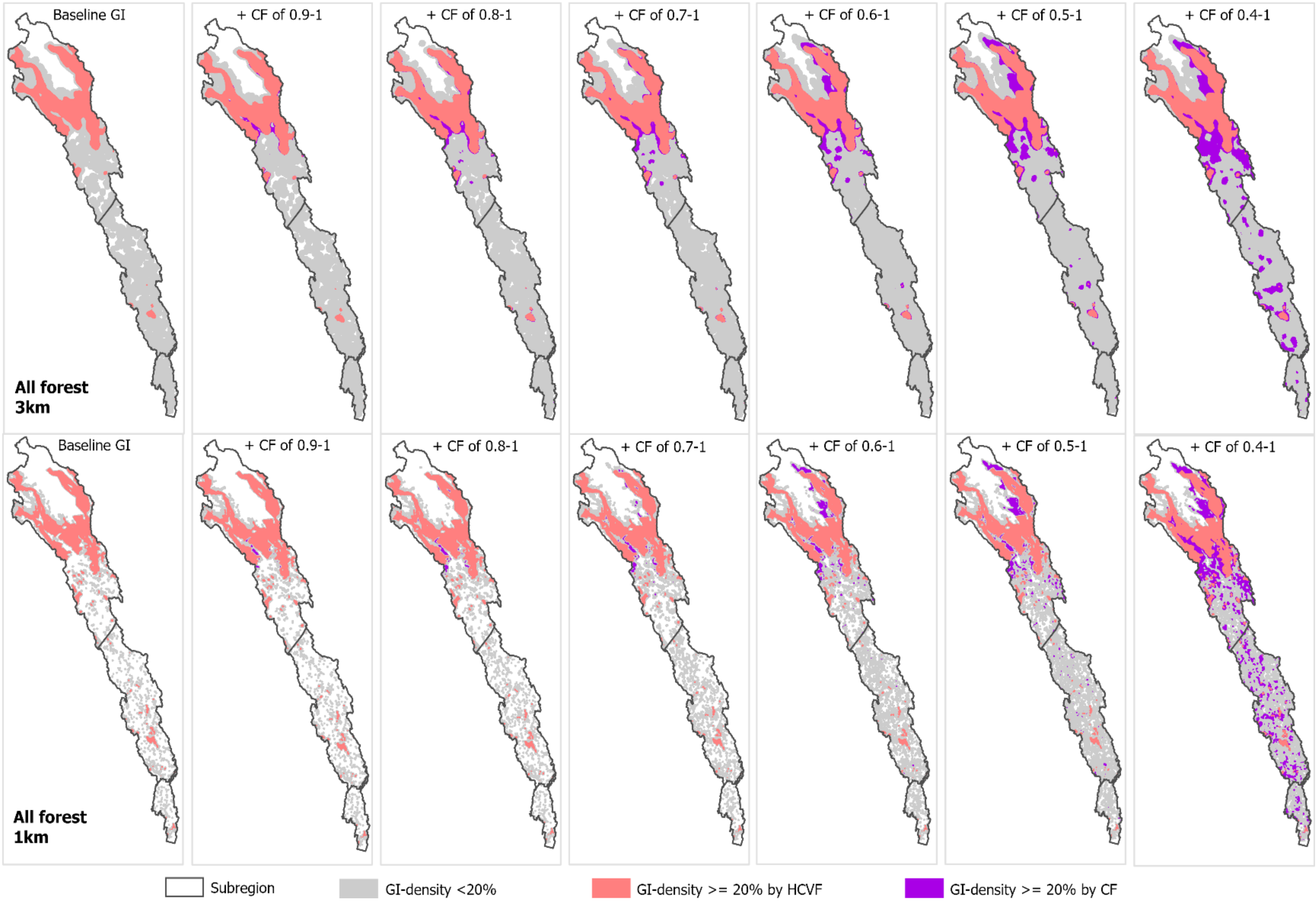

Figure 13. Variation of all forest (i.e., without separation of forest types) with green infrastructure (GI) density ≥ 20%, with the stepwise insertion of connectivity forest (CF); density filtered by a circular moving window of 3km radius (**upper panel**) and 1km radius (**lower panel**). Areas in light red indicates the patches with a GI-density ≥ 20% in the baseline GI, i.e., the high conservation value forests (HCVF); and areas in violate indicates the newly added patches of density ≥ 20% by the CF-insertions.

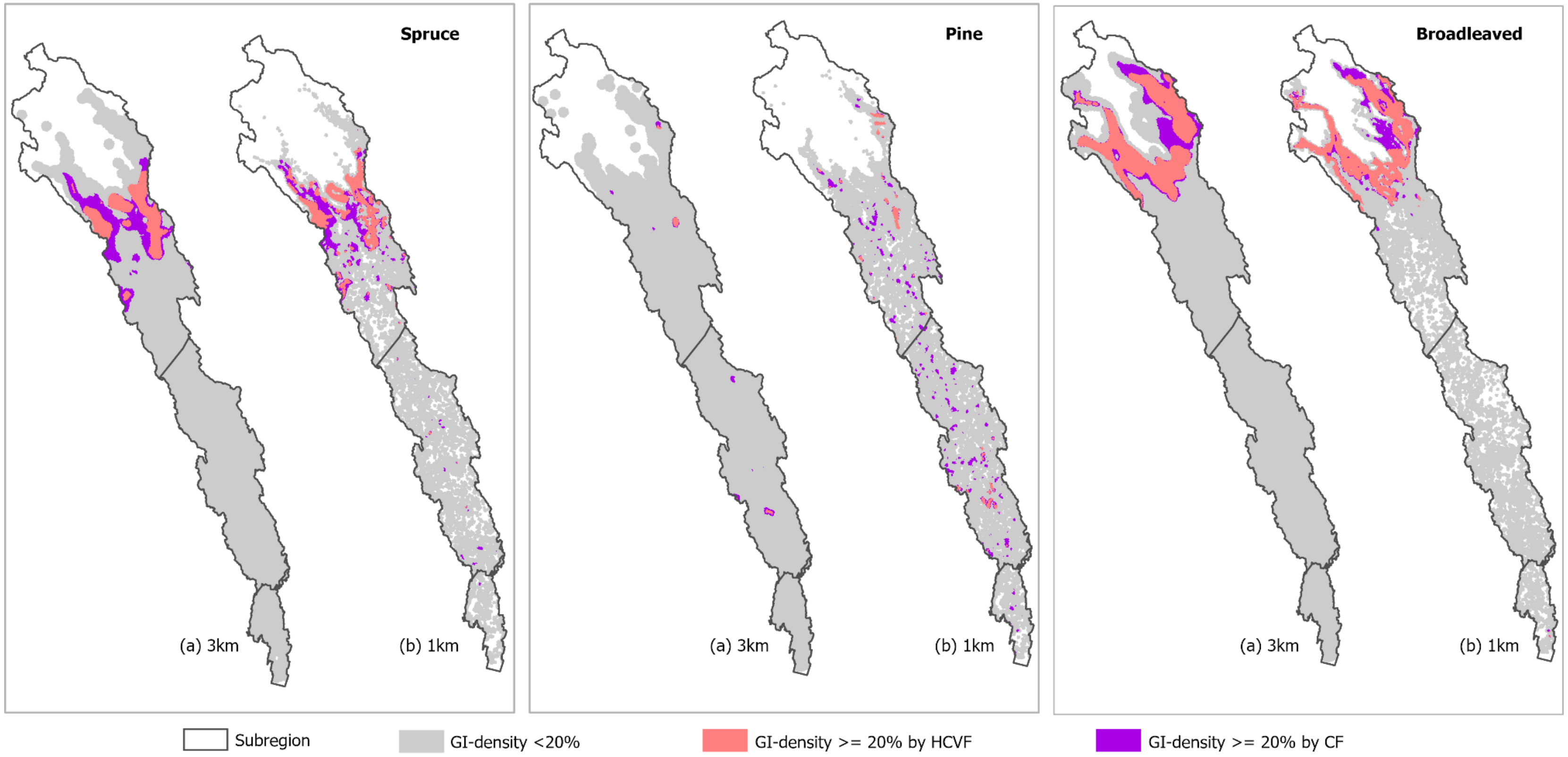

Figure 14. Areas of forest types* with green infrastructure (GI) density ≥ 20%, after the final insertion, i.e., after inserting all the connectivity forest (CF) areas with nested relative likelihood (RL) classes of 0.4-1; density filtered with a circular moving window of 3km radius (**a**) and 1km radius (**b**). Areas in light red indicates the patches with a GI-density ≥ 20% in the baseline GI, i.e., the high conservation value forests (HCVF); and areas in violate indicates the newly added patches of density ≥ 20% by the CF-insertions.

* Forest type " Spruce" : spruce forest plus coniferous mixed forest; " Pine" : pine forest plus coniferous mixed forest; " Broadleaved" : broadleaved forest plus broadleaved-coniferous mixed forest.

Find the full map series in Appendix 8 (Fig. A3 for " Spruce" ; Fig. A4 for " Pine" ; Fig. A5 for " Broadleaved").

3.3 Updated HCVF-tracts and identified restoration hot- versus coldspots

Compared with the *current HCVF-tracts (Metria)*, the updated HCVF-tracts displayed a visually significant area expansion in all three subregions. After the final insertion of CF (Fig. 15), the updated HCVF-tracts could, in general, achieve a full coverage of the coastal subregion; also, on the *updated HCVF-tracts (final)*, the cold spots/land-subsections, found in the inland subregion and still very visible on the *updated HCVF-tracts (intermediate)*, was basically eliminated.

Due to the CF-insertions, considerable amount of restoration hotspots was added to the updated HCVF-tracts. In the *updated HCVF-tracts (intermediate)*, the newly appeared hotspots equalled about 21%, 9% and 3% of the total area of the known hotspots in the mountainous, inland, and coastal subregion, respectively. In the *updated HCVF-tracts (final)*, the area share of these new hotspots increased to 60% in the mountainous subregion and over 300% in both inland and costal subregions (Table 5).

The individual tract identified in the *current HCVF-tracts (Metria)* or *updated HCVF-tracts (intermediate)* was, in general, smaller than its corresponding tract identified by the CAB of Västerbotten in the inland and coastal subregions but bigger in the mountainous subregion (Fig. 16 (a), (b)); but the *updated HCVF-tracts (final)* displayed a more extensive spatial coverage in all subregions than the *current HCVF-tracts (CAB Västerbotten)* (Fig. 16 (c)).

Table 5. Total area of the hotspots, i.e., the connectivity forest (CF) areas located in either the HCVF-tracts or the 3km-width buffer zones enclosing the HCVF-tracts. The column "known" presents the total area (in ha) of the hotspots identified within the currently known high conservation value forests (HCVF), and the column "inserted" presents the newly added areas (in ha and percentage) due to the insertion of CF. The percentages of the inserted hotspot areas are calculated relative to their corresponding known hotspot areas.

		Area of hotspots					
		Mountain		**Inland**		**Costal**	
		known (ha)	**inserted** (ha / %)	**known** (ha)	**inserted** (ha / %)	**known** (ha)	**inserted** (ha / %)
HCVF-tracts	Current	198 340	-	6 960	-	1 952	-
	Updated: by inserting all the CF of **0.7-1**	202 482	41 846 / 20.7%	7 564	682 / 9.0%	2 992	79 / 2.6%
	Updated: by inserting all the CF of **0.4-1**	205 150	118 880 / 57.9%	13 430	50 361 / 375.0%	4 028	13 123 / 325.8%

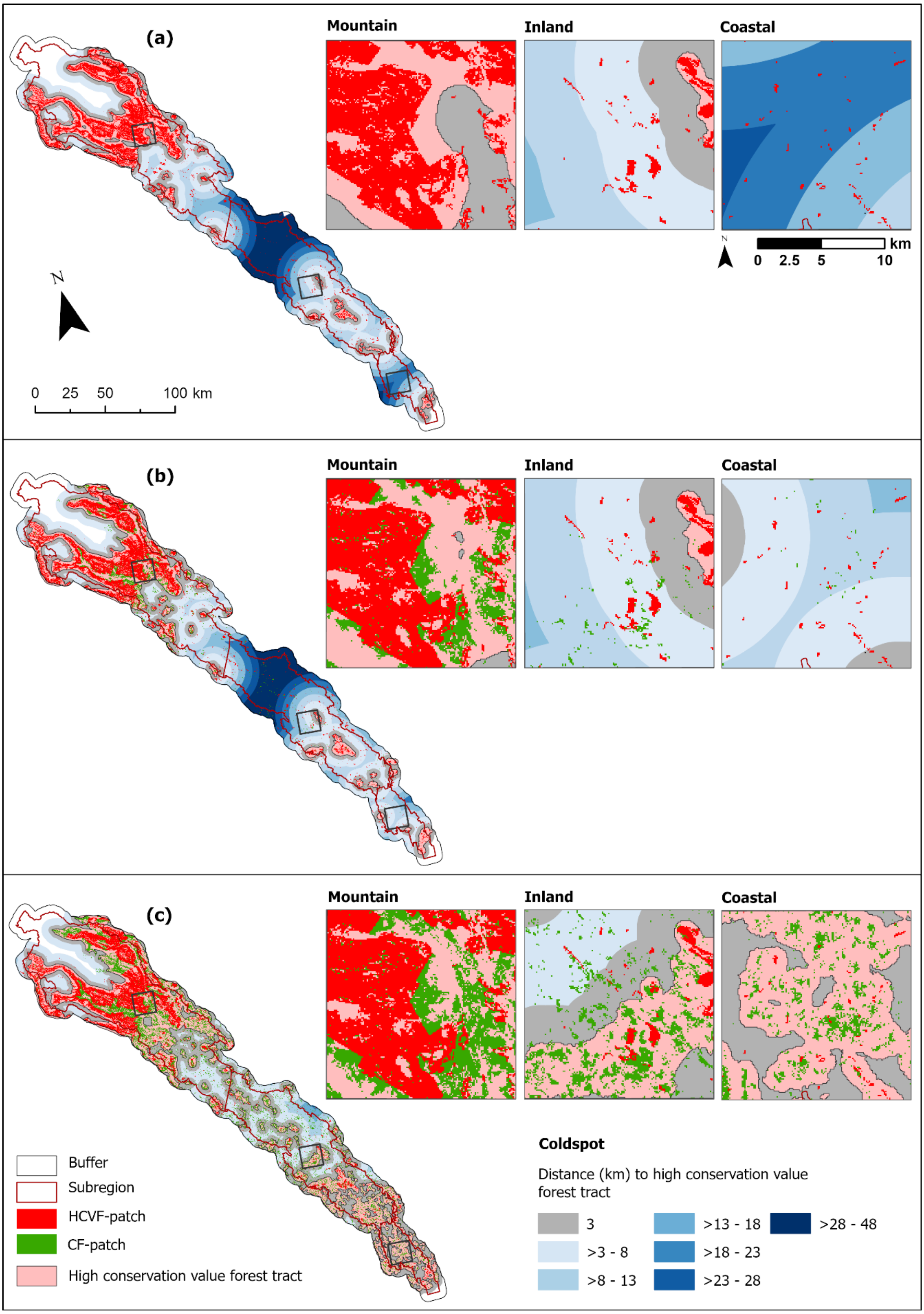

Figure 15. High conservation value forest tracts (HCVF-tracts), identified according to the criteria/procedures used by Metria AB (Bovin et al., 2017) and restoration hot- and coldspots.

(**a**) HCVF-tracts based on the current HCVF dataset.

(**b**) HCVF-tracts after inserting the continuity forests (CF) of nested relative likelihood (RL) classes 0.7-1.

(**c**) HCVF-tracts after inserting continuity forests (CF) of nested relative likelihood (RL) classes 0.4-1.

Hotspots:

Restoration hotspots identified as the inserted CF-areas (in green) within 1) the HCVF-tracts (the areas in light red) and 2) the 3km buffer zone (in grey) enclosing the HCVF-tracts. The inclusion of the 3km buffer zone was because the HCVF-tracts were identified based on GI-density filtered by the moving window of, maximum, 3km radius, and thus any input of CF within this 3km buffer could have impacted the appearance/distribution of the HCVF-tracts.

Coldspots:

The areas with varying blue shades represented the restoration cold-spots/cold-sections. The darker the blue shade, the colder the spot/land-section.

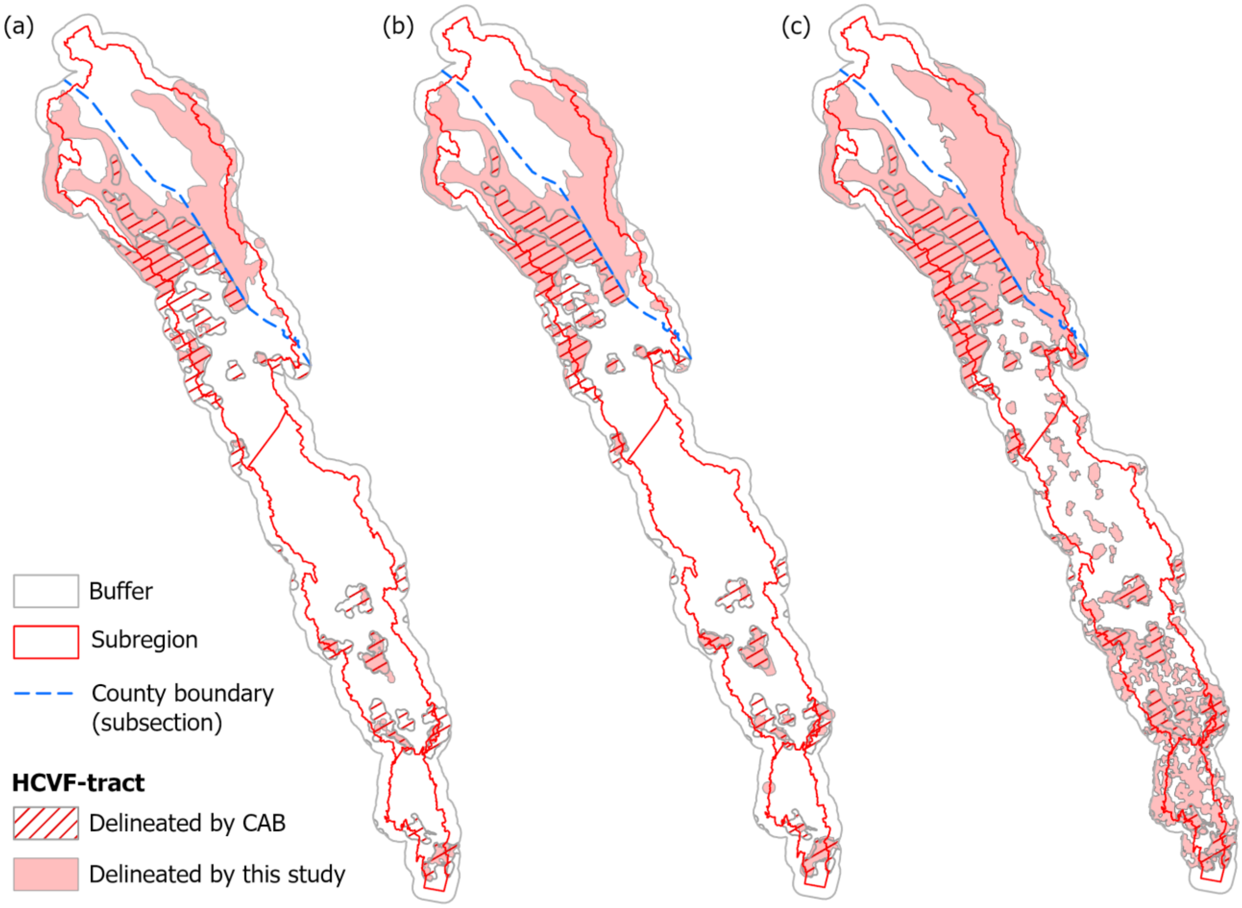

Figure 16. Comparison of the high conservation value forest tracts (HCVF-tracts) identified by this study and by the County Administrative Board of Västerbotten.

(**a**) The HCVF-tracts delineated based on the current HCVF data.

(**b**) The HCVF-tracts delineated after inserting the connectivity forests (CF) of nested relative likelihood (RL) classes 0.7-1.

(**c**) The HCVF-tracts delineated after inserting the connectivity forests (CF) of nested relative likelihood (RL) classes 0.4-1.

4. Discussion

4.1 Overview of the results

Planning and implementing GI is highlighted in Europe and in Sweden to halt biodiversity loss and secure functional forest ecosystems (EC, 2013; Hermoso et al., 2020). A common understanding is that large enough areas of representative forest habitats have not been protected, and that the spatial distribution of protected areas needs to be improved to maintain connectivity (Angelstam et al., 2020; Mikusinski et al., 2021). In Sweden, the HCVF database in combinations with other publicly available datasets provides a basis for further assessments.

Using a recently developed AI-model that predicts relative likelihood for HCVF occurrence over the forestland in Sweden, this study explores the potential to map connectivity forest as a way forward to establish a GI across an extended geographical gradient from the coast to the mountains in northern Sweden. Connectivity forests (CF) are forests with intermediate to high model-predicted relative likelihood (RL) that through restoration will support GI-functionality. With the extensive forest landscapes transformation that has resulted from industrial forest management, in Sweden and elsewhere (Curtis et al., 2018; Haddad et al., 2015), restoration is generally needed as a components in sustainable forest landscape management and governance (Angelstam et al., 2020; Chazdon, 2018; Mikusinski et al., 2021; Sayer, 2009; Svensson et al., 2020).

Under this background, this study assessed the effect of step-wisely restoring the CF on the GI construction over the boreal forest landscapes in the study area. The main findings are:

1) Across the three subregions, the majority of the CF was found in the mountainous subregion, formed mainly by the broadleaved and spruce forests. However, the respective CF over the inland and coastal subregions accounted for about 13% and 11% of the total forest areas within the corresponding subregions, which is also rather considerable in a subregional context.

2) The stepwise insertion of CF expanded the GI areas in all three subregions. After inserting all the prescribed CF, the total GI-area was increased by over 60% in the mountainous subregion, and by over 400% in both the inland and coastal subregions. The CF-insertions also decreased the proportion of broadleaved forest in the mountainous GI and increased the proportion of pine forest in inland and coastal subregions.

3) After each CF-insertion, the GI-density median was increased by a higher extent in the mountainous than in the other two subregions. However, the density median increase achieved upon per unit CF area input was lower in the mountainous subregion, than in the inland or costal subregion. Such correlation pattern of CF-input and density increase also held for three concerned forest types, i.e., spruce- , pine- and broadleaved (co-)dominated forest.

4) The CF-insertion increased the area of functioning habitat (i.e., area with a GI-density ≥ 20%) from 25% in the baseline GI to 40%. However, these functioning habitats were mainly strengthened in the mountainous subregion and maintained by broadleaved and spruce (co-

)dominated forests. The functioning habitat areas in the inland and coastal subregions and/or maintained by pine (co-)dominated forest, were increased marginally by the CF-insertions.

5) The CF-insertions significantly extended the HCVF-tracts, i.e., the prioritized area in practical conservation works by the authorities and added a substantial amount of restoration hotspots that could assist decision-making in the GI planning and management.

The interpretation and discussion of these findings will not only support the restoration planning over V-J, but also the GI constructions in boreal regions having similar geo-nature properties and conservation status.

4.2 Considerable amount of forest with high restoration value found in all subregions

This study suggests that a substantial amount (130 444 ha) of additional forests in the study area have the potential to be integrated into the restoration. This equals approx. 17% of the total forest area. These estimates and the ones in earlier studies (e.g., Svensson et al., 2020; Mikusinski et al., 2021) based on the proxy Continuity Forest dataset, pCF (Ahlcrona et al., 2017), commonly suggested a huge restoration potential among the forest areas outside the current HCVF. It is worth mentioning that compared to the pCF, the model prescribed a more conservative amount of forest with potential conservation/restoration values, which is considered an advantage since the pCF was likely to have an overestimation problem (Mikusinski et al., 2021).

In line with the spatial patterns found in pCF by Mikusinski et al. (2021), these model-prescribed forest resources (i.e., CF) also displayed a highly unbalanced spatial distribution along a north-western to south-eastern gradient, with a much lower amount of CF found in the south-eastern inland and costal subregions. This could be a consequence of the higher scale of anthropogenic alterations over these lowland boreal landscapes, characterised by forestry intensification (Heino et al., 2015; Jonsson et al., 2019), since production and conservation are heavily competing processes in Swedish forest management, as advocated by a case study by Naumov et al. (2018).

Nevertheless, the respective amount of CF within the inland and costal subregion accounted for 12.5% and 11.4% of the total forest areas in the corresponding subregion, which could be considered a rather high share in a subregional context. Such proportions become even higher when separating the CF into different forest types. For example, in both inland and coastal subregions, the accumulated amount of inserted spruce accounted for over 20%, relative to the total amount of spruce within the respective subregion.

Thus, this study argues that, though much less than the corresponding value in the mountainous subregion, the total amount of CF found in the inland and costal subregions was still considerable. As the current protected areas in these regional are small and fragmented (Svensson et al., 2020), this CF-potential indicates opportunities to expand the GI.

Further, through assessing the amount of CF by separate forest types, this study added the information that these two subregions could have higher potential for restoring certain forest type(s), assessed by the model-prescribed total amount of CF of the same forest type(s). After all the prescribed insertions, the inland subregion contributed more pine-dominated areas into the updated GI than that by the mountainous subregion (10.2% versus 6.4% of the total pine forest in V-J, see Appendix 6). Such phenomenon also suggested that the assessment of areal resource availability based on all forest, could not fully speak for the status concerning a specific tree species or forest type.

It should be noted, however, that the model prediction was not explicitly validated along the mountain-coast bio-eco-geographical gradient, nor upon specific forest types. Therefore, the estimation of CF specific to this study, across different subregions and forest types, could be associated with unknown errors.

4.3 Subregion-specific effect achieved by the CF-insertion

Over the whole study area, the insertion of CF has clearly increased the total area of GI and improved the generic structural connectivity, proxied by the increased density and size of the GI-patches. However, examined on a subregional scale, i.e., within each subregion of this study, the CF-insertion seems to have sub-regionally different effect.

4.3.1 Insertion of CF further strengthened the Mountainous subregion's pillar role

Both the baseline and each updated GI relied heavily on the mountainous forest. Compared with the other two subregions, the mountainous subregion presented a much higher concentration of GI-patches and was also the only subregion where the very large (>10 000 ha) GI-patch appeared. Further, the total area of these very large patches even increased as the insertion continued.

This is not surprising, since this mountainous subregion located among the Scandinavian Mountain Range, where the forest landscapes maintained largely continuous and intact (Svensson et al., 2020) due to the low impact of modern forestry, shielded by its low accessibility and an earlier settlement of conservational measures (Angelstam et al., 2011). Also because of the vast existence of this “green belt” (Svensson et al., 2020), the spatial configuration of GI over the whole Fennoscandia was heavily geared toward the mountainous area (Angelstam et al., 2020). In this study, the insertion of CF certainly reinforced such pattern over the study area since the majority of the CF were allocated in the mountainous subregion.

Such reinforcement is favourable considering that: 1) the GI formed over the mountainous area is pivotal for maintaining the biodiversity and connectivity of the whole boreal biome (Svensson et al., 2020) and 2) the forest landscapes, preserved in the mountainous area as fundamental GI-components, are receiving an increasing pressure of clear-cutting, especially at the foothills (Svensson et al., 2020).

However, this study suggested a lower input-output ratio in the mountainous subregion, in the sense that the GI-density increase achieved upon per unit area insertion of CF was lower in this subregion than in the inland or coastal subregion. For example, in the end of the insertions (i.e., after inserting all the CF of nested RL-classes 0.4-1), the total amount of CF inserted into the mountainous subregion was much higher than that into the inland and coastal subregions, however, the resulted GI-density increase was only moderately higher than that of the other two subregions. This phenomenon is further discussed in Section 4.3.3.

4.3.2 Marginal effect on counterworking the unbalanced subregional representativeness

This study displays an overall improvement of both amount, density, and patch size over the inland and coastal subregions, achieved by the prescribed CF-insertions. Some most evident improvements are: the major connectivity gaps found all over these two subregion in the baseline status, resulted from non-existence of any GI-patch, were gradually eliminated with the stepwise insertion of CF; and the area of the GI-patches continuously increased and some larger patches could, in the inland subregion, eventually exceed 10 000 ha per patch.

During the 20th century, the Inland and coastal areas in the central boreal Sweden have undergone the strongest anthropogenic landscape reconfiguration among the whole Swedish boreal landscapes (Svensson et al., 2022). These newly input GI-patches due to the CF-insertions could, then, function as local connectivity hotspots in these two subregions and thus support the subregional and even regional GI construction; simultaneously, establishment of these new GI-patches could, to some extent, counterwork the highly unbalanced spatial configuration of GI. However, with the prescribed extent and manner of CF-insertions, the effect of rebalancing the spatial representativeness of the regional GI was rather marginal. In the inland and coastal subregions, the density and patch size of the updated GIs were nothing comparable with the those in the mountainous subregion. These phenomena are both a sign and a consequence of the excessive forest extraction over these two subregions (Angelstam et al., 2020; Mikusinski et al., 2021; Östlund et al., 1997; Svensson et al., 2019a).

4.3.3 Stronger responsiveness to the CF-insertions in inland and coastal subregions

Compared with the mountainous subregion, an overall stronger responsiveness to the CF-insertions was displayed over these severely fragmented landscapes in the inland and costal subregions.

First, with the stepwise insertion of CF, the inland and coastal subregions exhibited, in general, a greater extent of GI-area increase compared to the mountainous subregion. After the final insertion, both the inland and coastal subregions achieved a striking 400% increase in GI area on top of their respective baseline GI areas (represented by the HCVF), which is in stark contrast to the corresponding 60% increase observed in the mountainous subregion. Such high responsiveness could be, at least partially, explained by the very poor baseline status in these two subregions. Even a small additional input of CF-areas could potentially induce drastic increase in relative forms (i.e., area percentage).

More importantly, when linking the increase of the median GI-density values to their corresponding total amount of inserted CF-areas, a higher per unit area density-improving effect was quite clearly displayed in the inland and costal subregions, meaning a less input of additional CF-areas could generate a relatively higher level of density increment. This higher efficiency of GI-density increase was even more evident across the updated GIs in the coastal subregion.

Similar response, i.e., higher conservation-contributing capacity over smaller patches, has been documented in recent years among the severely fragmented landscapes globally, from the habitat debris remained in the heavily deforested Amazon (Giannichi et al., 2020) to the smaller woodlands scattered over the agricultural landscapes in the European temperate forest biome (Valdés et al., 2020). Compared with larger patches, those smaller areas showed a higher performance in delivering various ecosystem services (Giannichi et al., 2020; Riva et al., 2022; Valdés et al., 2020), probably due to their capability of maximizing the total conserved areas in a severely fragmented landscape (Giannichi et al., 2020) and the positive edge effect (Valdés et al., 2020).

4.4 Dominant forest types had contrasting representativeness in the concerned GIs

One essential functionality of GI is to safeguard habitat network with sufficient size and connectivity for the featured species (Mikusinski et al., 2021). Over a given landscape, the higher the GI-density and the larger the size of GI-patches, the better the preconditions are for maintaining habitat and biodiversity (von Friesen & Uppsäll, 2016). In this light, this study also assessed the effect of the CF-insertions from a functioning habitat network point of view, through assessing the GI-patches fulfilled the assumed minimum density proxy, i.e., 20%.

Since the habitat in the mountainous region was already well-functioning in the baseline status (Svensson et al., 2020), the addition of functioning habitat patches to the inland and coastal subregions signals an opportunity to establish a well-functioning habitat network throughout the entire study area. By examining the forest composition of these habitats, it was clearly shown that the already well-functioned habitats found in the mountainous subregion were maintained by broadleaved forest at higher altitudes and spruce at lower altitudes. In contrast, the newly emerged functioning patches over the inland and coastal subregions were mostly maintained by pine forest. Therefore, we would argue that restoration of pine forest is critical for re-establishing ecological connectivity among the studied landscape in terms of a functional GI at the whole watershed scale.

The question is, then, whether these new habitat patches, added by the CF-insertions, could adequately represent the natural distribution, share and conservational significance of pine forest. Numerous studies have suggested the current HCVF provided different extent of support to different species (e.g., Angelstam & Andersson, 2013) and some forest types might be largely ignored (Angelstam et al., 2020; Nilsson & Götmark, 1992). This study suggests that this might be the case with pine forest. Considering the dominance of pine forest over the inland and coastal subregions, we would, naturally, expect a much better habitat functionality status similar to, e.g., the status displayed by broadleaved forest in the mountainous subregion (see Fig. 2(right) for tree species dominance over V-J) .

The natural variation in forest composition is shaped by the interplay of disturbance regimes, soil conditions and topography (Kuuluvainen et al., 2017); and thus could be highly spatial specific. Though still debatable, the pine forest seems to dominate naturally over the landscapes outside the mountainous area in V-J, since the historic fire disturbance regime (Axelsson & Östlund, 2001) and the "large number of sand heathlands and ridges in the forest landscape" (Gardeström et al., 2016) over the region strongly favoured the natural regeneration and development of pine (Gardeström et al., 2016). A reconstruction of the pre-industrial forest landscape, in the close neighbourhood of the inland subregion of this study but on a much smaller scale (i.e., Lycksele Parish), also confirmed the dominance of pine, at least since the early phase (1890s) of modern forestry (Axelsson & Östlund, 2001).

If pine forest naturally dominates the inland and coastal landscapes and if the conservation or restoration goals could be refined by, among other, the analogue of the natural or pre-industrial status of forest landscapes (Axelsson & Östlund, 2001), this study argues for a more urgent necessity of restoring pine forest, compared with the spruce and broadleaved forest. Both spruce and broadleaves have a much better representativeness over the mountainous landscapes where they naturally dominate.

More importantly, pine forest in the boreal biomes represents a high biodiversity value as well as a core habitat of the Sami livelihood and cultures (Berg et al., 2008; Kuuluvainen et al., 2017; Rikkonen et al., 2023). As a typical example, a rich diversity of lichen flora is harboured in the older, more open pine-dominated forest (Sandström et al., 2016), which is a critical winter-grazing resource for the traditional Sami reindeer husbandry (Sandström et al., 2016).

It should be addressed that, though calling for more attention on pine forest in the GI-planning, this study fully acknowledged the anthropogenic impact on the habitats maintained in broadleaved and spruce forest. As a matter of fact, the industrial forest production has modified the distribution, amount and structure of both pine, spruce and broadleaved forest (Hellberg et al., 2009), with clear-cutting, instead of fire, being the most prevailing factor of reconfiguring the forest landscape (Axelsson & Östlund, 2001). Consequently, the respective proportion of spruce and broadleaved species was lower than it should be (Sandström, 2018); the amount of functioning habitat networks within spruce and broadleaved forests are continuously shrinking (Angelstam & Manton, 2021); and the scarce of broadleaved-associated habitats, are considered "the most pressing GI challenge" (Mikusinski et al., 2021). In the case of V-J, the barely existed habitat patches outside the mountainous subregions could also be thought as "a net result of an intensive forestry" (Mikusinski et al., 2021).

4.5 Challenges encountered in fulfilling multiple conservation goals

The EU Biodiversity Strategy to 2020 (2011-2020) set a target for legally protecting 26% of the EU's terrestrial area (EC, n.d.-a). This goal was achieved at the EU level since 26.4% of the EU's land area was protected in 2021, where Sweden designated 14.1% of its land as protected areas (EEA, 2023). However, as a signatory of the United Nation CBD Aichi target#11 (CBD, 2020), Sweden also committed that at least 17% of the country's terrestrial areas shall be protected and conserved by 2020; at a domestic level, this goal has even been lifted to 20% by the Swedish government's Strategy for Biodiversity and Ecosystem service (Angelstam & Manton, 2021). Simultaneously, these policies emphasized that these quantitative goals understand functional connectivity, represented by a fully functioning habitat network with habitat patches of sufficient size and density fulfilling the requirement of the concerned species (Angelstam & Manton, 2021; Mikusinski et al., 2021). These goals were adopted in the action plan of Västerbotten County (von Friesen & Uppsäll, 2016).

The current GI was declared as "well-developed in larger parts of V-J" (Gardeström et al., 2016); this might be the case when assessing the whole study area, despite the contrasting forest compositions and bio-geo-ecological properties among this landscape. Measured by the areal size, the total HCVF is already above 17% in the baseline status without any insertion of CF, though not all the HCVF were formally protected. This value is consecutively increased by the stepwise insertion of CF. Even when considering jointly the functioning connectivity (indicated by a threshold density of 20%), an overall rather well-preserved habitat network was also found in the baseline as well as each updated GI.

However, as discussed in the previous sections, the seemingly good situation on such a "global" scale relied heavily on the intact forest landscapes preserved in the mountainous subregion; and the pictures could be much less satisfying when zooming into the landscapes outside the mountainous area and focusing separately on different forest types. In some cases, the discrepancies in size and/or functional connectivity were so large that the insertions of CF, at the prescribed scales, could only generate a marginal effect, such as the scarce of the functional habitat network provided by pine. Yet, such subregion or species-specific discrepancy is not unique to V-J, but rather a biased ecological representativeness of GI on a much broader spatial scale (e.g., over boreal Sweden) (Angelstam et al., 2020) that also shadowed V-J, as a consequence of long-time forest intensification (Angelstam et al., 2020; Angelstam & Manton, 2021; Mikusinski et al., 2021; Svensson et al., 2020). Under these circumstances, it seems that, beyond the dues of those policies (i.e., 2020), the conservation goals have not been fully achieved, at least not at the inland and costal subregions, and not for all the major forest types.

Considering that in total, the prescribed insertion of CF involved a quite substantial amount of additional forest areas, i.e., 17% of the total forest areas over V-J (equivalent to 130 444 ha), the mismatch with the conservation goals might imply that a restoration based solely on area expansion does not work very effectively, and the actual restoration work should be tactically planned, emphasizing the structural and quality improvement of the targeted forest areas.

4.6 Goal refinement and localised plan through HCVF-tracts and identified restoration hotspots

Goal refinement and regionalisation are of utter importance for more relevant and cost-efficient conservation gains (Axelsson & Östlund, 2001). The delineation of the HCVF-tracts was considered an "object, simple and effective" (Bovin et al., 2017) manner in solving these tasks. This study, by projecting two sets of updated HCVF-tracts for V-J, clearly delivered the future scene that could possibly be expected over the featured landscape. Considering that the HCVF-tracts are important information sources for authorities' practical works and that they are even, sometimes, referenced in planning voluntary set-aside areas in, e.g., Västerbotten County (Bovin et al., 2017; von Friesen & Uppsäll, 2016), these projected HCVF-tracts could powerfully assist the relevant policy- and decision-makings.

More importantly, the projections, based on the continuous feature of the model-predicted conservation likelihood values, visualized the transitioning of conservation hot- versus coldspots along the course of the CF-insertions, and pinpointed the key forest patches/stands most directly linked to the dynamic of HCVF-tracts. This is a unique feature that could hardly be achieved with the mainstream datasets used in relevant assessments, e.g., the pCF (Ahlcrona et al., 2017). Therefore, the projections provided in this study could be taken as a step forward in the development of the much-needed landscape plans that are able to explicitly specify the amount and location of the additional conservation/restoration areas (Felton et al., 2020; Mikusinski et al., 2021; Snäll et al., 2016).

Compared with the current status, a most prominent improvement shown in the projections is the expansion of the HCVF-tracts. Since the underlying rationale for HCVF-tracts, by essential, is that biodiversity can be better conserved as increased habitat size and decreased habitat isolation (Bovin et al., 2017; von Friesen & Uppsäll, 2016), such area expansion of HCVF-tracts, also represents an overall improved habitat network functionality.

Furthermore, with the stepwise insertion of CF, the HCVF-tracts became somewhat more evenly distributed over V-J, indicating a strengthened and more balanced subregional representativeness of GI, a desired effect that has been discussed in the previous sections. In response to this improved subregion representativeness, the cold-spots or landscape sections, found mostly in the inland and coastal subregions, were gradually minimized. The projections suggested, further, that to achieve an overall coldspot-eliminating effect, a restoration scale targeting all the CF with an $RL \geq 0.7$ should be considered.

It should be noted that, 1) the HCVF-tracts are not species-specifically delineated, which could be a major deficiency concerning the actual guidance effect of the HCVF-tracts (Bovin et al., 2017); 2) due to the differences in data input and involved criteria, the HCVF-tracts delineated in this study and the ones produced by the CAB of Västerbotten could not be fully compared, which could account for some of the non-overlapping parts in the comparisons.

For example, though the data inputs used by the CAB of Västerbotten were from a wider resource, the non-productivity forest was not included in the output. These non-productivity areas, however, could also harbour high conservation values for, e.g., lichen species (Josefsson et al., 2010).

4.7 Implications for restoration and GI-planning in V-J

The unknown areas with high conservation values need to be further identified and assessed, and when possible, restoration need to be applied to places with major conservation gaps or where an improved functionality is expected (Angelstam et al., 2011, 2020; Mikusinski et al., 2021). Such tasks should be "of urgent priority" (Svensson et al., 2020), especially in the context that Sweden is much delayed in meeting its conservation goals and thus the biodiversity and the extensive ecosystem functionalities preserved in its boreal forest landscapes are being further threatened.

This study assessed the effect of restoration based on model-prescribed forest areas with high conservation value and thus, detected some gaps and phenomena that probably should be aware in the regional GI-planning. These gaps and phenomena, mostly already been discussed in the above sections, will be synthesized, and further addressed in the following text.

1. Improve the representativeness of the inland and costal forest landscapes and address also the habitat maintained in the pine forest

GI should be planned at all administrative levels, over "the whole landscape" (Bovin et al., 2017) and established "as evenly as possible" across various spatial scales to ensure the representativeness of the conserved areas (Hanski, 2011; Rodrigues et al., 2004). Unfortunately, this is not the case in V-J, where the conserved forest areas are mostly located in the mountainous subregion, characterized by "a high-altitude and low-productivity forest ecosystem" (Andersson & Östlund, 2004; Fridman, 2000), an epitome of the biased ecoregion representativeness over a vast spatial extent in boreal Sweden.

While fully acknowledging the "mainland source" (Svensson et al., 2020) role of the mountainous GI to the biodiversity and ecosystem functionality on the whole boreal region in northern Europe, this study is in line with the previous ones (e.g., Svensson et al., 2019) calling for more effort on improving the representativeness of the inland and coastal subregions in the future GI-planning. As suggested by this study, such effort could benefit these two regions with, most prominently, increased density and size of GI-patches, strengthened habitat networks and enlarged HCVF-tracts. In the meantime, a GI configuration inclining toward the inland and coastal subregions, could intrinsically ensure a better habitat network conserved for the pine-dependent species and cultures, such as the reindeer and the traditional Sami reindeer herding (Berg et al., 2008; Rikkonen et al., 2023). The Sami culture with reindeer herding is an essential aspect for the study area as a UNESCO biosphere reserve. In addition to the assumably higher per area conservation/restoration value, the smaller patches also deliver high recreational and tourism values (Fredman &

Emmelin, 2001; Jonsson et al., 2019), among a landscape heavily reshaped by intensive forest productions. The considerable amount of model-prescribed forest areas with high restoration potentials indicated that these projected effects are not unachievable, resource-wisely.

The results of this study also demonstrate that to achieve an overall more "visible" progress in counterworking the severely biased GI representativeness, the inland and coastal areas should consider all the CF with an RL $\geq$ 0.7 or even 0.6, corresponding to 3 068 and 10 058 ha of additional forest areas as a minimum restoration scale (calculated collectively over inland and coastal subregions).

As suggested by this study, a GI-planning with more focus on the inland and coastal subregions, could be somewhat more cost-efficient. The improved GI status over these two subregions were achieved upon much less additional input, in terms of forest areas, compared with that in the mountainous subregion. This point will be further addressed in the following text.

2. More focus on local/stand scale and smaller forest patches

It is undeniable that biodiversity and habitat are best conserved in "really large and spatially connected areas" (von Friesen & Uppsäll, 2016) and the capacity of smaller conserved forest areas in providing habitat may depend on the quality and functionality of their surrounding matrix (Angelstam et al., 2020; Orlikowska et al., 2020). Still, this study calls for more attention on those patches smaller in size and scattered over the heavily modified forest landscapes in, e.g., the inland and costal subregions, which tended to be neglected in current GI-plannings.

As discussed in Section 4.3.3, the smaller patches, found in the inland and costal subregions, displayed higher unit area capacity in improving the GI-densities, and thus a possibly higher return of "investment". The economic benefit associated with smaller GI-components has been documented in, e.g., watershed management: a benefit-cost ratio assessment proved that implementing numerous small-sized GI-facilities (i.e., rain garden) greatly lowered the cost of stormwater treatment (Heidari et al., 2022). Similar analyses, featuring economic cost and gains across various spatial scales, are much needed in the GI-planning over the forest landscapes.

Besides, strategically integrating the smaller patches/stands into the GI-planning could help achieve localised conservation benefits, which is important since multiple studies have addressed that the effect of conservation/restoration could be scale-dependent (Angelstam & Manton, 2021; Felton et al., 2020). Thus, an overall positive effect on a broader scale (e.g., regional) doesn't necessarily guarantee the positive change on, e.g., local and stand scale.

In this study, the restoration hotspots pinpointed on the updated HCVF-tracts, could, therefore, serve as the starting points of the restoration/conservation-oriented field investigations.

3. Effective restoration incorporating diversified forest management

The model prediction in this study and some previous assessments based on the pCF, commonly suggested that a substantial amount of forest areas, outside the current HCVF, are associated with high conservation/restoration values. However, it should be noted that this is rather an idealised estimate than a true reflection of the reality. The actual “availability” of these areas could be much questioned. As a matter of fact, over the studied landscape where forestry plays a fundamental socioeconomic role, one biggest hinder for the restoration work is, as clearly pointed out by Angelstam et al. (2011) and Hanski (2011), that there is simply not much forest left to be set aside for conservation/restoration purpose, especially the larger continuous areas. As addressed by many (e.g., Mikusinski et al., 2021), GI-planning does not exclude forest production and land use.

Clearly, an area-preserving based restoration and GI-planning strategy will, inevitably, involve more forest production land (Jönsson et al., 2009). How to strategically address the potential conflict in land use and balance the restoration work against production, economic and social considerations is, a most challenging question in GI-planning, which is beyond the scope of this study. Nevertheless, the results of this study could, at least, suggest that, 1) those small-sized restoration hotspots identified over the coastal and inland areas might associate with higher cost-efficiency, which has also been mentioned in the first point of this section; and 2) a restoration strategy based on passively preserving relevant areas might hardly be goal-achieving, since the prescribed insertions in this study mimics actually a scenario of restoring an additional 17% of the total forest areas.

This study is in line with numeric studies that addressed the implementation of diversified forms of conservation and forest management (Angelstam & Andersson, 2001). Such as the well-known “third-of-third” approach (Hanski, 2011) (i.e., a third of the multi-use conservation landscapes, integrating both conservation and production and accounting for, roughly, a third of the total land area, should be protected), proposed to address the urgent necessity of conservation over the much-exploited landscapes. Addressing the necessity of restoring pine-dominated forest areas over V-J, it was suggested that a multi-aged pine forest with setting aside areas for ecological restoration, could possibly be achieved by selective harvesting and simultaneously strategic fire management (Axelsson & Östlund, 2001). All in all, as concluded by Felton et al. (2020), if diversified forestry practices are more widely adopted, the need for additional conserved forest areas might be reduced.

4.8 Limitations of this study and future work

Some limitations of this study

- The results of this study depended a lot on the chosen threshold values, such as the RL threshold of 0.4 and the density threshold of 20%. However, the contrasting bio-geo-ecological context and anthropogenic impact level between the mountainous and the non-mountainous (inland and coastal) areas, all imply that this threshold values should be tailored to a specific subregion and/or forest type, to generate refined and more indicative assessments.

- In interpreting and discussing the results, the current/baseline status was mostly compared with the "final" GI, which is the GI achieved after inserting all the prescribed conservation features. However, this approach cannot effectively represent the dynamics of GI as it transitions, and the properties of each updated GI have not yet been fully explored. Furthermore, the effective discretization of the connectivity forest during the stepwise insertion process is a question that remains to be discussed.

- In many cases, the interpretation and discussion of the results did not differentiate between the inland and coastal subregions. However, as demonstrated in this study, the current state of GI in these two subregions varies in terms of, e.g., area and density, and the effects of CF-insertions on these subregions also differ. Therefore, the findings of this study may have different implications for restoration and conservation efforts in the two subregions.

Future work

This study provides a foundation for further research and improvement. In future work, I plan to conduct a landownership analysis of the conservation feature areas and/or the baseline and updated GIs, specifically targeting the smaller forest patches in the inland and coastal subregions. Such analysis is expected to yield valuable insights for local and regional forest management and conservation operations. Additionally, it is recommended that future studies utilizing the implication of KubAI address the limitations mentioned in this study or find ways to effectively minimize them.

5. Conclusion

This study proposed an innovative restoration approach based on AI-model prescribed CF, i.e., the non-HCVF forest areas with model-predicted high conservation likelihood. The spatial size and distribution of these CF areas were analysed and the effect of step-wisely restoring the CF on the structural connectivity among the reconfigured GIs was examined. From these assessments, both some opportunities and challenges in the future GI-planning featuring the study area as well as the boreal Sweden were revealed.

This study demonstrates that the study area has good restoration potentials, since considerable amount of CF were identified by the model KubAI in all three subregions of the study area. By step-wisely restoring the CF, the current GI-area, represented by the HCVF, was consecutively expanded and the density of GI-patches was increased, indicating an overall strengthened GI with improved structural connectivity. However, adding the CF areas couldn’t effectively counter work the unbalanced spatial distribution of GI across the study area, which is concentrated in the mountainous subregion. In addition, the restoration of CF in this study has much better support for the habitats maintained by broadleaved or spruce forest than those by pine forest. The largely underrepresented pine forest across the GI in the study area is unfavourable since pine forest represents comprehensive values for, among others, Sami culture in the boreal region.

Due to the deficiency of GI in the inland and coastal areas and the underrepresented pine forest, this study concludes that the quantitative conservation goals, set by the EU Biodiversity Strategy to 2020, CBD Aichi target#11 and Sweden’s Strategy for Biodiversity and Ecosystem Services, are still not fully achieved across the entire studied landscape. The new EU Biodiversity Strategy for 2030, adopted in 2021, aims to protect 30% of the EU's terrestrial area by 2030 (EC, n.d.-b). Additionally, the ongoing negotiation of the CBD post-2020 global biodiversity framework also aims to endorse more ambitious conservation targets (OECD, 2019). Therefore, it is important to note that challenges in reaching these conservation goals will likely become increasingly significant if effective action is not taken.

Given that this study has restored an additional 17% of the total forest lands in the study area, it suggested a restoration regime solely based on passive area-preserves could hardly be goal-reaching and might face significant socio-economic challenges. Instead, diversified forest management approach with strategic integration of conservation/restoration efforts might be key to achieving functional GI. As demonstrated in this study, those forest patches, of combined or separate forest types, exhibited a higher per-unit-area capacity of increasing GI-density in the inland and costal than in the mountainous subregion. With adequate cost-efficient analysis and strategic management applied, these forest patches could provide an opportunity for GI-planning over these heavily transformed inland and coastal landscapes. Thus, this study highlights the need for greater attention on these smaller areas, which are often overlooked in current GI-planning and conservation/restoration efforts (Valdés et al., 2020).

Furthermore, this study localises two sets of restoration hotspots based on the CF-areas, corresponding to two restoration scenarios echoing intermediate versus high restoration ambitions. The hotspots could potentially function as the starting point of the future restoration practices.

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Supplementary

Appendix 1: A brief summary of KubAI's constitution of variables and data sources

The following information is based on the working paper presenting KubAI by Bubnicki et al. (2022, in rev.). Since this work is not publicly available at the time of publishing this thesis paper, detailed information about the KubAI model can be obtained by contacting Jakub W. Bubnicki at the Mammal Research Institute, Polish Academy of Science.

The model KubAI was developed to assess the naturalness of forests in Sweden using region-specific models for four biogeographical regions: the North boreal, South boreal, Hemiboreal, and Nemoral regions. Each region-specific model utilized a unique combination of variables, ranging from a minimum of 41 to a maximum of 45 variables, which represented forest naturalness across various dimensions and spatial scales. These variables included physical landscape features (such as elevation and slope), tree stand bio-physical structure (e.g., % of forest land, forest type diversity, forest height, and canopy gap fraction), and socio-economic factors related to human impacts on the forest (e.g., human population size and land pollution with night-time lights). For each region, the top six strongest explanatory variables were listed in Table A1.

The variables that were kept in the final models were selected from the originally over a hundred variables after a variable selection procedure. All the variables involved in the model training were extracted from six spatial datasets listed in below:

1. Swedish national HCVF dataset, which served as the source of information for forests with known high levels of naturalness (i.e., conservation values).
2. Swedish national landcover data, NMD, which provided information on forest types, forest height, forest productivity, and the category of non-forest land cover.
3. Digital elevation model (DEM) of Sweden.
4. Global Forest Change maps, which served as an information source for global forest loss during 2000-2020 and gain during 2000-2012.
5. A harmonized global night-time light dataset, which provided information about human impact.
6. Total population map in Sweden, which provided information about human impact.

Table A1. Top six strongest explanatory variables for each model in each region.

Variables	North boreal	South boreal	Hemiboreal	Nemoral
1	HG5v	HG5c	HANComb	BROADLEAF
2	HG5c	HANComb005	BROADLEAF	SLOPE
3	DEM	FOPEN	HG5c	HG5c
4	SLOPE	SLOPE	FOPEN003	SHAFOR
5	ROADS	DEM	FOPEN011	SLOPEv
6	FOPEN	HG5v	ROADS	AGRI011

HG5v: forest height, tree > 5m

HG5c: regionally corrected forest height, trees > 5m

DEM: elevation

SLOPE and SLOPEv: slope

ROADS: % of roads

FOPEN: % of temporary non-forest (logged) or young plantation (003 and 011 represents two spatial scales, at 0.3 km and 1.1km)

HANComb: % of merged forest loss (2000-2020) and gain (2000-2012)

BROADLEAF: % of broadleaf forest

SHAFOR: Shannon’s Index for forested areas only; forest type diversity

AGRI: % of agricultural areas

Appendix 2: RL-map over the study region

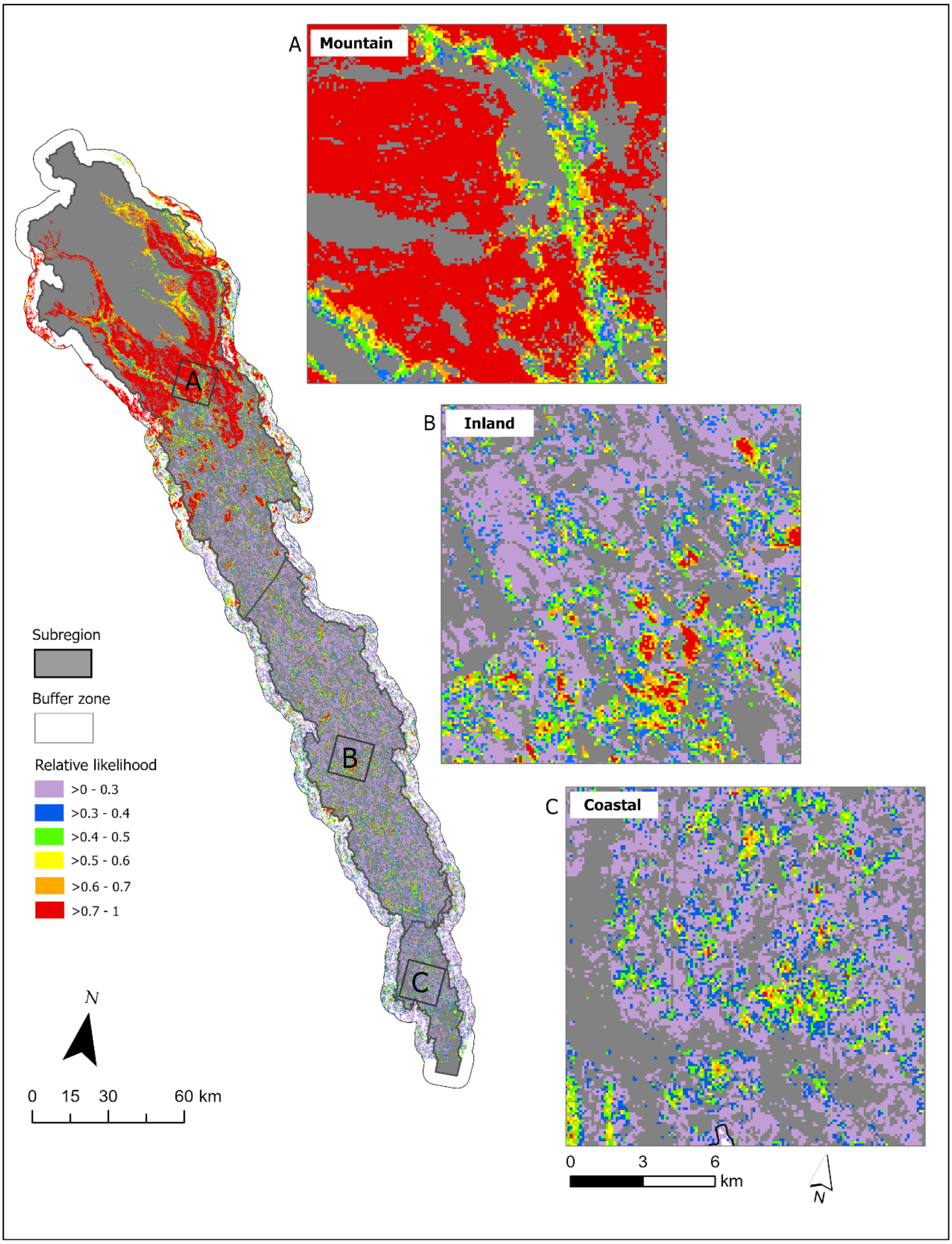

Figure A1. Relative likelihood (RL) map over the study area, rendered upon a grey background colour. The RL changes along a gradient of 0-1, and the higher the RL is, the greater the model-predicted conservation value is. The RL of 0-0.3 and 0.7-1 are classified into two groups, for visualization's purpose. A closer demonstration of the model prediction is shown, respectively, for three sample squares placed randomly in the three subregions (Mountain, Inland and Coastal); each sample square represents an area of 22 500 ha (15 × 15 km^2).

Appendix 3: Distribution of model-predicted relative likelihood

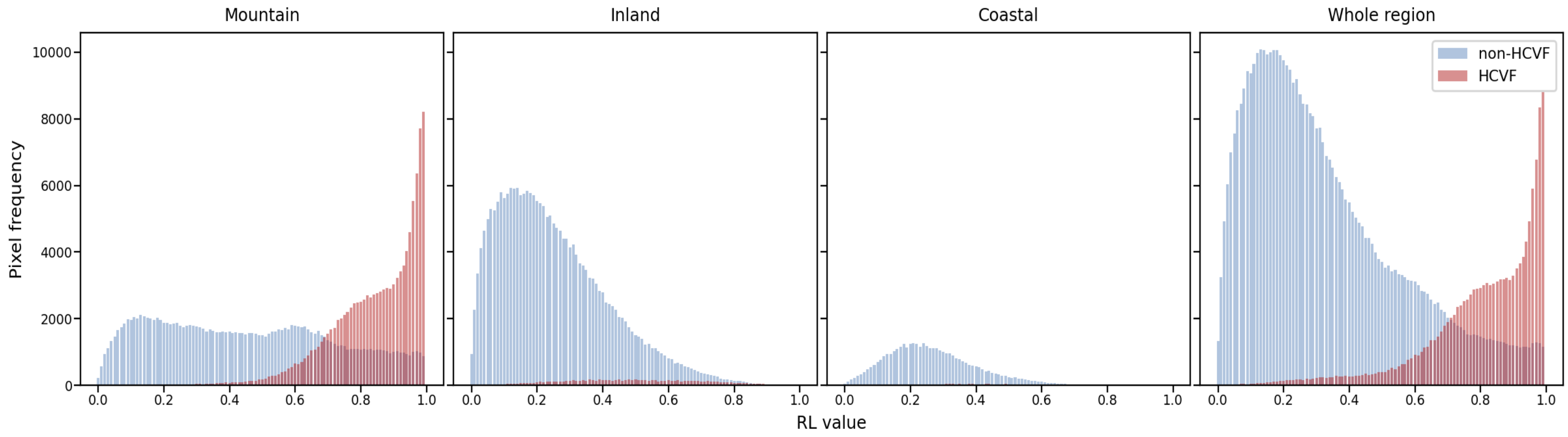

Figure A2. Distribution of model-predicted relative likelihood (RL) over the whole study region (“ Whole region”) and the three subregions (“ Mountain” , “ Inland” , “ Coastal”).

As shown in Fig. A2, the RL distribution contrasted largely between the mountainous and the rest two subregions. The HCVF within the mountainous subregion were, overall, associated with much higher RL-values than the other two subregions. About 3/4 of the mountainous HCVF areas showed an RL above 0.8, whereas in the inland and costal subregions, more than half of the HCVF areas displayed an RL below 0.5. The inland and costal subregions were dominated by non-HCVF areas with low RL (< 0.35), while half of the non-HCVF areas in the mountainous subregion were still associated with RL-values greater than 0.44.

Appendix 4: Methods of patch-size assessment over the GI of all forest

In addition to GI density, the size of the GI-patches was assessed as a secondary metric of the structural connectivity. A GI-patch referred to a contiguous cluster of pixels representing a subarea of GI, where the contiguity was valid between a focal pixel and its eight neighbouring pixels. The GI-patches were sorted into six size classes of ≤ 10, ≤ 100, ≤ 1000, ≤ 10000 and > 10000 ha, and the total area of each class was calculated, over the baseline as well as each updated GI. To maintain the contiguous area found by the boundary of the study area, the GI-patches were identified over the collective spatial extent of V-J and its 5km-width buffer zone.

It should be addressed that this study collected the patches of each size class from the original GI maps without moving window filtering. This was different from many habitat studies (e.g., Angelstam et al., 2020; Mikusinski et al., 2021; Svensson et al., 2019) where the patch-size analysis was applied to the output of GI density analyses, aiming for locating the habitat-patches fulfilling both the density and size requirements of a featured species . The density-independent patch-size identification of this study was because: 1) the patch-size was assessed as a secondary proxy of the structural connectivity status among the concerned GIs, rather than a metric of a detailed habitat examination for one or multiple species; and 2) aiming for delineation of the HCVF-tracts (Bovin et al., 2017), the window sizes used for filtering the GI density were much larger than those normally used for the habitat assessment over the boreal forest landscapes; and thus, the number of the GI-patches, counted over the output of density analysis, could be underestimated.

Reference:

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

Bovin M., Elcim, E., & Wennberg, S. (2017). Landskapsanalys av skogliga värdekärnor i boreal region (Preliminär slutrapport). Metria AB på uppdrag av Naturvårdsverket.

Mikusinski, G., Orlikowska, E. H., Bubnicki, J. W., Jonsson, B.-G., & Svensson, J. (2021). Strengthening the Network of High Conservation Value Forests in Boreal Landscapes. Frontiers in Ecology and Evolution, 8. http://urn.kb.se/resolve?urn=urn:nbn:se:miun:diva-41230

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

Appendix 5: Information box for delineating HCVF-tracts

Box. A brief description and comparison of data, criteria and procedures used by 1) Metria AB, 2) this study and 3) CAB of Västerbotten for delineating the high conservation value forest tracts (HCVF-tracts).

Criteria and procedures used for delineating HCVF-tracts

Metria AB

HCVF (retrieved in 2016-09)

Step 1: Use three moving windows of different sizes (radius = 1km/3km/5km) to filter the GI-density, respectively; from the resulted three GI-density maps, select and merge all the forest landscape subsections with a density value ≥ 20%.

Step 2: Separate the three GI-density maps into different nature-geographic (NG) regions (see the figure within this box); within each NG region, select the forest landscape subsections with the highest possible GI-densities, until the accumulated area of these subsections reaches 10% of the total forest area of that specific NG region. Merge the selected subsections with the subsections resulted from Step 1.

Step 3: identify the HCVF-tracts as the forest areas fulfilling simultaneously two conditions: 1) the total area of the subsections, identified through Step 1 and 2, should accounts for at least 5% of a single HCVF-tract and 2) the area of a single HCVF-tract should be no less than 1000 ha.

This study

- HCVF (retrieved in 2022-09)
- model-predicted CF

Following the above procedures by Metria AB, with two minor adjustments:

- In Step 1, the GI-density (≥ 20%) was filtered by a moving window of 1km or 3km radius (moving window of 5km radius was not used in this study).
- In Step 2, the "highest possible GI-density" within each NG region was taken directly from Metria's results (see the table within this box), no matter whether the area requirement of 10% was met or not.

CAB of Västerbotten

Major differences compared with the data and criteria/procedures used by Metria AB:

- The HCVF-tracts identified by the CAB of Västerbotten used more extensive and county-specific data sources concerning forest areas with conservation values, compared with the national HCVF dataset used by Metria.
- The identification by the CAB of Västerbotten featured only the productive forests, whereas the Metria output featured also the non-productive forests.
- The specific criteria/procedures used by the CAB of Västerbotten were different from the ones used by Metria; see von Friesen & Uppsäll (2016) for detailed information.

Table. The highest possible density value that could be found over at least 10% of the total forest area within each NG region. The table is a reproduction of that given by Bovin et al. (2017).

		Nature-geographic region				
		36	33	32	30	29
Threshold density value	1km radius	79%	57%	20%	7%	4%
	3km radius	61%	42%	18%	8%	5%

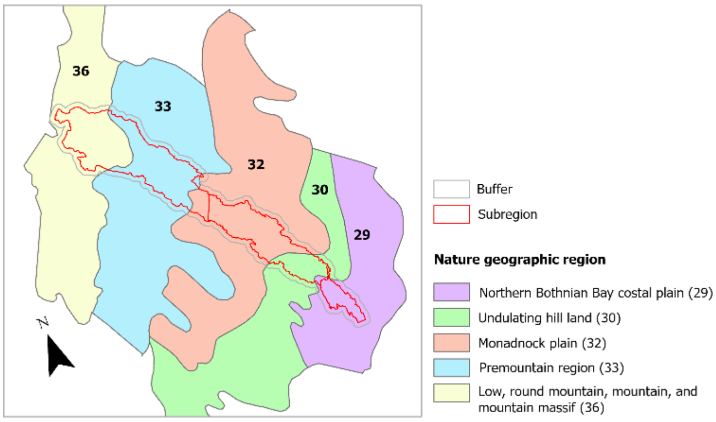

Figure. Nature-geographic (NG) regions involved in this study. The NG dataset (Naturvårdsverket, 2021) was retrieved from Miljödataportalen (https://miljodataportalen.naturvardsverket.se/miljodataportalen/) in Nov 2022; more information about NG region found at Miljödataportalen.

Appendix 6: Area statistics of the CF across nested RL-classes

Table A2. Area statistics of connectivity forest (CF), of all forest and per forest type, accumulated across nested relative likelihood classes (RL-classes) for the study area and the subregions; the percentages calculated based on the area of each forest type (including all forest as one type) in the whole study area or in each subregion.

Forest type	CF of nested RL-classes	Area (ha)			Area in % of total **regional** forest area			Area in % of total **subregional** forest area		
		Mountain	Inland	Coastal	Mountain	Inland	Coastal	Mountain	Inland	Coastal
All forest	0.9-1	9 318	42	0	1.23	0.01	0.00	2.62	0.01	0.00
	0.8-1	20 840	834	8	2.75	0.11	0.00	5.85	0.24	0.01
	0.7-1	31 298	2 962	106	4.13	0.39	0.01	8.79	0.86	0.18
	0.6-1	49 074	9 314	744	6.48	1.23	0.10	13.78	2.71	1.29
	0.5-1	63 851	19 704	2 256	8.43	2.60	0.30	17.94	5.74	3.90
	0.4-1	80 981	42 901	6 562	10.70	5.67	0.87	22.75	12.50	11.36
Pine	0.9-1	917	13	0	0.41	0.01	0.00	1.55	0.01	0.00
	0.8-1	2 329	449	3	1.03	0.20	0.00	3.92	0.31	0.01
	0.7-1	3 695	1 636	59	1.63	0.72	0.03	6.23	1.13	0.27
	0.6-1	6 248	5 019	404	2.76	2.22	0.18	10.53	3.45	1.86
	0.5-1	9 355	10 572	1 148	4.13	4.67	0.51	15.77	7.27	5.29
	0.4-1	14 527	23 181	3 251	6.42	10.24	1.44	24.48	15.95	14.99
Spruce	0.9-1	4 496	20	0	3.79	0.02	0.00	5.67	0.06	0.00
	0.8-1	9 366	203	2	7.89	0.17	0.00	11.82	0.59	0.04
	0.7-1	12 732	687	24	10.73	0.58	0.02	16.07	2.00	0.47
	0.6-1	16 784	2 017	135	14.14	1.70	0.11	21.18	5.88	2.63
	0.5-1	20 273	4 061	423	17.08	3.42	0.36	25.58	11.84	8.25
	0.4-1	24 816	7 983	1 061	20.91	6.73	0.89	31.32	23.28	20.70
Coniferous mixed	0.9-1	313	4	0	0.91	0.01	0.00	2.29	0.02	0.00
	0.8-1	863	68	1	2.51	0.20	0.00	6.31	0.36	0.06
	0.7-1	1 354	234	7	3.94	0.68	0.02	9.90	1.23	0.41
	0.6-1	2 130	691	65	6.20	2.01	0.19	15.58	3.64	3.77
	0.5-1	2 873	1 404	178	8.36	4.08	0.52	21.01	7.40	10.32
	0.4-1	4 098	3 038	396	11.92	8.84	1.15	29.97	16.00	22.96
Broadleaved-coniferous mixed	0.9-1	2 145	5	0	2.28	0.01	0.00	4.54	0.01	0.00
	0.8-1	4 100	79	0	4.35	0.08	0.00	8.67	0.20	0.00
	0.7-1	5 492	310	12	5.83	0.33	0.01	11.61	0.78	0.16
	0.6-1	7 191	1 041	99	7.63	1.10	0.11	15.21	2.64	1.32
	0.5-1	8 872	2 282	315	9.41	2.42	0.33	18.76	5.78	4.22
	0.4-1	11 463	5 204	968	12.16	5.52	1.03	24.24	13.18	12.96
Broadleaved	0.9-1	1 431	0	0	1.08	0.00	0.00	1.36	0.00	0.00
	0.8-1	4 012	14	0	3.04	0.01	0.00	3.81	0.08	0.00
	0.7-1	7 642	74	2	5.79	0.06	0.00	7.27	0.41	0.02
	0.6-1	15 936	245	25	12.08	0.19	0.02	15.15	1.36	0.29
	0.5-1	21 256	594	125	16.11	0.45	0.09	20.21	3.29	1.43
	0.4-1	24 044	1 516	628	18.23	1.15	0.48	22.86	8.41	7.20
Temporarily not forested	0.9-1	16	0	0	0.01	0.00	0.00	0.03	0.00	0.00
	0.8-1	170	21	2	0.11	0.01	0.00	0.33	0.02	0.02
	0.7-1	383	21	2	0.25	0.01	0.00	0.75	0.02	0.02
	0.6-1	785	301	16	0.52	0.20	0.01	1.53	0.35	0.12
	0.5-1	1 222	791	67	0.81	0.52	0.04	2.38	0.91	0.51
	0.4-1	2 033	1 979	258	1.34	1.31	0.17	3.96	2.27	1.98

Appendix 7: patch-size assessment over GI of all forest

The patch-size analyses showed that within each resulted GI, in all three subregions, the stepwise CF-insertion increased the total area of the GI-patches at all the concerned size scales (Table A3). However, patches of larger size (> 1 000 ha) were found almost exclusively in the mountainous subregion, across the resulted GIs.

Table A3. Total areas of GI-patches at different size scales within each subregion.

Subregion	Patch size	Area (1000 ha)						
		Baseline GI	**+ CF of 0.9-1**	**+ CF of 0.8-1**	**+ CF of 0.7-1**	**+ CF of 0.6-1**	**+ CF of 0.5-1**	**+ CF of 0.4-1**
Mountain	≤ 10 ha	5.46	6.06	6.62	7.72	9.85	11.16	13.02
	≤ 100 ha	7.85	7.96	9.12	10.41	12.49	15.54	17.57
	≤ 1 000 ha	13.82	15.19	18.52	18.31	21.57	23.47	27.10
	≤ 10 000 ha	2.93	3.96	4.88	8.68	11.13	17.60	19.70
	>10 000 ha	175.44	184.77	195.33	205.55	221.86	231.96	250.33
Inland	≤ 10 ha	2.74	2.76	3.35	4.83	8.68	13.21	17.78
	≤ 100 ha	5.84	5.90	6.17	7.32	10.71	17.91	33.38
	≤ 1 000 ha	6.20	6.21	6.37	6.71	8.47	8.57	22.64
	≤ 10 000 ha	-	-	-	-	-	3.29	3.67
	>10 000 ha	-	-	-	-	-	-	-
Coastal	≤ 10 ha	0.83	0.83	0.84	0.99	1.76	2.79	4.44
	≤ 100 ha	1.92	1.92	1.92	1.84	2.26	3.68	6.99
	≤ 1 000 ha	1.28	1.28	1.28	1.39	1.45	2.03	5.72
	≤ 10 000 ha	-	-	-	-	-	-	-
	>10 000 ha	-	-	-	-	-	-	-

Appendix 8: Full map series of areas of three forest types with GI-density ≥ 20%

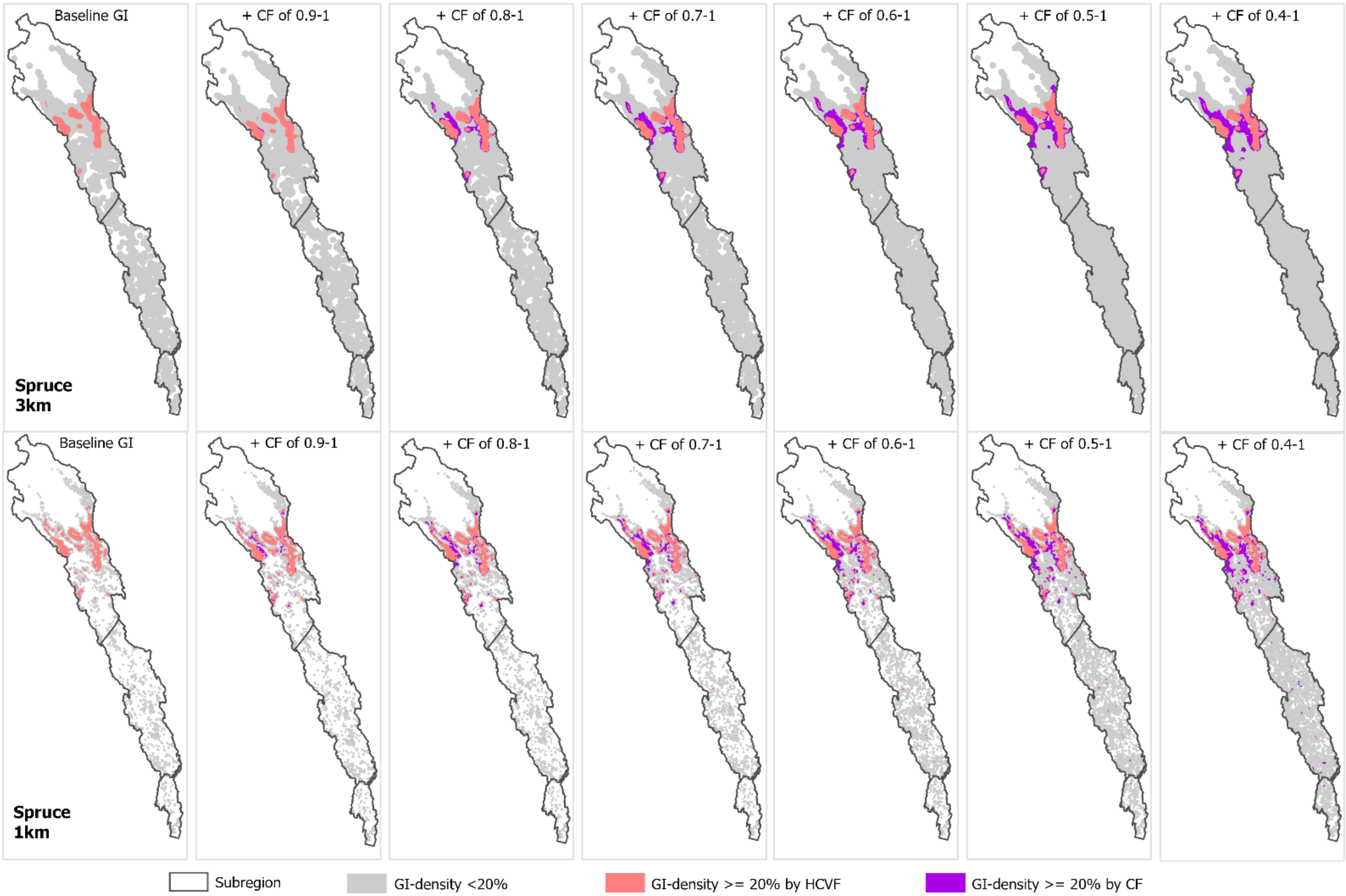

Figure A3. Variation of **spruce** (co-)dominated forest* areas with green infrastructure (GI) density ≥ 20%, with the stepwise insertion of connectivity forest (CF). Density was filtered with a circular moving window of 3km radius(**upper panel**) and 1km radius (**lower panel**). Areas in light red indicates the patches with a GI-density ≥ 20% in the baseline GI, i.e., the high conservation value forests (HCVF); and areas in violate indicates the newly added patches of density ≥ 20% by the CF-insertions. * Spruce (co-)dominated forest: spruce forest plus mixed coniferous forest.

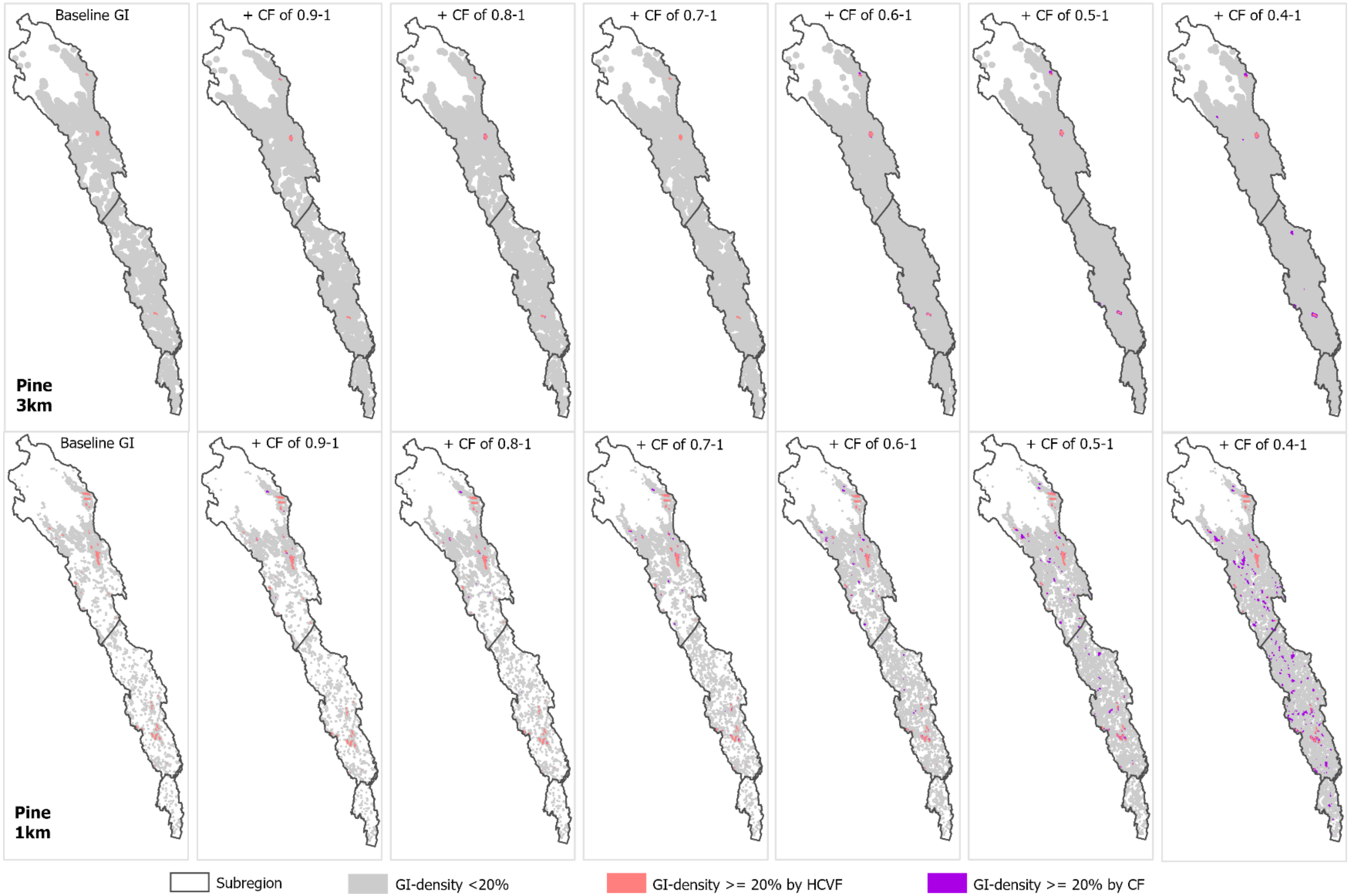

Figure A4. Variation of **pine** (co-)dominated forest* areas with green infrastructure (GI) density ≥ 20%, with the stepwise insertion of connectivity forest (CF). Density was filtered with a circular moving window of 3km radius(**upper panel**) and 1km radius (**lower panel**). Areas in light red indicates the patches with a GI-density ≥ 20% in the baseline GI, i.e., the high conservation value forests (HCVF); and areas in violate indicates the newly added patches of density ≥ 20% by the CF-insertions. * Pine (co-)dominated forest: pine forest plus mixed coniferous forest.

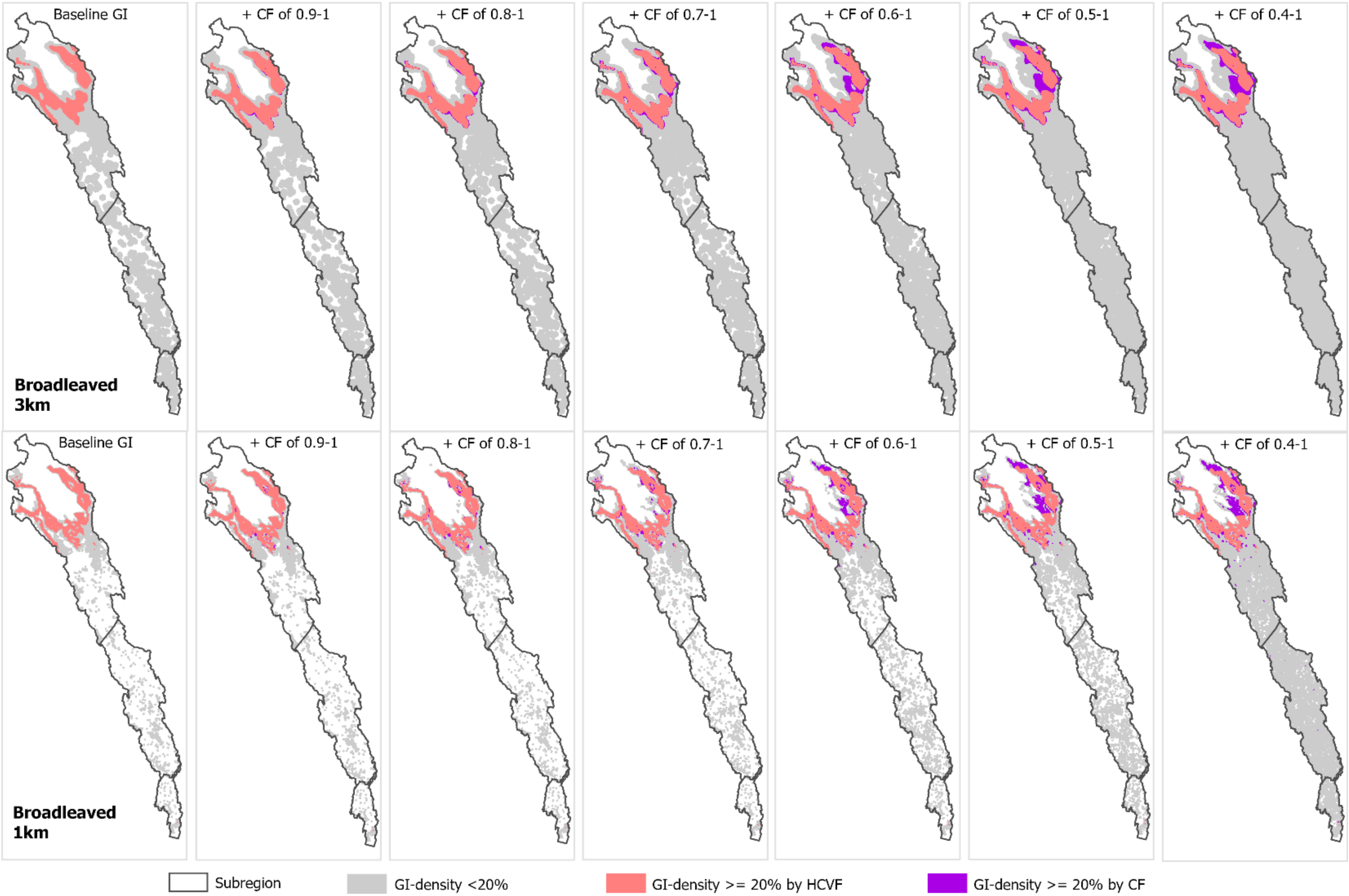

Figure A5. Variation of **broadleaved** species (co-)dominated forest* areas with green infrastructure (GI) density ≥ 20%, with the stepwise insertion of connectivity forest (CF). Density was filtered with a circular moving window of 3km radius(**upper panel**) and 1km radius (**lower panel**). Areas in light red indicates the patches with a GI-density ≥ 20% in the baseline GI, i.e., the high conservation value forests (HCVF); and areas in violate indicates the newly added patches of density ≥ 20% by the CF-insertions. * Broadleaved species (co-)dominated forest: broadleaved forest plus broadleaved-coniferous mixed forest.

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