



Conservation significance of intact forest landscapes in the Scandinavian Mountains Green Belt

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Abstract

Context As forest harvesting remains high, there is a crucial need to assess the remaining large, contiguous and intact forests, regionally, nationally and globally. **Objectives** Our objective was to analyze the spatial patterns and structural connectivity of intact and primary forests in northern Sweden with focus on the Scandinavian Mountain region; one of the few remaining large European intact forest landscapes.

Methods Over 22 million ha with 14.5 million ha boreal and subalpine forest and with data consisting of a 60–70 year retrospective sequence, we analyzed distribution, density and connectivity of forests that have not been clear cut, using moving window and landscape analyzes derived from Circuitscape.

Results We revealed a contiguous, connected and semi-connected intact forest landscape forming a distinct Green Belt south to north along the mountain range. Almost 60% of the forestland remains intact, including contiguous clusters 10,000 ha and larger. The connectivity is particularly high in protected areas with primary forests outside contributing substantially to overall connectivity. We found gaps in connectivity

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in the southern parts, and furthermore low or absent connectivity across the whole inland and coastal areas of northern Sweden.

Conclusions Given its ecological values, the Scandinavian Mountains Green Belt is a key entity supporting ecological legacies, boreal biodiversity and ecosystem services, resilience and adaptive capacity, which needs to be safeguarded for the future. On the very large areas outside the mountain region, forestlands are severely fragmented, connectivity values are lost, and forest landscape restoration is needed for conservation and functional green infrastructure.

Keywords Boreal · Forest connectivity · Green infrastructure · Landscape transformation · Continuity forests · Sweden

Introduction

With 70% and more of the earth's land surface (Barnosky et al. 2012) and 80% and more of remaining forests (Watson et al. 2018) modified by land use, the Anthropocene human footprint immensely influences key ecological functions, habitat characteristics, ecosystem services and biodiversity (e.g., Venter et al. 2016; Tucker et al. 2018). Forests are subject to extensive logging worldwide that, beyond relocating natural forest frontiers, also affects the functionality of protected areas, remaining primary forests and intact forest landscapes (Heino et al. 2015; Potapov et al. 2017; Jones et al. 2018; Sabatini et al. 2018). The consequences of forest fragmentation and loss are increasingly debated on global scale and for many forest regions (e.g., Defries et al. 2010; Hansen et al. 2013; Watson et al. 2018). In the boreal biome, natural configuration of forest landscapes are seriously transformed by rotation forestry systems that, amongst other impacts, interrupt spatial connectivity and temporal continuity of forest cover (e.g., Boucher et al. 2009; Svensson et al. 2018). Given the circumpolar range, large area and rich ecological values in the boreal biome (e.g., Moen et al. 2014) this transformation profoundly impacts a globally important biodiversity and ecosystem services source, disturbs ecosystem resilience to climate and land use changes (Mantyka-Pringle et al. 2012; Blumroeder et al. 2019), and contests sustainability- and conservation-oriented policies and

environmental targets (Sverdrup-Thygeson et al. 2014; Chazdon et al. 2016; IPBES 2018; Angelstam et al. 2020). In combination with climate change, intensive forestry and other drivers of ecosystem change, a sledgehammer effect is foreseen where boreal ecosystems as well as ecosystems in other biogeographic regions are at risk of entering new and potentially irreversible ecological states (Barnosky et al. 2012). Besides a need for larger areas of protected forests (e.g., EC 2020) there is also a strong movement towards increasing forest cover, forest landscapes and ecosystem restoration (Aerts and Honnay 2011), as expressed in the UN Declaration of Ecosystem Restoration (UN 2019). Accordingly, remaining primary forests, old-growth forests and intact forest landscapes needs to be identified, mapped and assessed regarding threats to and opportunities for maintaining their ecological status (Potapov et al. 2017; EC 2020).

The exploitation pressure in many regions remains high even in the last intact forest landscapes (e.g., Potapov et al. 2008; Chazdon et al. 2017; Müller et al. 2018; EC 2020). In Europe, with a long and intensive land-use history, intact forest landscapes are very rare and those remaining deserve particular attention (e.g., Wallenius et al. 2010). Intact forest landscapes are defined as larger (> 500 km²) mosaics of forests and natural open ecosystems that include primary forests that show no or low influence of human activities and habitat fragmentation, but where some historic human influence of, e.g., preindustrial selective logging, may have occurred (Potapov et al. 2008, 2017). Primary forests are defined as naturally regenerated forest with native tree species where there are no clearly visible signs of human influence and where the ecological processes are not significantly disturbed (FRA 2020). It is also increasingly accepted that effective nature conservation will have to move beyond passive protection of remaining high conservation value forests into complementary active restoration of transformed forest areas on both stand and landscape level through advanced conservation-oriented management strategies and practices (e.g., Kuuluvainen 2009; Stanturf et al. 2014; Spathelf et al. 2018). Hence, attention is simultaneously directed to the distinct values of primary forests, large, contiguous and intact forest landscapes, and to promoting a sustainable, holistic, multiple-scale and multiple-use spatial landscape governance and management (Sayer 2009; Arts et al. 2017; Sabatini et al. 2018).

The concept of green infrastructure, which as a fervent EU initiative is integrated into one or more policy sectors in all member states (Slätmo et al. 2019), aims to secure biodiversity, habitat resilience and ecosystem services at multiple spatial scales (Liquete et al. 2015). Thus, green infrastructure promotes landscape-scale and holistic planning based on known conservation core areas and their functional connectivity in the existing matrix, as, for example, the Yellowstone to Yukon Conservation Initiative in North America (Mahr 2007) and the Australian Alps to Atherton Connectivity Conservation Area (Pulsford et al. 2010). In practice this implies that green infrastructure requires a spatio-temporal perspective ranging from local species occurrence and microsites, to habitats, landscapes and entire regions (e.g., Heller and Zavaleta 2009; Gustafsson et al. 2012). Furthermore, a functional green infrastructure intrinsically relies on a continuum of intra- and inter-connected land cover types and their transitions, temporal land-use changes, natural succession and dynamics, and also restoration of transformed matrix surrounding the core areas (Sayer 2009; Chazdon et al. 2016; Chazdon 2018). Hence, for green infrastructure focusing on forest ecosystems, intact forest landscapes play a paramount role. The landscape-scale and holistic approach in the green infrastructure concept is recognized in the Aichi target 7 on sustainable management, biodiversity and conservation in target 11 on setting aside a minimum of 17% of terrestrial areas, and in target 15 on restoring degraded ecosystems (CBD 2010). Although frequently promoted, however, landscape approaches aiming for advanced nature conservation are often not successful in practice and hence need to be further developed (e.g., Chazdon et al. 2017; IPBES 2018).

Intact forest landscapes support globally significant ecological legacies (e.g., Potapov et al. 2017; Watson et al. 2018; Jonsson et al. 2019) because of maintained ecosystem structures and function, continuous forest cover, old-growth forest habitat attributes and continuity of natural dynamics including disturbance processes and successions. The actual functional size and spatial configuration of the forest patches is important to consider when discussing their functionality as habitat. A basic assumption is that the center of intact forest patches harbors higher intrinsic natural values than the periphery, and thus that the distance to edges and influences from the surrounding matrix is a

critical factor (e.g., Riitters et al. 2016; Pfeifer et al. 2017). On global scale, Haddad et al. (2015) found that 70% of the remaining primary forest areas are within 1 km and 50% within 500 m from forest edge, and that a predominance of remaining intact forest fragments are only 10 ha or less in size. On national scale—for Sweden—Esseen et al. (2016) found that forest edge towards clearcuts was the most common type of edge below the mountain region. Thus, identification, mapping and spatial assessment of remaining intact forest landscapes is critically important. In their global-scale analysis, Potapov et al. (2008) identified three intact boreal forest landscapes on the Fennoscandian shield (i.e., Norway, Sweden, Finland and Northwest Russia); the forest belt on the Swedish side of the Scandinavian Mountain Range, the forest border-area between Finland and Northwest Russia, and the Kola Peninsula forest belt. These intact forest landscapes were also identified by Watson et al. (2018) as among the last remaining wilderness areas. Of these, only the Scandinavian Mountain range forest belt is entirely within the European Union (Jonsson et al. 2019).

This study is focused on primary forest and intact forest landscapes in boreal and subalpine Sweden and in particular on the remaining natural and near-natural forests and woodlands in the foothill's landscapes along the east slopes of the Scandinavian Mountain Range. The holistic spatial dimensions of this truly extensive intact forest landscape has previously not been studied in greater detail and its significance for the entire regional-scale boreal biome has not been assessed. Our study thereby complements and deepens earlier research on intact forest landscapes at pan-national and global scales, such as those by Hansen et al. (2013) and Potapov et al. (2008, 2011) on remaining intact forest landscapes, and by Heino et al. (2015) on forest loss in protected and intact forest areas. This study contributes a regional-scale assessment of forest and forest landscape intactness and connectivity, at a resolution that allows for input to green infrastructure planning, and as such a case study approach to applied landscape ecology.

Our study objectives were to analyze areal and density distribution, contiguous forest-cluster size and spatial distribution and connectivity attributes, of primary forest relative to all forestland and to existing protected areas. Thus, a generic assumption is that such forests maintain, or potentially maintain, forest

and forest landscape attributes that are lost or disturbed by extensive clearcutting practices elsewhere in the landscape (cf. Curtis et al. 2018; Blumroeder et al. 2019). Our study covered a 22.2 million ha forest-dominated region, pre-dominantly with extensive rotation forestry impacts. The input data consisted of forests that have not been harvested since the 1950s to 1960s, which broadly covers the rotation forestry era in the region (Lundmark et al. 2013; Jonsson et al. 2019). We simultaneously provide a comprehensive regional spatio-temporal impact assessment of rotation forestry resulting in severe loss and fragmentation of intact forest landscapes, and assess the spatial patterns and connectivity of the Scandinavian mountains “green belt” (sensu Terry et al. 2006). The forestland in the Swedish mountain region is currently a subject of a heated debate concerning a continued conservation and small-scale governance and management direction, or a direction towards more intensive forestry (Jonsson et al. 2019). This debate is one of many debates on the same theme worldwide (e.g., IBPES 2018). Our results are discussed in the context of strategic and operational prospects to address forest green infrastructure functionality in boreal forest landscapes, as a way forward to mitigate the negative consequences of forest fragmentation and loss.

Materials and methods

Study region

The study region (22.2 million ha land area; SLU 2018) extends from the southern boreal Gulf of Bothnia coast to the northern boreal and alpine tree line of the Scandinavian Mountain Range (Gustafsson and Ahlén 1996) (Fig. 1). To assess differences within this large and diverse study region through pattern-oriented analyses, we divided it into nine sub regions (SR hereafter). Forests covers 14.5 million ha (see Table 1) which equals over 50% of all forest land and over 60% of the boreal forests in Sweden (Esseen et al. 1997; SLU 2018). Noteworthy, the forest area in the study region is equal to about 20% of the all forest land in northern Europe (Forest Europe 2015). Scots pine (*Pinus sylvestris*) is the dominant tree species with 44% of the total productive forest area (tree growth > 1 m³/ha/year on average over a 100 year rotation

period; excluding formally protected forest), followed by Norway spruce (*Picea abies*) with 23% (SLU 2018). The subalpine mountain birch (*Betula pubescens* ssp. *czerepanovii*) covers about 970,000 ha in the study region, equal to more than 95% of its total cover in Sweden (Hedenäs et al. 2016).

The study region includes gradients in latitude and altitude with associated species distributions patterns, in rotation forestry duration and degree of impact, and in forest landscape configuration and productivity from more fertile forest sites in the south and east to poor woodland sites at higher altitudes in the north and west. The forest management history can be traced back to the 1600 s with more pronounced exploitation since the mid-1800s (Lundmark et al. 2013). Although forest harvesting, dimension cuttings and selective thinning have occurred for centuries (Esseen et al. 1997; Östlund et al. 2015), the most extensive and systematic impacts have taken place during the last 60–70 years with the onset of widespread rotation forestry (Ecke et al. 2013; Moen et al. 2014; Peura et al. 2018). In addition to removing all or most trees and shrubs over large areas, soil scarification, re-planting with non-native and modified genotypes in monocultures, draining and road infrastructure development, have resulted in a seriously transformed landscape dominated by plantation forests, planted forest and naturally regenerated forests (FRA 2020). Hence, this industrial forestry system has caused cumulative impacts on forest ecosystems uniformly and systematically across site types and over large areas. Ecosystem legacies are disrupted and continuity values have been lost (Svensson et al. 2018).

Data

The data represents a publicly available, high-resolution (10 × 10 m raster), complete and consistent mapping of forests that have not been clear cut, developed, compiled and validated by Metria AB on commission by the Swedish Environmental Protection Agency (Ahlcrona et al. 2017a) for the entire boreal biome in Sweden. The mapping was performed as an automatic retrospective change detection analysis of satellite images from 1973 to 2016 and aerial photos from the 1950s and 1960s. The starting reference year for detecting the earliest clear cuts and young artificially regenerated forests was set to 1960 ± 5 years as an average across the region. All forest patches 0.5 ha

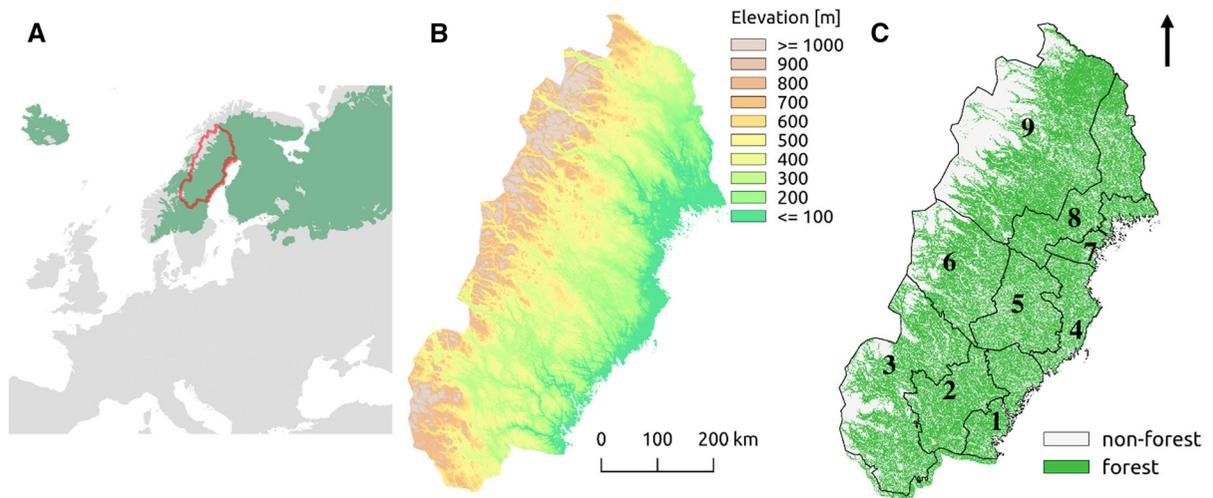


Fig. 1 **a** The location of the study region in Europe (red line) with the extension of the boreal biome highlighted in green. **b** The elevation (m) above sea level across the study region calculated from the elevation model. **c** Total forest land (green) with the nine analysis sub-regions; (1) South coastal, (2) South inland, (3) South mountain, (4) Central coastal, (5) Central inland, (6) Central mountain, (7) North coastal, (8) North inland, (9) North mountain. The subregions were divided by counties

south (Västernorrland and Jämtland), central (Västerbotten) to north (Norrbotten) and by municipalities in zones east to west. The coastal zone covered all ($n = 13$) municipalities that border the Gulf of Bothnia east coast, the inland zone covered all municipalities ($n = 18$) not bordering the coast and the mountains, and the mountain zone all ($n = 13$) municipalities in the Scandinavian mountain range

Table 1 The area (in 1000 ha) of total forest land (TFL) with its proportion of formally protected forest (FPF), and the area of proxy continuity forest (pCF) with its proportion of total forest land and of formal protected forest, presented for the 9 subregions

Subregions	Total forest land (TFL)		Proxy continuity forests (pCF)		
	Area (kha)	FPF (%)	Area (kha)	TFL (%)	FPF (%)
1 South Coastal	965	1.9	444	46.0	3.3
2 South Inland	1313	1.4	447	34.1	3.1
3 South Mountain ^a	2481	8.6	1413	57.0	12.6
4 Central Coastal	829	1.5	419	50.5	2.2
5 Central Inland	1284	2.0	459	35.8	4.5
6 Central Mountain ^b	1567	22.8	1076	68.7	29.4
7 North Coastal	575	1.8	332	57.8	2.6
8 North Inland	1861	4.4	1002	53.9	6.7
9 North Mountain ^c	3659	36.7	2752	75.2	39.5
Total	14,532	14.3	8345	57.4	20.5

^a190,000 ha mountain birch forest, equal to 8% of TFL and 13% of the pCF-area

^b40,000 ha mountain birch forest, equal to 3% of TFL and 4% of the pCF-area

^c740,000 ha mountain birch forest, equal to 20% of TFL and 27% of the pCF-area. The Mountain birch estimates are presented in Online Appendix S3

and larger and forest belts 20 m or wider were identified and registered. For comparison, the average size of clearcuts in Västerbotten county, located in the middle of our study area, has been estimated to 14.1 ha

and 7.2 ha in 1960 and 2010, respectively (Nordström 2017). The mapping had the highest precision in the central and northern part of the boreal biome (Ahlcrona et al. 2017a), which is included in this

study. Based on validation against independent data derived from the Swedish National Forest Inventory, the stand age of not clear-cut forests varied between 120 and 144 years and the precision accuracy for stand age varied between 90 and 93% for ≥ 70 year and between 76 and 86% for stand age ≥ 120 years (Ibid.). The south part of the boreal biome (i.e. Dalarna and Gävleborg counties) where the mapping has a lower precision (94–123 years, 84% to 90%, and 75% to 80%, in comparison to the above), was not included. A feasibility study (Ahlcrona et al. 2017b) in the southeast parts of the study region indicates that a fraction of the data includes forest areas that were harvested too early to be detected, forest with a tree cover too low to be detected as forests, and forests with traces of forest management. The resulting overestimation of not clear-cut forest is mainly to be expected along the coast and river valleys where a longer and more tangible land use history have taken place (Svensson et al. 2018). In recognizing that the data is remote-sensing generated, we term the detected not harvested forest patches “proxy continuity forests” (pCF hereafter) following Svensson et al. (2018) and corresponding to proxies of primary forests (FRA 2020). More details about the entire pCF-data generation process and validation can be found in the supplementary material.

Auxiliary data sources include raster layers of forest cover (TFL hereafter, i.e. total forest land area) and the digital elevation model, both acquired from Copernicus (2018). The data on formally protected forests (FPF hereafter) were acquired from the Swedish Environmental Protection Agency (2018), and the mountain forest border from the Swedish Forest Agency (2018). The mountain forest border (SCB 2019) was established in the Swedish forest policy in 1991 and delineate the subalpine foothills forest landscape, wherein stricter regulation of forest harvesting is applied in current national forestry and environmental policies (Jonsson et al. 2019).

Analyses

In the first step, all spatial datasets including the original 10×10 m pCF-raster were imported to and preprocessed using the GRASS GIS software (Neteler et al. 2012 Ver. 7.4.0). Next, to reduce the complexity of the analysis we re-sampled the original pCF-raster (81.3 million pixels) to a coarser grid using mode-

based aggregation, and selected 50 m resolution (0.25 ha; 3.3 million pixels) as an appropriate trade-off that allowed efficient computation and at the same time did not change the spatial structure of the original data. All maps were created using the open source software QGIS (QGIS Development Team 2017 Ver. 2.18). Supporting analyses information is provided in Online Appendices 1 and 2.

To visualize and numerically describe the spatial pCF-patterns for the nine SRs, we performed a moving window analysis using GRASS GIS and Python library SciPy (Oliphant 2007) that generated an output raster data on the proportion of pCF within a 1, 25 and 100 km² moving window centered on each pixel. To compare the mean and differences in pCF patterns between the SRs, we first selected all pixels with forest cover $\geq 75\%$, and then used this subset to randomly sample pCF-density in 1000 pixels for each SR. This approach allowed us to account for differences in landscape configuration between sub-regions, to focus on those parts of a landscape that are dominated by forest, and to generate reliable numerical comparison between the SRs.

Further, we defined a pCF-cluster as a contiguous area of 50 m pixels with $\geq 50\%$ pCF-cover within a 1 km² window, and identified contiguous pCF-clusters of ≥ 10 , ≥ 100 , ≥ 1000 and $\geq 100,000$ ha in size. The size of the window corresponds to the findings by Haddad et al. (2015), who established that 70% of the remaining intact forest are within 1 km from forest edge. We consider a pCF-cluster as a basic spatial unit that is dominated (i.e. $> 50\%$ within a 1 km²) by primary forests and supporting mature and older forests, which represents intact forest landscape. By using a 1 km² window around each pCF-pixel and the majority rule to define a pCF-cluster together with the applied minimum patch-size rule (e.g., 25 ha for the connectivity analysis), we assured that only the least fragmented patches of intact forest landscapes were taken into account in our analysis, excluding the smallest patches (< 10 ha) which can be considered as spatial noise in the data.

To assess the connectivity between pCF-clusters, we used a connectivity model derived from circuit electric flow theory (McRae et al. 2008) and implemented in the Circuitscape software (2018 Ver. 4.0.5). Circuitscape modeling is used in conservation planning for assessing ecological connectivity and is predicted to be an increasingly important tool for

researchers and practitioners (Dickson et al. 2019) as well as for analyzing connectivity in fragmented landscapes (McGuire et al. 2016). Since we were aiming at modeling overall (“global”, i.e. for the entire study region) connectivity and at assessing how connectivity differs between the SRs, we followed a method by Koen et al. (2014) that is insensitive to the placement of source and destination nodes and that does not require a selection of a focal species or independent data. To adjust to computational limits, we further down-sampled the pCF-raster from the 50×50 m resolution to 500×500 m resolution prior to running the Circuitscape algorithm. As we analyzed the global patterns and as coarsening the input grid usually generates results that closely approximate those generated at fine-scale resolution (i.e. Circuitscape is robust to scale change; see McRae et al. 2008), we foresee no detectable effects of this broader resolution on the final results and conclusions. We considered two land-type classes when designing the Circuitscape resistance surface; pCF-clusters ≥ 25 ha (resistance value 1), and non-forest and clear-cut forest areas surrounding these (resistance value 100), respectively. The resistance values were chosen to assure contrast without influencing the connectivity distribution results, with reference to, e.g., the “one-stage expert approach” (Zeller et al. 2012) and customary approaches to assign increasing resistance values when empirical data is unavailable (Koen et al. 2014; Braaker et al. 2014).

The measure of connectivity used was cumulative current density (CCD), estimated for each pixel of the resistance surface raster. The estimated CCD values resulted from the connectivity (current flow) between all pairs of 24 focal nodes (552 combinations) randomly placed along the perimeter of a 50 km buffer zone around the study region, following the approach by Koen et al. (2014). We summarized the CCD-results for each SR using four quantile-based connectivity classes; < 0.25 (low), ≥ 0.25 (moderate), ≥ 0.50 (high) and ≥ 0.75 (highest), with the latter class corresponding to the most important connectivity “pinch points” (McRae et al. 2008). Finally, for each pCF-cluster, we estimated the area-weighted connectivity score (AWCS) following Dickson et al. (2013); defined as the sum of the cumulative current flow across all pixels in each pCF-cluster divided by its area. The AWCS thus detects the

connectivity contribution based on both the size and the spatial location of individual clusters.

Results

The total forestland area was estimated to 14,532,000 ha with the largest share (53%) in the mountain SRs combined, and in particular large in the north mountain SR (Table 1). In total 14.3% (2,078,000 ha) is formally protected, with the largest proportion (59.5%) in the central and north mountain SRs combined. For the inland and coastal SRs, the protected proportion ranges from only 1.4 to 4.4%. The pCF-area was estimated to 8,345,000 ha with the largest areas in the mountain SRs and the lowest in the coastal SRs. The pCF-proportion of total forestland was 57.4% and ranged from 75.2% in the north mountain SR to 34.1% and 35.8% in the south and central inland SRs, respectively. The proportion of protected pCF was 20.5% (1,711,000 ha), i.e. higher than the protected proportion of total forest land for the study region, and further also higher than on total forest land in each of the SRs. Generally, the proportion of protected pCF was highest in the mountain SRs, in particular the north mountain SR, and lowest in the coastal SRs and the south and central inland SRs. Mountain birch covers a substantial fraction of the forest and woodland in the mountain SRs. The estimates indicate in total 970,000 ha mountain birch forest, covering 7% and 12% of total forest land and pCF-area, respectively, with the highest estimates in the north and the lowest in the central mountain SR.

The moving window analyses (Fig. 2) detected a contiguous pCF-cluster pattern in the northern parts of the mountain range, and a more fragmented pattern in the south and central parts. For the 1 km^2 window, areas with high pCF cluster density ($> 50\%$) were found scattered in the north inland and in the coastal SRs, but for the 25 km^2 and even more so for the 100 km^2 window, high cluster density was almost solely detected in the mountain SRs. The increase in search-window size step-wise withdrew pCF-clusters in the inland and coastal SRs to the east, but also isolated pCF-clusters on higher altitudes to the west; i.e., the belt with a concentration of high pCF-cluster density was sequentially delimited. The median density was highest in the north mountain SR for all window sizes,

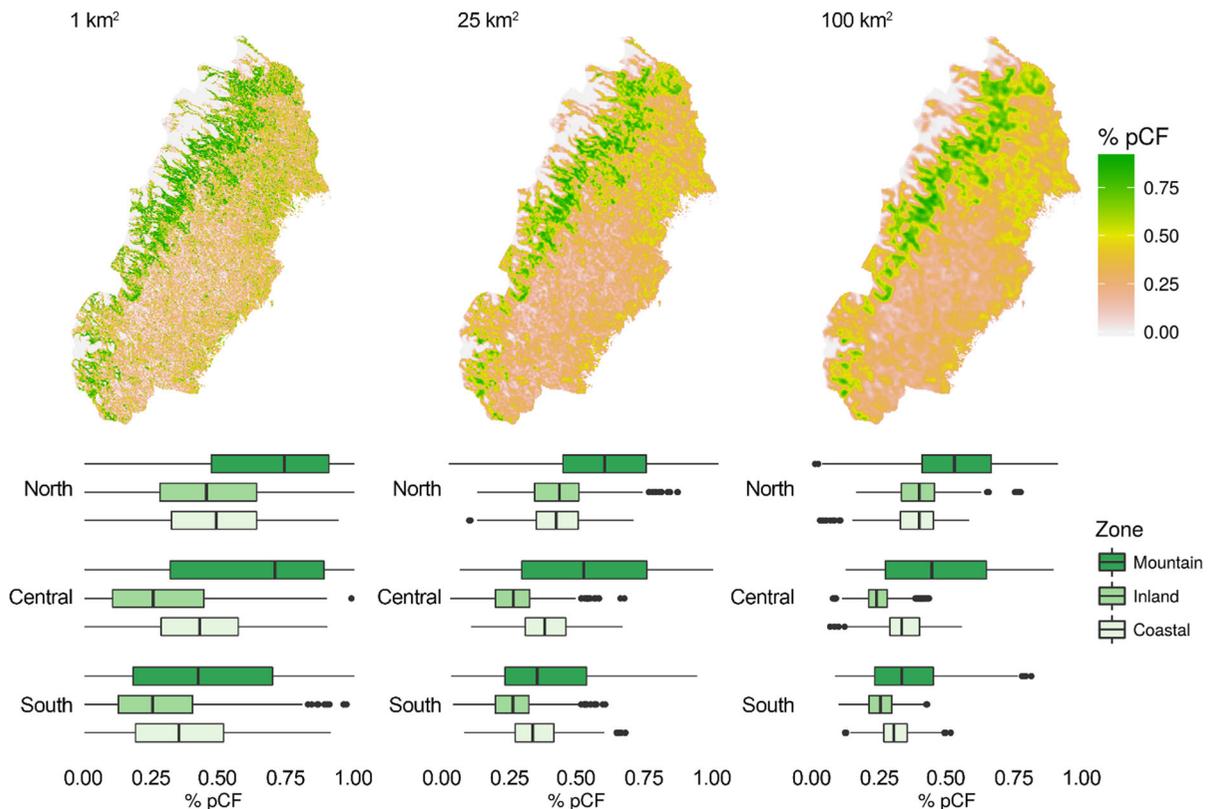


Fig. 2 The study region with per cent proxy continuity forest (pCF) shown in a continuous scale where areas dominated by pCF are highlighted in green. The maps are based on a 1×1 km, 5×5 km and 10×10 km moving window analyses centered on each 50×50 m pixel. The boxplots are based

and lowest in the south inland SR for the 1 km^2 and 25 km^2 and in the central inland SR for the 100 km^2 size. The pCF density variability increased with moving window size and from the coastal and inland SRs to the mountain SRs.

The pCF-cluster analyses (Table 2) revealed that pCF-clusters larger than 10,000 ha were found in all SRs, whereof as much as 91% (4,366,000 ha) in the mountain SRs combined; equal to 81.5% of the total pCF-cluster area in the mountain SRs and 58.0% of all detected pCF-cluster area in the study region. The fraction of clusters larger than 10,000 ha in the inland SRs (245,000 ha) is mainly parts of clusters that had their main location in the mountain SRs. In the coastal SRs, clusters larger than 10,000 ha covered about 149,000 ha. Medium size clusters (> 100 ha and $\leq 10,000$ ha) dominated in the coastal and inland SRs. The actual proportion of pCF in the clusters

on 1000 random samples of pCF-proportion of total forest land area, in areas with forest cover $\geq 75\%$ for each sub region. The boxplots visualize the median, the first and third quartiles, 1.5 times the inter-quartile range, and all outlier points plotted individually

increased from the coastal (69.4%) to the inland (72.1%) and the mountain (80.3%) SRs. Sequentially larger clusters thus included a larger proportion of pCF, indicating lower fragmentation of pCF-patches within intact forest landscapes.

The geographical distribution of pCF-clusters (Fig. 3) shows that clusters $\geq 10,000$ ha exist almost only at higher elevations to the west of the mountain forest border, with a disrupted distribution in the middle part of the south mountain SR. Still, a considerable total area of clusters $\geq 10,000$ ha (644,000 ha in 23 clusters) was detected in the south mountain SR. Outside the mountain SRs, clusters $\geq 10,000$ ha were only found in scattered clusters in the north inland and coastal SRs. Clusters ≥ 1000 ha were more frequent and occurred in a more contiguous pattern, in particular in the north SRs and within a narrow belt along the coast.

Table 2 Proxy continuity forest (pCF) cluster area (in 1000 ha) and the actual pCF-proportion of the cluster area, presented in five cluster-size classes and in total, for coastal, inland and mountain zones. pCF-clusters were defined as contiguous areas of pixels with $\geq 50\%$ of proxy continuity forest (pCF) within a 1 km² window. The pCF cluster numbers and class proportions, the cluster area and class proportions, the pCF area and class proportions, and the proportion pCF area of cluster area, are presented in Online Appendix S4 for all cluster size classes for all nine subregions (SR)

Zones	Cluster size class (ha)	Cluster area (kha)	pCF proportion (%) of cluster
Coastal	≤ 10	3.4	50.2
	10– ≤ 100	53.4	69.0
	100– ≤ 1000	282.5	69.8
	1000– $\leq 10,000$	316.4	69.4
	$\geq 10,000$	148.6	69.4
	Total	804.3	69.4
Inland	≤ 10	5.2	51.4
	10– ≤ 100	94.7	71.5
	100– ≤ 1000	410.3	71.6
	1000– $\leq 10,000$	412.2	71.9
	$\geq 10,000$	245.5	73.8
	Total	1168.0	72.1
Mountain	≤ 10	5.3	54.4
	10– ≤ 100	85.7	71.8
	100– ≤ 1000	397.1	73.1
	1000– $\leq 10,000$	414.9	75.3
	$\geq 10,000$	3972.3	81.8
	Total	4875.4	80.3

Clusters > 100 ha and > 10 ha are more frequent in the north inland and coastal SRs than in central and south inland and coastal SRs, with a pronounced loss also of these smaller size classes in particular indicated in the inland SRs.

Across the whole study region, high pCF-connectivity was detected in an elongated belt in the mountain SRs, and to a lesser and more scattered extent in the north inland and coastal SRs (Fig. 4a). In contrast, we documented very low connectivity in the south and central inland and coastal SRs, although with some scattered pCF-clusters with high AWCS values that, hence, represents key areas for the remaining connectivity in these forest landscapes (Fig. 4b). Clusters with low to moderate connectivity (< 0.50 quantile) were detected in all SRs and dominated in the inland and coastal SRs, whereas the highest (≥ 0.75) and high (≥ 0.50 and < 0.75) connectivity was largely confined to the mountain SRs (Fig. 4c, d). Connectivity in the central and south inland SRs was generally low with the highest connectivity class nearly absent.

For the coastal and inland SRs, the area and proportion of total forest land with low and moderate connectivity classes were found to be consistently larger than the area and proportion with high and highest connectivity (Table 3). In contrast, both area

and proportion of the high and highest connectivity classes were larger in the south and north mountains SRs and the highest connectivity class larger in the central mountain SR, with 793,000 ha and a proportion of 21.7% of the highest connectivity in the north mountain SR as the largest values. A large fraction of protected pCF-clusters was found in the mountain SRs (Table 3), with the largest proportions equal to 47.7% and 46.7% of total forest land in the high and highest connectivity classes in the north mountain SR, respectively. In the mountain SRs, the lowest fractions of protected pCF-clusters, in those connectivity classes, were found in the south mountain SR (13.8% and 22.4%). This contrasts the inland SRs where the protected proportion of the high and highest connectivity classes varied between 4.9% (north) and 8.1% (south), and in the coastal SRs between 2.2% (central) and 4.2% (north).

There were important differences among the mountain SRs. The north mountain SR had the overall highest connectivity, i.e. the largest areas with pCF-clusters of any connectivity class (Fig. 4; Table 3) and also a relatively even distribution of clusters across all connectivity classes. Both the central and south mountain SRs had areas with the highest connectivity class weighted to total forest land (21.8% and 17.8%, respectively) at comparable proportion to the north

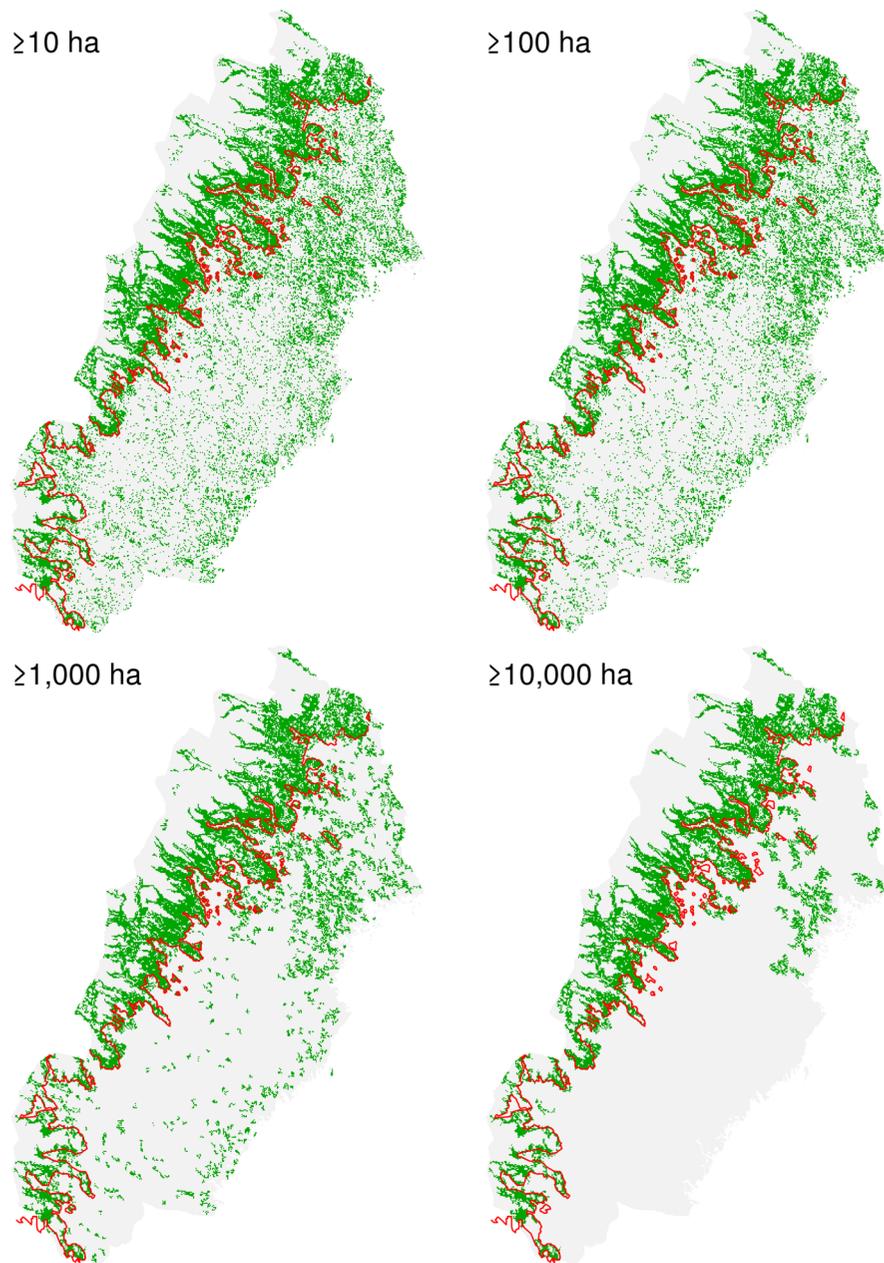


Fig. 3 The spatial distribution of the pCF-clusters (green) showed for clusters ≥ 10 , ≥ 100 , ≥ 1000 and $\geq 10,000$ ha in size. Clusters were defined as contiguous areas of pixels

with $\geq 50\%$ of proxy continuity forest (pCF) within a 1 km^2 window. The red line presents the mountain foothills border (Swedish: “fjällnära gränsen”)

mountain SR (19.6%). However, the weighted areas of low, moderate and high connectivity classes, especially the two latter, were much smaller which thus shows a skewed connectivity distribution. For the south mountain SR in particular, the overall

connectivity within intact forest landscapes relies on the fraction of highest connectivity.

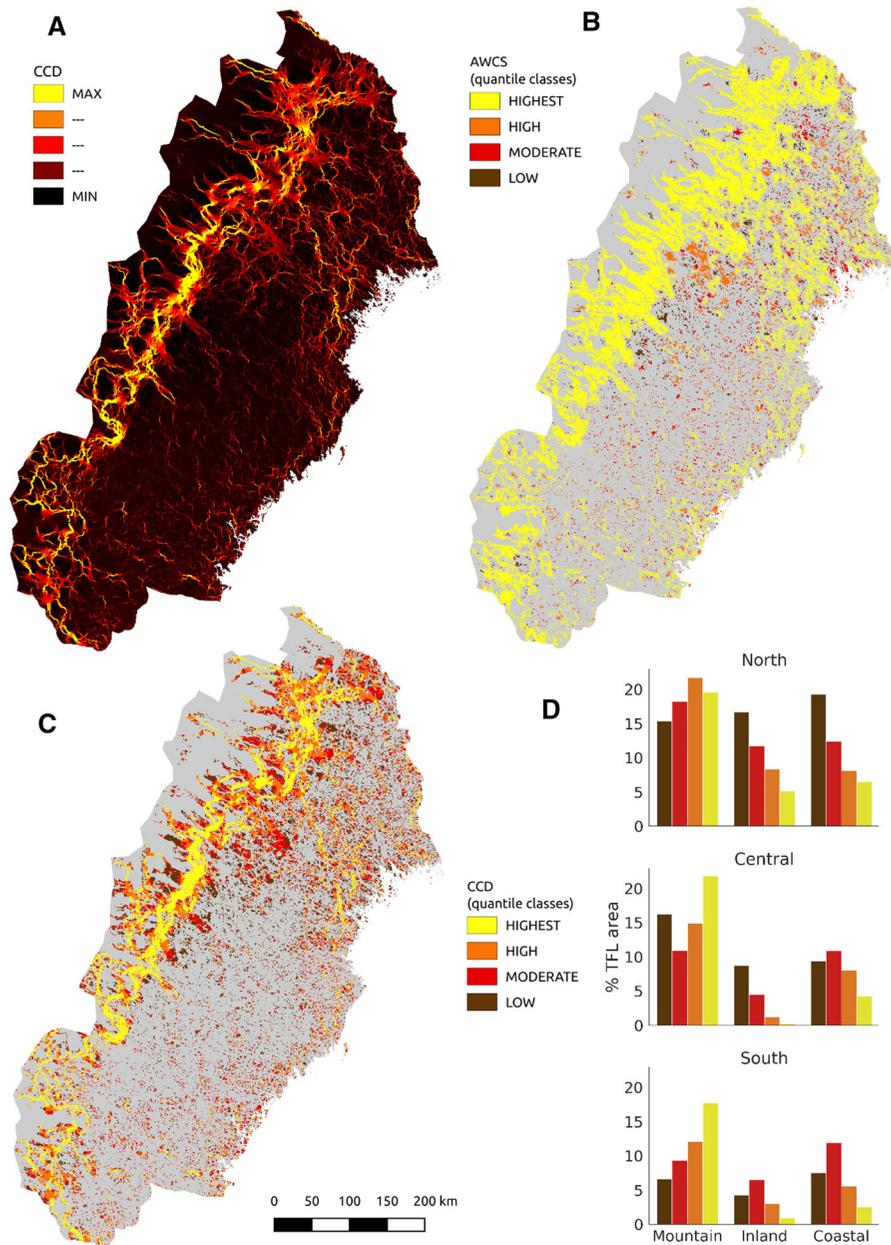


Fig. 4 **a** Cumulative current density (CCD) mapping illustrating the global connectivity between proxy continuity forest (pCF) clusters ≥ 10 ha. The color scale from brown to red to orange and to yellow shows areas with subsequently higher current density. **b** pCF-cluster importance mapping derived from the area-weighted connectivity score (AWCS) estimated

for each pCF-cluster and presented in four quantile classes. Grey is masked non pCF and other land cover types than forest land, as also in **c**. **c** Cumulative current density (CCD) mapping presented in four quantile classes. **d** The CCD corresponding barplots shows, for each subregion, the proportion of given connectivity class of total forest land area in that subregion

Discussion

Intact forest landscapes are becoming rare globally and now occurs mainly in remote hinterland areas

(e.g., Hansen et al. 2013; Watson et al. 2018). Although the commonly-held view is that much of the forest landscape in Sweden has been largely transformed by forestry and other human influence

Table 3 Summary of the global connectivity between pCF-clusters ≥ 25 ha measured as the cumulative current density (CCD) for each pixel of the resistance surface (see methods section and Online Appendix S1), presented in four quantile classes (A) < 0.25 , (B) ≥ 0.25 , (C) ≥ 0.50 , and (D) ≥ 0.75 ,

with the following statistics presented for the sub regions: pCF-clusters area (in 1000 ha) per class, class proportion of total forest land (TFL), and class proportion of formally protected forest (FPF)

	South			Central			North		
	Coastal	Inland	Mountain	Coastal	Inland	Mountain	Coastal	Inland	Mountain
Connectivity class 0 to < 25									
Area (kha)	72.8	56.3	164.7	77.5	112.0	253.7	110.6	311.2	563.0
Proportion of TFL (%)	7.5	4.3	6.6	9.4	8.7	16.2	19.3	16.7	15.4
Proportion of FPF (%)	4.1	3.0	7.7	2.3	7.7	23.5	2.4	8.9	25.0
Connectivity class 25 to < 50									
Area (kha)	115.1	85.5	231.0	89.8	57.4	170.8	71.4	218.5	665.9
Proportion of TFL (%)	11.9	6.5	9.3	10.9	4.5	10.9	12.4	11.7	18.2
Proportion of FPF (%)	5.1	5.6	9.3	2.0	7.2	30.2	2.6	10.6	38.5
Connectivity class 50 to < 75									
Area (kha)	54.2	39.4	299.5	66.2	15.0	232.8	47.0	155.2	793.0
Proportion of TFL (%)	5.6	3.0	12.1	8.0	1.2	14.9	8.2	8.3	21.7
Proportion of FPF (%)	2.6	8.1	13.8	2.2	5.3	31.5	4.2	4.9	47.8
Connectivity class 75 to 100									
Area (kha)	24.8	12.4	440.6	35.5	3.2	341.3	37.3	95.8	716.5
Proportion of TFL (%)	2.6	0.9	17.8	4.3	0.2	21.8	6.5	5.1	19.6
Proportion of FPF (%)	2.4	3.8	22.4	2.1	13.3	38.8	2.7	3.3	46.7

through time (Esseen et al. 1997; Pape and Löffler 2012; Moen et al. 2014; Östlund et al. 2015), the boreal to sub alpine forests and woodlands of the Scandinavian mountain range have been identified as one of very few remaining large, contiguous intact forest landscapes in Europe (e.g., Potapov et al. 2008). Our study reveals the unambiguous existence of a connected network of primary forests along the eastern foothills of the mountain range. More than half (57.4%) of the forestland has not been clear-cut during the latest 60–70 year, with a particularly large fraction (75.2%) remaining in the north. We documented high forest connectivity along the whole mountain stretch, with the exception of apparent connectivity gaps in the south part. This Scandinavian Mountains Green Belt extends for around 800 km straight-line distance south to north, i.e. for about half of the total length of the entire mountain range from the high arctic Nordkap to the southern boreal Stavanger in Norway. In light of climate change, this green belt, as other large intact forest landscapes, can be assumed to harbor capacity and resilience to adapt

to changes and provide critical northward dispersal, migration and connectivity routes for species, habitats, and ecosystem processes and services (e.g., Elmhagen et al. 2015; Jansson et al. 2015; McGuire et al. 2016).

We have applied the term “green belt” for the intact Scandinavian Mountain range forest landscape. The Green Belt initiative is one of several initiatives to promote conservation of significant ecologically functional networks of protected areas and bridging links. The initiative was launched by the IUCN (Terry et al. 2006), to contribute to, e.g., the implementation of the EU Habitats Directive. In this study, we confirm the existence of such quality characteristic for a forest landscape green belt along the east slopes of the Scandinavian mountain range.

There is rich evidence that intact forest landscapes and generally old forests support globally significant environmental values, such as native biodiversity, carbon sequestration and storage, fresh water provision, but also indigenous cultures (Watson et al. 2018; Thom et al. 2019). In this light, we argue that the maintenance of the Scandinavian Mountains Green

Belt is of highest international interest, both for efficient nature conservation and for the achievement of long-term sustainability in fragile, hinterland regions of the European north. We also argue that it, as other intact forest landscapes, are invaluable assets as key components in establishing an functional green infrastructure in Europe and elsewhere (cf. Liqete et al. 2015; Slätmo et al. 2019) as well as represents an unique reference area for basic and applied research (Kuuluvainen et al 2017). A recent study by Hermoso et al. (2020) concerning EU's Green Infrastructure Strategy underscored the importance of supra-national planning as often being superior to national and sub-national planning. We argue that the Scandinavian Mountains Green Belt, in this perspective, is to be understood as a core component for green infrastructure in the European boreal forest region.

The forest landscapes of the European north are dominated by systematic clear cutting rotation forestry and thus have undergone extensive transformation (e.g. Peura et al. 2018). Data that allows change detection of how, where and to what extent this transformation have influenced the natural landscape configuration, such as the data applied in this study, are very valuable. Detailed spatial analyses of remaining intact forest landscapes and primary forests on local and regional scale, clearly fill a knowledge gap for national (e.g., Angelstam et al. 2020) and European and other pan-national contexts (e.g., Sabatini et al 2018), beyond adding functional dimensions to green infrastructure planning. Similar approaches in other European regions, and potentially also for other land-cover types than forests, would provide a much needed supra-national perspective on functional green infrastructure assessments (Slätmo et al. 2019; Hermoso et al. 2020).

The Swedish mountain foothills forest landscapes remain in a natural and near-natural state, including very large ($\geq 10,000$ ha) contiguous forest components. Although various historical land uses including preindustrial tree harvesting has influenced forest stand and landscape configuration, high nature conservation values still subsists—as clearly expressed in the large proportion of already protected forests and the intrinsic conservation values registered in the national woodland key habitat inventory and national forest inventory (Jonsson et al. 2019). As of December 2018, 56.3% of all forest land and 52.5% of the productive forest land above the mountain forest

border is formally protected (SCB 2019). However, as established in this study, there are also large areas of primary forests that currently are not protected. A combination of additional protection, landscape restoration and high-ambition nature conservation considerations, can indeed contribute to improved connectivity and functional green infrastructure. It is well established that managed forests can be restored, matrix quality can be improved and that such measures will support functional connectivity (e.g., Heller and Zavaleta 2009; Dondina et al. 2017; Chazdon 2018). Maintaining, and where possible restoring, intact forests, is thus of urgent priority to current global efforts for halting biodiversity loss, mitigate adaptive ecosystem capacity to climate change and to achieve sustainability goals (e.g., Watson et al. 2018; UN 2019; EC 2020). The biotic gradients in the northern boreal to alpine transition, alongside with the natural habitat fragmentation, habitat-type transition zones and land-cover heterogeneity, provide a diversity of ecosystems and their services (Grêt-Regamey et al. 2012; Blicharska et al. 2017). If governed and managed in a sustainable way and according to current conservation policies, the Scandinavian Mountains Green Belt can play a key role in European conservation policy far into the future.

In contrast to the mountain foothills forest landscape, the inland and coastal areas, in particular in the central and south parts encompassing about 4.4 million ha, are extensively modified by rotation forestry. Here, only fragments of the forest landscape have escaped clear cutting and transformation into artificially regenerated forests. Our results show, however, that some forest connectivity remains—albeit at lower levels, in particular in the north part of the study region in a geographically semi-connected network from the mountains across the inland to the coast and further south along the coast. The remaining clusters are few and scattered, but are still important for the local connectivity and generally also as components supporting functional green infrastructure on larger scales (Svensson et al. 2018).

The strongly modified inland and coastal landscapes emphasize the importance of maintaining the Scandinavian Mountains Green Belt, as it can serve as a mainland source to support re-colonization and re-establishment of natural forest ecosystem processes, species, biodiversity, ecosystem services and climate change adaptive ecosystem capacity. Thus, its

continued existence is essential for the “global” connectivity in boreal Fennoscandia and northern Europe. Furthermore, an interesting feature is the indigenous Sapmi people reindeer (*Rangifer tardanus*) husbandry that is an ongoing land use across the whole study region, alongside with and on the same land as forestry and other land uses (Sandström et al. 2016). As a note, the definition of primary forests (FRA 2020), which is applied in this paper, recognizes the existence of indigenous peoples and their culture as part of intact forest landscapes and other wilderness areas (e.g. Watson et al. 2018). The traditional semi-nomadic reindeer husbandry system includes annual migrations from the mountain area in the summer season to the inland and coastal areas in the winter season. This migration relies on connected reindeer movement routes and on continuous grazing access to ground and arboreal lichens in relatively open forests with mature and old trees (Pape and Löffler 2012). Thereby, an expansion of intact forest networks to the inland and coastal areas through directed forest stand, landscape and ecosystem restoration, will support also this internationally significant indigenous culture that exists across the European north in Norway, Sweden, Finland and Northwest Russia. That is, a green infrastructure planning and implementation that maintain and expand forest connectivity with the Scandinavian Mountains Green Belt as an axis component, will support multiple ecosystem and landscape values and services across a very large region.

For the mountain and northernmost parts of the study region, a proportion of the intact forest consists of subalpine mountain birch. Notably, the density analysis step-wise omitted smaller, isolated and elongated forests and woodlands in high altitude mountain valleys dominated by mountain birch. Thus, the main connectivity route was concentrated to larger, more contiguous, and more coniferous dominated forests. The highest connectivity was detected in the central mountain SR where the proportion of mountain birch forest was estimated to be the lowest. This partly indicates that connectivity there largely is associated with coniferous forests but also is the effect of our assumptions for a connectivity analysis (i.e. that only larger contiguous forest clusters were taken into account) and our definition of an intact forest landscape cluster (see the methods section). By

contrast, the connectivity in the north mountain SR is associated with a higher share of mountain birch forests, in a landscape characterized by large mires, rocky outcrops, etc., land without or with low cover of trees (SLU 2018). This mosaic landscape naturally implies a lower level of natural forest connectivity, as detected in this study. However, it is also assumed that limited accessibility for forestry and already large protected areas explains the patterns in the north SR. Thus, our connectivity analysis is found to be sensitive to differences in natural landscape configuration. However, it should be stressed that open and semi-open forests on both productive and non-productive forest land can harbor significant continuity values (Hemäläinen et al. 2017) and hence contribute to functional green infrastructure.

There is an increasing interest in identification of remaining intact and wilderness forest areas on pan-national and global scales, and there is a critical need for policy recognition and protection of such areas. Recent publications include for example Haddad et al. (2015), Heino et al. (2015), Potapov et al. (2017), Jones et al. (2018), Müller et al. (2018) and Watson et al. (2018). Our study contributes precision and resolution in one of those areas that have been identified, at a scale that allows for strategic and operational planning. In addition to the existing protected areas, we have identified forest areas for future conservation, restoration and adaptive management in a structured, systematic manner across a large region. Our analysis revealed general pattern of structural connectivity of primary forests in intact forest landscapes, however, without distinguishing between different forest types and assuming homogeneous non-forest matrix between those areas. Further studies are needed for understanding the functional ecological aspects of intact forest landscapes and connectivity from the perspective of different groups of organisms in boreal forest landscapes, both forest specialists and generalists, especially taking into account their ecological traits, habitat and landscape requirements and sensitivity to forest clear cutting and other anthropogenic disturbances. Also, further studies on natural (e.g. topography, spatial distribution of open mires and major waterbodies) and human (e.g. historic land-use, transport infrastructure) causes to the patterns of remaining primary forests and intact

forest landscapes needs further attention (Axelsson and Östlund 2001; Mikusiński et al. 2003; Angelstam et al. 2004; Boucher et al. 2009).

Our study contributes baseline information on the much needed balancing of biogeographical representative protection. Currently, only 8% of all Swedish forestland and mountain woodland is formally protected (SCB 2019), with a strong bias to the northern boreal and sub alpine mountain areas (Jonsson et al. 2019). We reveal that for the mountain region (here, mountain SRs), the protection levels range from 8.6% of the total forest land in the south to 36.7% in the north, from 12.6% of the pCF in the south to 39.5% in the north, and that the highest level of pCF-connectivity was found in 22.4% to 46.7% of the protected area in the mountain region. The protection levels in the inland and coastal SRs ranges from 1.4 to 4.4% of the total forest land and from 2.2 to 6.7% of the pCF-area, which for both area and functionality requirements, i.e. connectivity, is way below the Aichi target #11 (CBD 2010). Here, forest landscape restoration is needed for successful green infrastructure implementation. Restoring values connected to natural forests takes time, however. For northern boreal Norway spruce forest old-growth habitat characteristics, Lilja et al. (2006) estimated up to a 300 year formation time.

A higher connectivity of primary forests was expected in the mountain area due to the later arrival of modern forestry and due to the emphasis on nature conservation in northwestern Sweden since the 1970s (e.g., Angelstam et al. 2011). From a policy perspective, the effect of the mountain forest border, illustrated in Fig. 3, is noteworthy. This legally defined border delineates the area of a stricter regulation of rotation forestry in Sweden (Jonsson et al. 2019). In the Forestry Act (2018), Section 15 states that the Swedish Forest Agency has to explicitly approve harvesting above this border instead of passively acknowledging applications, and Sect. 18 that harvesting can be prohibited if values associated with nature conservation, cultural heritage or reindeer husbandry may be negatively affected. Obviously, this policy regulation has helped secure the intact forest landscape, and thus represents an example of a policy that in practice successfully supports landscape approaches, which is not commonly recognized (Sayer 2009; Chazdon et al. 2017; Mansourian 2017). However, the narrow west to east extension of the

Scandinavian Mountains Green Belt and also existing connectivity gaps, clearly indicates that further forest fragmentation and loss may cause a “sledgehammer” (Barnosky et al. 2012) effect and, potentially, irreversible loss of the widespread and contagious intact forest values. This is particularly important with respect to the areas with low forest connectivity that has resulted from the extensive landscape transformation in the inland and coastal areas of northern Sweden as well as generally across the boreal forest biome (e.g., Potapov et al. 2017; Peura et al. 2018; Svensson et al. 2018). Hence, maintaining and strengthening a restrictive forestry policy above the mountain forest border, and also promoting a more ambitious conservation policy generally in the boreal biome, is much needed to secure effective and functional conservation, green infrastructure, and future provisioning of ecosystems services and ecosystem adaptive capacity in boreal forest landscapes.

Conclusions

This study focused on one of very few large intact forest landscapes in northern Europe, where we identified and analyzed distribution, density and connectivity of remnant primary forests, using proxies generated by remote sensing mapping on forest area not subject to systematic rotation forestry.

Our results reveal that close to 60% of the forest land remains intact, including all narrow, small and unproductive forests that are not subject to forestry, but with the absolute majority in a belt consisting of contiguous, connected and semi-connected forests extending south to north along the Scandinavian mountain range. We detected vast areas of forest components 10,000 ha in size and larger, encompassing half of the total area of intact forests in the study region, and an overall high connectivity within protected forests. Our results also show that currently not protected forests contribute substantially to connectivity, while connectivity gaps exists in the southern parts of the Scandinavian Mountains Green Belt. There, forests are severely fragmented and continuity values are lost, and thus forest landscape restoration is needed to re-establish connectivity and green infrastructure functionality. The Scandinavian mountains green belt should be regarded as an essential asset in national, European and global conservation policies

as an ecological legacy and critical mainland source for species, biodiversity, ecosystem services, climate change resilience and land use adaptive capacity for a very large region of the boreal biome.

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