Spatial co-occurrence between wind power and boreal forestlands with lichen important for reindeer browsing

– A landscape analysis

Rumsliga förhållandet mellan vindkraft och boreala skogsmarker med lavförekomst viktiga för renbetet – En landskapsanalys

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Swedish University of Agricultural Sciences
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Abstract

To meet the increasing demand of renewable energy, Sweden aim to expand the onshore wind power production from 30 TWh today, to 80 TWh by 2040. Most wind power sites will be placed in Northern Sweden, which coincides with the reindeer husbandry area, where indigenous Sami have a legislated reindeer husbandry right. Several studies show that reindeer are negatively affected by wind power in terms avoidance and habitat selection within several kilometers from the wind power sites, hence reduces the availability of reindeer winter forage. In winter, reindeer rely heavily on ground and epiphytic lichen. Therefore, the aim with my analysis was to assess the spatial relationship between wind power sites and forest with ground and epiphytic lichen occurrence within the reindeer husbandry area, with three main research objectives: (1) Compare lichen occurrence within spatial scales of wind power sites relevant for reindeer behavior to the site and planning areas in the national wind strategy, (2) estimate the possible reduction of reindeer winter forage due to wind power expansion in Jämtland, Västernorrland, Västerbotten and Norrbotten, and (3) compare how wind power affect reindeer winter forage in the reindeer herding communities Vilhelmina Södra and Östra Kikkejaure today. All spatial analyses were done with a geographical information system.

My result showed that up to 12 % respective 14% of forest with high ground and epiphytic lichen occurrence are affected by wind power sites in the reindeer husbandry area today. Västernorrland has the largest proportion of reindeer forage impacted both today and in future scenarios, while Västerbotten is facing the largest change from the situation today. Reindeer forage was especially impacted within Östra Kikkejaure, where around 30% of all forests with high ground and epiphytic lichen occurrence is affected by wind power today. Consequently, even though the physical wind power sites occupy a rather small area, it indirectly affects a substantial proportion of the available forage within the reindeer husbandry area, with an even larger impact on a more local scale, hence threatening the survival of reindeer husbandry as we know it today. By quantifying reindeer winter forage affected by wind power, the analysis contributes important information that can improve the knowledge for a more sustainable landscape planning in the multifunctional landscape of today.

Keywords: Lichen, QGIS, reindeer, reindeer husbandry, spatial analysis, wind power

Preface

First, I would like to thank my supervisors Wiebke Neumann, Johan Svensson and Sven Adler for their expertise in spatial analysis and land use conflict, who have provided me with crucial input throughout this project. Thank you, Wiebke, for your many hours helping me out in QGIS and RStudio when nothing seemed to work. Thank you, Johan, for helping me to get my story in order and for suggesting this project as topic for my thesis in the first place. Thank you, Sven, for your detailed input regarding reindeer husbandry and for providing the ground lichen model, which made this project possible. Next, a special thank you to Jenny Wik Karlsson and Maria Boström from Svenska Samernas Riksförbund for taking time to listen to my result and contributing with knowledge for a better understanding how wind power could affect reindeer husbandry.

During the master's program I have gained a special interest the field of spatial planning that combine ecological issues with human interests and conflicts. Over my master's thesis I have gained more knowledge over the complexity of these issues, which have been highly motivating for my future career.

Umeå, 20 January 2022
Erik Lundmark

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Abbreviations

NFI	National forest inventory
RHA	Reindeer husbandry area
RHC	Reindeer herding community

1. Introduction

Traditional Landscape values and land uses under threat

The anthropogenic need to harvest ecosystem goods is a key driver in transforming natural landscapes (Foley et al., 2005), resulting in trade-offs between humans' direct harvest needs and other vital ecosystem services (DeFries et al., 2004). This transformation has led to habitat fragmentation, degradation, and destruction, with severe consequences for biodiversity on a global scale (Pimm & Raven, 2005; Haddad et al., 2015; IUCN, 2013). In Sweden with 20 out of 28 million ha forestlands available for wood harvesting (Anon. 2021), the intensive forestry has re-shaped the forest landscape to meet the wood fiber demand of the forest-sector (Östlund et al., 1997; Lundmark et al., 2013), which has consequences for other goods, services, and values. The forest landscapes of northern Sweden, i.e., 55% of the Swedish land base (Sandström et al. 2016) has been used by indigenous Sami for centuries to millennia, for hunting, gathering and a pastoralist lifestyle. Due to colonization of these lands and discrimination of Sami rights by the Swedish crown and government (Lundmark, 1998), the Sami have lost accessibility to the land, making it more difficult to practice their exclusive right of reindeer herding. In addition to forestry, the northern Swedish forest landscapes are resources for several other land users and stakeholders, such as water and wind power companies, mining, and tourism. This cumulative pressure threatens the traditional values and land use of Sami people and survival of their cultural heritage (Rosqvist et al. 2021).

Renewable energy to combat climate change

The anthropogenic-caused global warming rate is unprecedented in the last 2000 years (IPCC, 2021). Forecasts predicts more frequent extreme weather events with higher intensity, with adverse effects on both humans and ecosystems and with a risk of an irreversible impact (Ibid.). This emphasizes the urgent need to shift from fossil energy towards green, renewable energy sources as a strategy to mitigate negative human impacts on the world climatic. Between 2015 and 2020, the energy produced by wind and solar increased from 4,6% to 9,8% on a global scale, where the majority is derived from wind power (Jones et al., 2020; BP, 2020). Long term forecasts expect wind power to expand to 35 % of the global energy production by 2050 (IRENA, 2019).

Swedish renewable energy goals

Sweden's energy consumption is expected to increase from 140 TWh to 200 TWh by 2040, of which 100 % should derive from renewable energy sources according to the national wind strategy (Swedish Energy Authority, 2021; Svensk Vindenergi, 2021). Out of five scenarios that the Swedish Energy Authority have created, on shore wind power evenly spread over the country according to energy consumption, area, and population (Swedish Energy Authority, 2021), is the option that has the highest probability of being implemented to achieve this goal (Swedish Energy Authority, 2019). This implies that the energy produced by wind power should increase from 30 TWh today, to 100 TWh by 2040, of which 80 TWh is based on land (Swedish Energy Authority, 2021; Svensk Vindenergi, 2021). However, due to the ongoing electrification, development of fossil free steel (Pei et al., 2020) and debate to shift from nuclear power, 80 TWh might be an understatement. On shore wind power will likely stand for a larger proportion in the future (Svenska Kraftnät, 2021). Such an increase of wind power energy also implies an increase in land exploitation, which is expected to lead to various and extensive negative ecological consequences (Arnett & May, 2018; Helldin et al., 2012; Skarin et al., 2021)

Conflict between two national interests

Areas important for reindeer husbandry and wind power are both considered as national interests (Environmental Code 1998:808). National interests are legally delimited areas and objects, which are especially important to protect from other land-use actions that might threaten a specific interest. However, many of these interests overlap, which means that conflicts are arduous to avoid. In a study of national interests in northern Sweden, eleven different national interests including land used for forestry claim up to 2-4 times the terrestrial area available (Svensson et al., 2020). According to Chapter 3 §10 in the Environmental Code, if two interests collide, the interest that favors a long term and sustainable use of the area should be prioritized. To date, wind power has commonly been given priority over reindeer husbandry (Swedish Energy Authority, 2020), with tendencies of a slight shift.

Historical and future transformation of northern Sweden

Reindeer husbandry is a spatially extensive land use that covers large areas and occurs in conjunction with other land uses, such as energy production, forestry, and mining, and as such takes place in multi-functional landscape. The national wind strategy defines the area needed for wind power expansion (with 6 MWh turbines) for each county, of which the major expansion is projected in northern Sweden (Swedish Energy Authority, 2021; Svensk Vindenergi, 2021) and to a large extent within the reindeer husbandry area (hereafter RHA), where indigenous Sami have a legislated reindeer husbandry right (Reindeer Husbandry Law, 1971:437) to use the land for their livestock. Today, there are 1,559 established wind power sites within the RHA, and op top of this 1,458 that are approved and another 280 that are in process (County Administrative Board, 2021; Figure 1). Northern Sweden has undergone a major transformation since the end of the 19th century, especially due to modern forestry and effective fire suppression (Jansson et al., 2011). Today, the forest structure is more homogenous, with single storied, young, and dense stands, compared to the structure before transformation with multistoried old-growth forests with long continuity, shaped by the natural dynamics of forest fire (Östlund el al., 1997). The remaining patches of old growth forest are now scattered within the productive landscape and in total cover only 12-15% of the forest landscape in northern Sweden (Kivinen et al., 2012; Anon, 2021).

A consequence of the changed forest structure is the reduction of both ground and epiphytic lichen, such as *Cladonia spp. and Bryoria spp.*, which stands for a crucial part (80%) of reindeer (*Rangifer tarandus tarandus*) diet (Danell & Nieminen, 1997; Kivinen et al., 2012). The effect of forest management on lichen is well-studied. For example, Sandström et al. (2016) revealed a 71 % loss of areas abundant of ground lichen between 1953-2013, which was explained by the loss of old and open Scots pine (*Pinus sylvestris*) forests. Studies on epiphytic lichen and Norway Spruce (*Picea abies*) have highlighted a similar trend. Esseen et al. (1996) showed that the amount of epiphytic lichen was six times as high per branch in old growth forest compared to managed stands. On landscape level, the abundance of epiphytic lichen has shown to be twice as high within natural landscape compared to managed ones (Dettki & Esseen, 1998). The dense and fast growing forests that are generated by the intensive forestry practice, in combination with the absence of forest

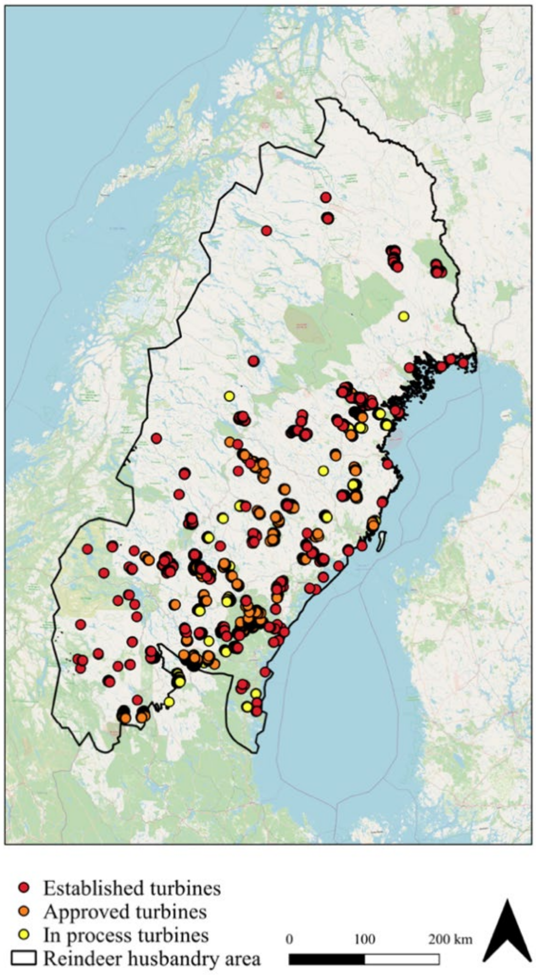


Figure 1. *Established (red) approved (orange) and in process (yellow) turbines within the reindeer husbandry area, based on data from the County Administrative Board (accessed September 10, 2021).*

fire (Östlund el al., 1997) provide unfavorable conditions for lichens (Horstkotte & Moen, 2019; Zackrisson, 1977). Importantly, simulations suggest that the amount of lichen will likely decrease if forest management will stay the same during the upcoming century (Horstkotte et al., 2011).

Climate change is expected to directly affect lichen abundance. Studies by Cornelissen et al. (2001) showed that lichens may decline in response to climate change, since an expected increase in vascular plants reduces the amount of lichen. Given the expected increase in woody vegetation as a response due to climate change, Skarin et al. (2020) argued for more research regarding the reindeer ability to respond and adjust to the impact of climate change. Next to the threat by forestry and climate change, the expansion of wind power might lead to further pressure on remaining reindeer forage and lead to a structural segmentation of the landscape and a restriction of the accessibility to the foraging areas that are left.

The exploitation of reindeer forage reduces reindeer husbandry's ability to adapt to environmental stochasticity (Horstkotte et al., 2014). Both spatial and temporal connectivity of forage are important, since the seasonal and weather changes influence the accessibility and reindeer choice of areas (Horstkotte et al., 2014). So-called rain-on-snow events have become more common during late winter in the boreal and arctic regions, creating an icy crust covering the ground lichen and reducing the availability for the reindeer to dig down to the ground, which may have fatal consequences on their health and survival (Bartsch et al., 2010; Forbes et al., 2016). During periods with low accessibility of ground lichen epiphytic lichen provides a replacement and thus additionally important source of food (Rominger & Robbins, 1996; Rosqvist et al., 2021). Therefore, there is a need for functional landscapes with spatial and temporal connectedness to forestlands with lichens throughout the year.

Current research on reindeer and wind power

Overexploitation of land is one of the key drivers in the declining wildlife populations (Rosser & Mainka, 2002). The negative impact by wind power per se is established mainly for flying animals such as bats and birds (Arnett & May, 2018; Cryan et al., 2014). Research on large terrestrial mammals, like reindeer, has been scarce until the last decade (Helldin et al. 2012). Several studies now show that wind power sites do have an impact on reindeer behavior in terms of movement, habitat selection and calving sites on both local and regional scale studies (Skarin et al. 2015, 2016, 2017, 2018, 2021; Strand et al., 2018; Eftestøl et al., 2021). Reindeer tend to avoid wind power sites both during construction and operation phase. Skarin et al. (2016) showed that reindeer tend to avoid areas within 3 km during the operational phase. Other studies show that proximity to operational wind power sites led to a decrease in reindeer habitat selection, especially due to the visibility of turbines (Skarin et al., 2018). Habitat selection of forests without visibility of operating turbines increased with 79 %, at a 5 km distance, compared to before the construction. The effect decreased and eventually could not be detected at approximately 10 km (Ibid.). Verdicts at Swedish court cases also state that wind power park/turbines do influence reindeer within 3-5 km (Swedish Energy Authority, 2020). The change in documented reindeer behavior aligns well with reindeer herders' experiences of how reindeer react to wind power sites (Skarin et al., 2016).

Knowledge gap

To date, there is a lack of studies that analyze the spatial relationship between wind power sites and lichen occurrence on a landscape perspective. Due to increased pressure and conflict over the landscape of northern Sweden (Widmark, 2009; Svensson et al., 2020), there is an increasing need for regional and landscape analysis to understand the impacts of further exploitation of lichen-rich areas. This type of analysis is now possible thanks to the recently estimated ground lichen map (Adler et al., 2021), which predicts the likelihood of ground lichen at a given place. With this available dataset, and with estimates on epiphytic lichen, it is possible to make a more precise analysis of the impact of wind farms on reindeer forage. To date, such an analysis has not been made in Sweden.

1.1. Aim

The aim of this study was to assess the spatial relationship between forests with high likelihood for ground and epiphytic lichen occurrence, i.e., as a proxy for high abundance of reindeer winter forage, and different spatial scales of wind power sites in northern Sweden. Hence, quantifying reindeer winter forage affected by wind power can increase the understanding of what consequences wind power expansion will have for reindeer and reindeer husbandry, especially during the winter months when the food resources are scarce. Specifically, I addressed the three following research objectives:

1) *How does wind power sites relate spatially to potential reindeer winter forage, at spatial scales relevant for reindeer behavior compared to wind power establishments site and planning areas?*

2) *How large reduction of future reindeer winter forage should be expected in Jämtland, Västernorrland, Västerbotten and Norrbotten counties, due to the forecasted wind power expansion in the National wind strategy?*

3) *How does wind power sites relate spatially to potential reindeer winter forage, at spatial scales relevant for reindeer behavior compared to wind power establishments site and planning areas, specifically for the communities of Vilhelmina Södra and Östra Kikkejaure?*

2. Method

2.1. Study area

The study area includes northern Sweden delimited by the borders of the RHA and below the mountain forest border. This delineation was based on the extension of the RHA and on the limitations on further expansion of wind power in the mountain region as expressed in the wind power strategy (Swedish Energy Authority, 2021), here understood as the area above the mountain forest border.

Northern Sweden covers a wide span of latitudes from south to north and longitudes from east to west, accompanied with altitude increases from the Bothnian bay to the mountains. These factors influence the climate, with cold winters in the most northern part and mild winters in the southern part, with increasing precipitation from east to west. Roughly, the length of the snow cover stretches from November-May (SMHI, 2018). The northern climate makes the seasonal variation prominent and, together with factors as altitude and disturbance regime, it influences the forests' species composition and structure (Bradshaw et al., 1993; Anon, 2021). Below the mountain forest border, forest covers 13,5 million ha in Northern Sweden, corresponding to almost 50% of all Swedish forests (Anon, 2021). Pine and spruce are the dominating species, where the former is more dominant further north and south (Anon, 2021), partly due to forest management and fire suppression (Östlund et al., 1997; Jansson et al., 2011), even if they both occur naturally. Northern Sweden holds one of the last remaining intact forest landscapes (Potapov et al., 2008), of which the density of intact forest landscapes and continuity forests is the highest above the mountain forest border (Svensson et al., 2019). Below the mountain forest border, forests are more fragmented and forest landscapes are more transformed, although at lesser degree in Norrbotten county (Ibid.).

2.2. Environmental Data

The reindeer lichen map (Adler et al., 2021) plays a central role in this analysis. It is based on Sentinel 2 satellite data, lidar-data for height and vegetation cover, soil map and inventory data from National Forest Inventory (hereafter NFI; Figure 2). A Generalized Additive Model (GAM; Hastie & Tibshirani, 1990) was used to create the final lichen map. The spectral data from Sentinel 2 located areas that likely have ground lichen and the data from NFI was used to decide the lichen coverage in the given location. Since the model trains its predictions on data from NFI, it creates an understanding of which variables that likely affect the occurrence and coverage of ground lichen. The preliminary lichen map was the result of these steps, which is the map used in my analysis. The final lichen map is on local scale for each reindeer herding community (hereafter RHC), which have better predictive capacity. Therefore, the preliminary lichen map I have used is underestimating the lichen coverage, but not the occurrence of lichen (Adler et al., 2021)

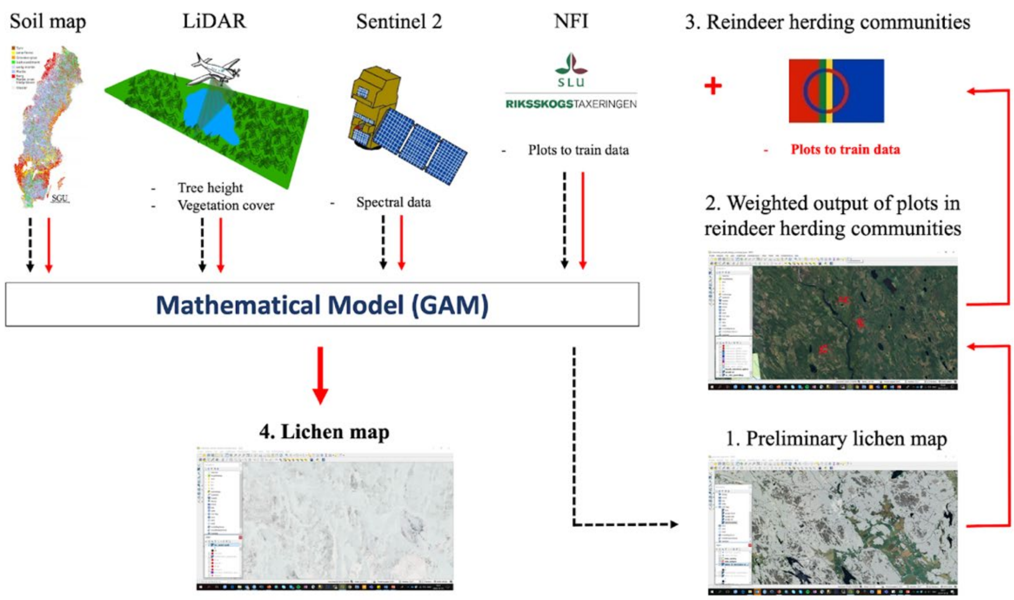


Figure 2. *All Geodata (soil map, tree height, veg. cover and spectral data) and the inventory data (NFI) that was applied in the Generalized Additive Model (GAM) to create the preliminary lichen map used in this study. Step 2-4 was made to enhance the predictive capacity of the final lichen map that is on a local scale for each reindeer herding community (Modified from source: Adler et al., 2021).*

I subdivided the lichen occurrence into two classes of coverage (Table 1). To suit my analysis and given the skewed coverage among classes, I reclassified the data, creating two new classes (0-10 %, > 10 %). I applied 10 % coverage as a threshold,

since forests with > 10 % lichen coverage are of interest for reindeer husbandry (Hedenås et al., 2017).
In addition to the ground lichen map, I applied a variety of geodata to generate a proxy for epiphytic lichen occurrence. I used land cover data (Swedish EPA, 2021), a proxy for continuity forest (Ibid.) and Lorey's height (Swedish Forest Agency, 2021). From the ground cover data, I created two new classes (coniferous forest and non-coniferous forests). I applied continuity forests as a constraint to select only forests that were included in the dataset, i.e., forests older than 70 years, with an 80-90 % certainty (Ahlkrona et al., 2017a). By combining the proxy for continuity forests and the land cover data, I could identify and select older, coniferous forests. The land cover data differ from many of the inventory plots by the NFI, regarding whether it is temporary non-forest (trees < 5 m) or forested area (trees > 5 m) (Nilsson et al., 2020). Therefore, I filtered out forests that should be excluded by creating two new classes using Lorey's height (< 5 m, > 5 m) on forestland. Using the raster calculator, I created a new map as a proxy for epiphytic lichen with two new classes (Low proxy, high proxy; Figure 3; Table 1).

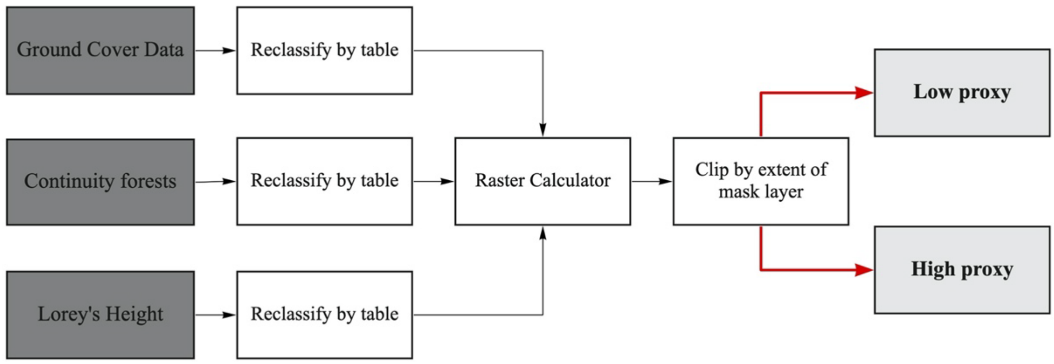


Figure 3. *A simplification over the process of how I created the proxy for forests with high probability of epiphytic lichen in QGIS.*

Table 1. *Classes in my analysis. The ground lichen data originates from the coverage within the ground lichen map, of which the chosen thresholds are based on reindeer herders' preferences. Since I have no data over epiphytic lichen occurrence, the classes for epiphytic lichen occurrence are based on the assumption that coniferous, proxy continuity forests over 5 meters have higher probability of having epiphytic lichen.*

Lichen	*Class*	*Description*
Ground	**0-10 %**	Ground lichen coverage is smaller 10 % and of low interest for reindeer husbandry.
Ground	**> 10 %**	Ground lichen coverage is larger than 10% and of high interest for reindeer husbandry.
Epiphytic	**Low proxy**	Low probability of epiphytic lichen occurrence. Class includes deciduous forests, non-continuity forests and forests below 5 meters.
Epiphytic	**High proxy**	High probability of epiphytic lichen occurrence. Class only includes coniferous, continuity forests above 5 meters.

Table 2. *Geodata used in the analysis. All data have the coordinate reference system SWEREF 99™.*

Description	*Source, access date*	*Format*	*Extent*	*Resolution*
Lichen Map	Adler et al. 2021, 2021-09-10	Raster.tif	N. Swe	10x10
Ground cover data	Swedish EPA (2021), 2021-09-10	Raster.tif	Sweden	10x10
Continuity forests	Swedish EPA (2021), 2021-09-10	Raster.img	N. Swe	10x10
Lorey's height	Swedish Forest Agency (2021), 2021-09-16	Raster.tif	Sweden	12,5x12,5
Mountain Forest border	Swedish Forest Agency (2021), 2021-09-21	Shape-file	N. Swe	-
Wind power sites	County Administrative Board (2021), 2021-09-10	Shape-file	Sweden	-
Reindeer husbandry area	County Administrative Board (2021), 2021-09-13	Shape-file	N. Swe	-
County borders	Swedish Land Survey (2021), 2021-09-21	Shape-file	Sweden	-

2.3. Approach

2.3.1. Extent of my analysis

The analyses were performed on three different geographical scales; the entire reindeer husbandry area below the mountain forest border, the counties of Västernorrland, Jämtland, Västerbotten and Norrbotten, and two RHCs, Vilhelmina Södra and Östra Kikkejaure. The RHC:s were subjectively selected to represent a mountain-to-coast community and a within-forestland community (Figure 4; Swedish Energy Authority, 2021). On the county scale, I excluded Dalarnas and Gävleborgs counties due to large areas outside the RHA borders. I used the scale of the RHA to address my first research question, the county scale to address my second question, and the smallest scale of two reindeer herding communities, to address the final question.

The national wind strategy (Swedish Energy Authority, 2021) includes proposals on how much area is needed in each county to fulfill the Swedish energy goals. Since the numbers are estimated for each county, only the counties that are within the borders of the reindeer husbandry area were suitable in this analysis. The largest scale (first question) is of importance for a better understanding of how wind power, in general, is affecting all reindeer forage today. The county analysis is important to analyze how the availability of reindeer forage will change with increased wind power production levels and how it differs regionally. The counties of Jämtland, Västerbotten and Norrbotten are in full within the borders of the RHA, while a small part (2,81%) of Västernorrland is outside of the RHA. Therefore, all results concerning the second question are adjusted to the share of Västernorrland within the RHA, by reducing the total county area in the estimates. The final step is a further in-depth approach and the most relevant for reindeer husbandry since the reindeer herders are delimited by their RHC borders. Due to overlapping borders between the majority of all RHCs, estimating the impact by wind power in each community is challenging. Since the RHA is divided into 51 RHCs, the extent of the third question covers in particular two RHCs, one mountain (Vilhelmina Södra), and one forest RHC (Östra Kikkejaure), as a working example of how wind power sites impact reindeer forage on a local scale. Thus, my analysis includes both general and more specific information about lichen occurrence and the impact from wind power at different spatial scales in the RHA.

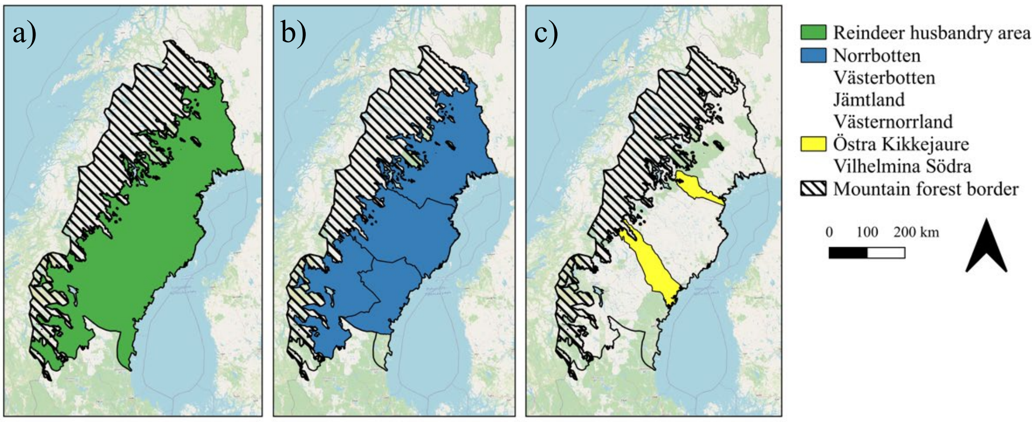


Figure 4. *Extent of the study area for* **a)** *question 1 (green)* **b)** *question 2 (blue) and* **c)** *question 3 (yellow). All study areas exclude the area above the mountain forest border (striped).*

2.3.2. Spatial relationship between wind power sites and reindeer winter forage (Q1)

To estimate the impact of wind power sites on forests with high lichen occurrence, I selected all established wind power turbines within the RHA. I created buffers around each turbine with three different buffers (*3-5-10 km*), which are based on previous studies of the impact by wind power on reindeer (Skarin et al., 2016; Skarin et al., 2018). I dissolved all overlapping buffers to prevent overlap in the analysis. Further, I applied tabulate intersection on both proxies to estimate how much of each buffer size includes a certain class of lichen occurrence.

To compare the scientific buffers with the national wind strategy, I estimated the direct and indirect impact of all wind power sites. The *direct impact* covers the area that is covered by turbines, with a 300 m buffer since the rotor blades prevent other use within this area, i.e., the site areas. The *indirect impact* is estimated to be three times the direct impact, with the purpose to give enough space for the planning of other infrastructure in connection to the wind power establishment, i.e., the planning areas (Swedish Energy Authority, 2021).

First, by grouping turbines using the ID of their project area, I created polygons for each site. I created two different types of polygons: A concave entity that follows the distribution of turbines across space very closely, and a convex entity that is delimited by the location of the outer turbines. Thus, the concave is a more conservative approach, whilst the convex generate a larger impact area (Figure 5). I chose to create these two types to be able to compare different potential impact areas that combined relate to different types of impact and different planning premises given how landscape features affect the distribution of turbines at given place. Wind power sites that only have one or two turbines have too few points to create a polygon. Therefore, I sorted these out manually. I created a 300 m buffer for wind power sites with only one turbine. To connect the turbines in wind power sites with two turbines, I created a line between the turbines and then added a 300 m buffer. I merged and dissolved all polygons to prevent overlapping data. As before, I applied tabulate intersection to quantify lichen occurrence within the site areas.

To estimate the indirect impact, I used the location and area of the direct impact. In contrast to the direct impact, with a known shape due to the turbines' placement, the shape of the indirect impact is unknown. Thus, instead of enlarging the polygon for direct impact three times the size with the same shape, I made a new, circular polygon, three times the size. The location of the enlarged polygon was based on the centroid of the initial polygon. In this way, I focused only on the area that is claimed, with the assumption that the shape is different from the direct impact, which also led to a more consistent approach for all sites. I dissolved all polygons and I applied tabulate intersection to estimate the lichen occurrence within the planning areas.

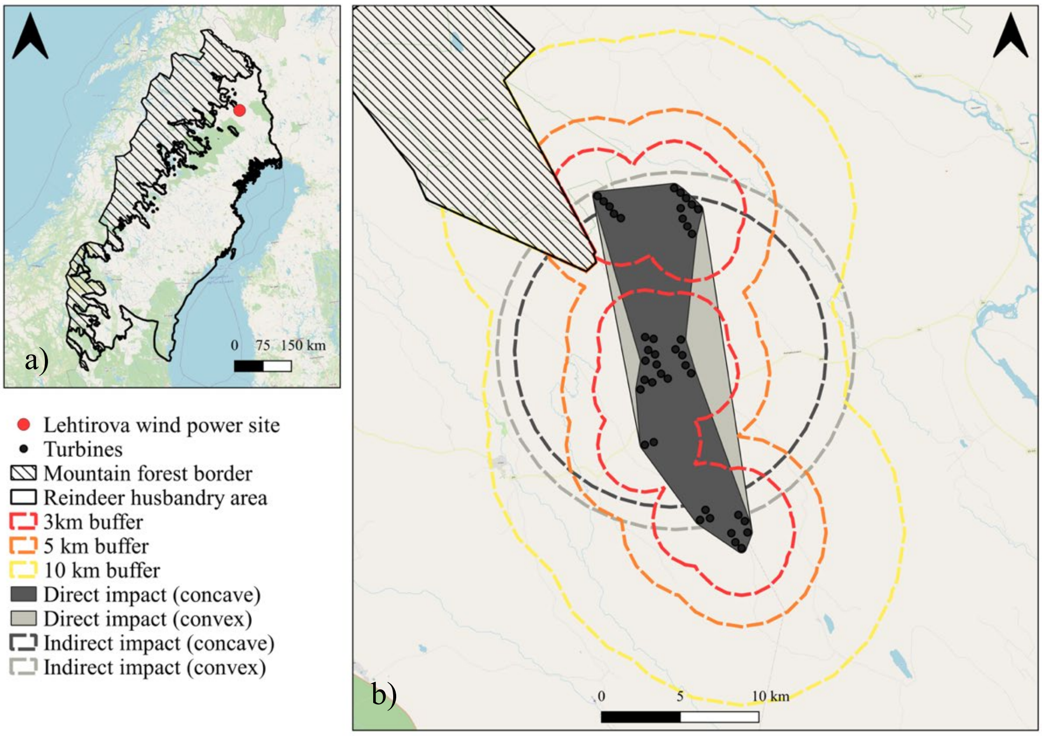


Figure 5. *Illustration of layout for direct and indirect area estimates and buffers.* **a)** *Location of Lehtirova wind power site in Norrbotten county.* **b)** *The spatial difference between the 3, 5 and 10 km buffers, which are based on studies of reindeer response to wind power sites, compared to the direct and indirect impact based on the demanded area for a wind power site in the national wind strategy. The direct and indirect impact is estimated with both a concave (i.e., more conservative) and a convex (i.e., more generous) estimation.*

2.3.3. Expected reduction of reindeer winter forage in Jämtland, Västernorrland, Västerbotten and Norrbotten due to future wind power expansion (Q2)

To estimate the occurrence of lichen within wind power sites, today and with increased production levels, I extracted the dissolved polygons of the site and planning areas that I used in research question 1 but to the extent of Jämtland, Västernorrland Västerbotten and Norrbotten, below the mountain forest border. Since the placement and shape of future wind power sites is unknown, I estimated the lichen occurrence based on the stands which are affected by wind power sites today. Therefore, I compared the area that is affected by wind power today with how much area is suggested by the national wind strategy within a given county (Swedish Energy Authority, 2021). I used the relationship between these two for each county and multiplied the classes of lichen occurrence today to estimate the future area of each lichen class within wind power sites. From there, I calculated how much of each class that is needed per TWh with 6 MW-capacity turbines, which was the capacity used to estimate the extent of wind power sites in the 80 TWh scenario (Ibid.) and thus made is possible to estimate the area of each lichen class within the site and planning areas at higher forecasted production levels.

Based on the report by Svenska Kraftnät (2019), the electrification scenario with an out phasing of nuclear power suggests a production level at 98 TWh by 2045; i.e., beyond the 80 TWh estimate by the Energy Agency (2021). To meet this possible increased future energy and to meet possible even higher demands, I created a 100 TWh and a 120 TWh scenario on top of the original 80 TWh scenario. I applied tabulate intersection to estimate the occurrence of ground and epiphytic lichen within the site and planning areas for all three scenarios.

2.3.4. Spatial relationship between wind power sites and reindeer winter forage in Vilhelmina Södra and Östra Kikkejaure (Q3)

My in-depth analysis was divided into two different steps – (1) estimating the lichen occurrence within all RHCs and their overlapping areas, and (2) estimating the lichen occurrence within the spatial scales relevant for reindeer (*3-5-10 km*) and the site and planning areas of wind power sites in Vilhelmina Södra and Östra Kikkejaure. Initially, I applied intersection on the RHC borders with itself, resulting in new attributes that include the overlapping area. Further, with the overlapping and non-overlapping areas, I applied tabulate intersection on the ground lichen model and the proxy for epiphytic lichen. By doing this, I could estimate how much reindeer forage that is within the overlapping and non-overlapping area, but also decide how many times a RHC overlaps with another. Hence, it gives a better understanding how large proportion of a RHCs reindeer forage that needs to be shared with another RHC. The second step focus on the lichen occurrence that is affected by wind power sites in Södra Vilhelmina and Östra Kikkejaure today. Like in research question 1, I estimated the lichen occurrence within 3, 5 and 10 km radius of the turbines, and within the site and planning areas. To delimit the affected area of wind power sites to only Södra Vilhelmina and Östra Kikkejaure, I extracted the dissolved polygons for the buffers and site and planning areas that I used for the whole RHA, to the extent of the RHCs borders. As before, I applied tabulate intersection to estimate the lichen occurrence affected by wind power sites.

All spatial analyses were done in the open-source geographical information system QGIS version 3.20 (QGIS development team, 2021), with some further analysis in RStudio version 1.4 (RStudio Team, 2021).

2.3.5. Ethical considerations

I have had a dialogue with Svenska Samernas Riksförbund throughout this study, including a presentation of preliminary result, who have provided me with important input. A collaborative process like this ensures that reindeer herders' knowledge is included in the process, which is especially important in a study that covers a topic which correlates with their livelihood.

3. Result

At a landscape perspective, the amount of both ground and epiphytic lichen coverage is low within the RHA. Most of the area (98,8 %) has little ground lichen with a coverage of 10% or less per 10 m^2. The proxy for epiphytic lichen suggests a higher occurrence (21 %) of the forest land within the RHA is coniferous continuity forests over 5 meters, indicating a high likelihood for epiphytic lichen occurrence (Table 3). Within the RHA, about one-quarter to one third of the area is water or non-forestland, resulting in no lichen occurrence at these places at all (ground lichen model: 31,4 %, epiphytic lichen proxy: 22,7%). For my further analysis, I excluded these areas as “No Data” when estimating lichen occurrence, because it is of no interest for the analysis.

Table 3. *The proportional cover of ground and epiphytic lichen per cover class within the reindeer husbandry area below the mountain forest border (RHA). Ground lichen is separated into classes based on their percentage coverage. Epiphytic lichen is separated based on whether it is conifer forest, continuity forest and height > 5 m (middle/high proxy) or non-coniferous continuity forest below 5 m or non-continuity forest over 5 m height (low proxy). Middle and high proxy indicate that it is conifer continuity forest over 5 respectively 15 m height. Hereafter, all results are separated into two classes for both ground and epiphytic lichen, which are compared with the lichen occurrence in the RHA for two classes.*

Lichen	**Coverage Class**			
Ground Lichen	*0-10 %*	*10-25 %*	*25-50 %*	*50-100 %*
Proportion within RHA	**98,81%**	**0,98%**	**0,15%**	**0,06%**
Epiphytic Lichen	*Low proxy*	*Middle proxy*	*High proxy*	
Proportion within RHA	**79,32%**	**12,67%**	**8,01%**	

The following result highlight the area that is affected by wind power sites today and what is expected to affect in the future according to the national wind strategy. Different perspectives determine the scale of a possible impact. If the analysis is based on impact buffers (Figure 6a) or a direct and indirect site and planning perspective (Figure 6b), clearly influences the size of impact, where all buffers have a larger spatial scale than both the site (*direct impact*) and planning areas (*indirect impact*).

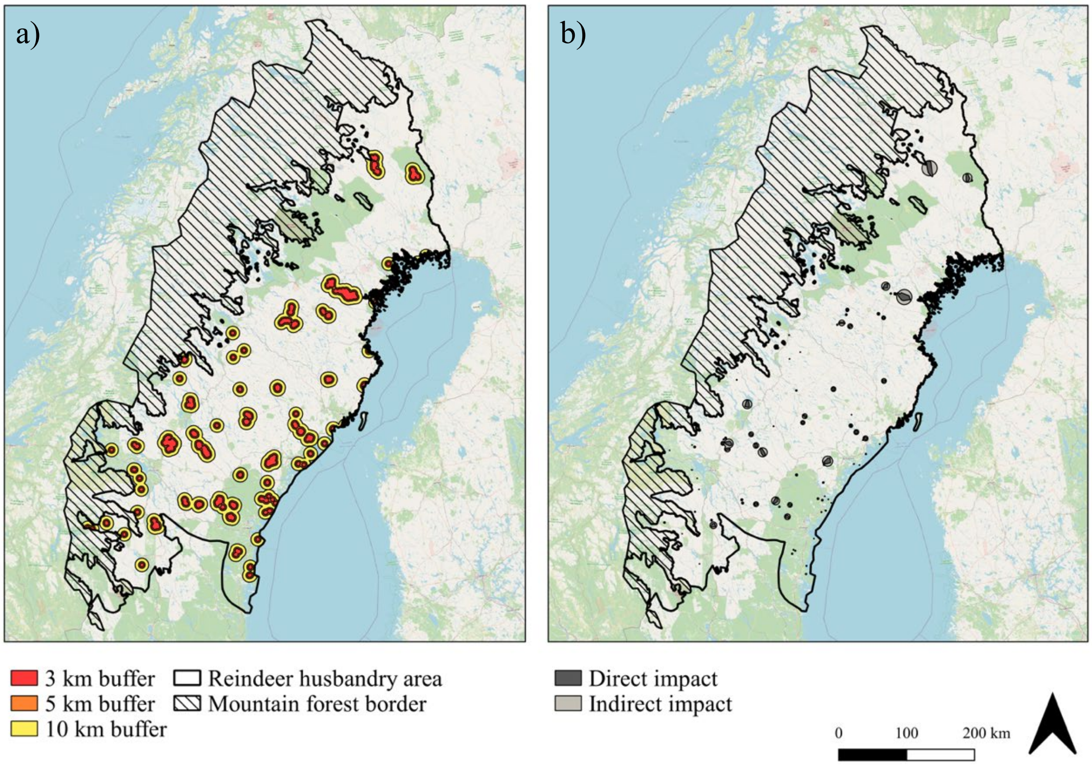


Figure 6. **a)** *The spatial scale of a 3 km (red), 5 km (orange) and 10 km (yellow) buffer around established wind power sites within the reindeer husbandry area below the mountain forest border.* **b)** *The spatial scale of the direct (dark grey) and indirect (bright grey) impact of established wind power sites within the reindeer husbandry area, below the mountain forest border. In this figure the direct and indirect impact is based on the convex, i.e., more generous, estimation.*

3.1. Spatial relationship between wind power sites and reindeer winter forage (Q1)

3-5-10 km buffers

A substantial proportion of all forests with high ground lichen coverage lies within the wind power sites in the RHA but constitutes a rather small area. Within a 3 km buffer, forests with high lichen coverage constitute a proportion of 2 % of all forests with high lichen coverage within the RHA. By increasing the buffer size to 5 km, the proportion doubled to 4%, and further increased to 12 % within a 10 m buffer (Figure 7a). The three buffers around the wind power sites corresponds to 30-160 km^2 of forests with high ground lichen coverage (Figure 7b), which make up 1 % of the total area within the given buffer. Overall, the result indicates a rather low proportion of ground lichen within the wind power sites, but also on a landscape level (Appendix 1).

Most of the forests affected by wind power sites have low probability of epiphytic lichen. Yet, in comparison to ground lichen occurrence, the probability of epiphytic lichen is larger by proportion but especially by area. Within different buffers sizes, the proportion of forests with high probability of epiphytic lichen ranges between 3-14 % of all forests with high probability of epiphytic lichen within the RHA (Figure 7c), which correspond to 707-3,627 km^2 (Figure 7d), i.e., a much larger area than the forests with high ground lichen occurrence. A fifth of the forests, within all buffer sizes, has high probability of epiphytic lichen, which is lower than the corresponding proportion in the RHA (Appendix 2).

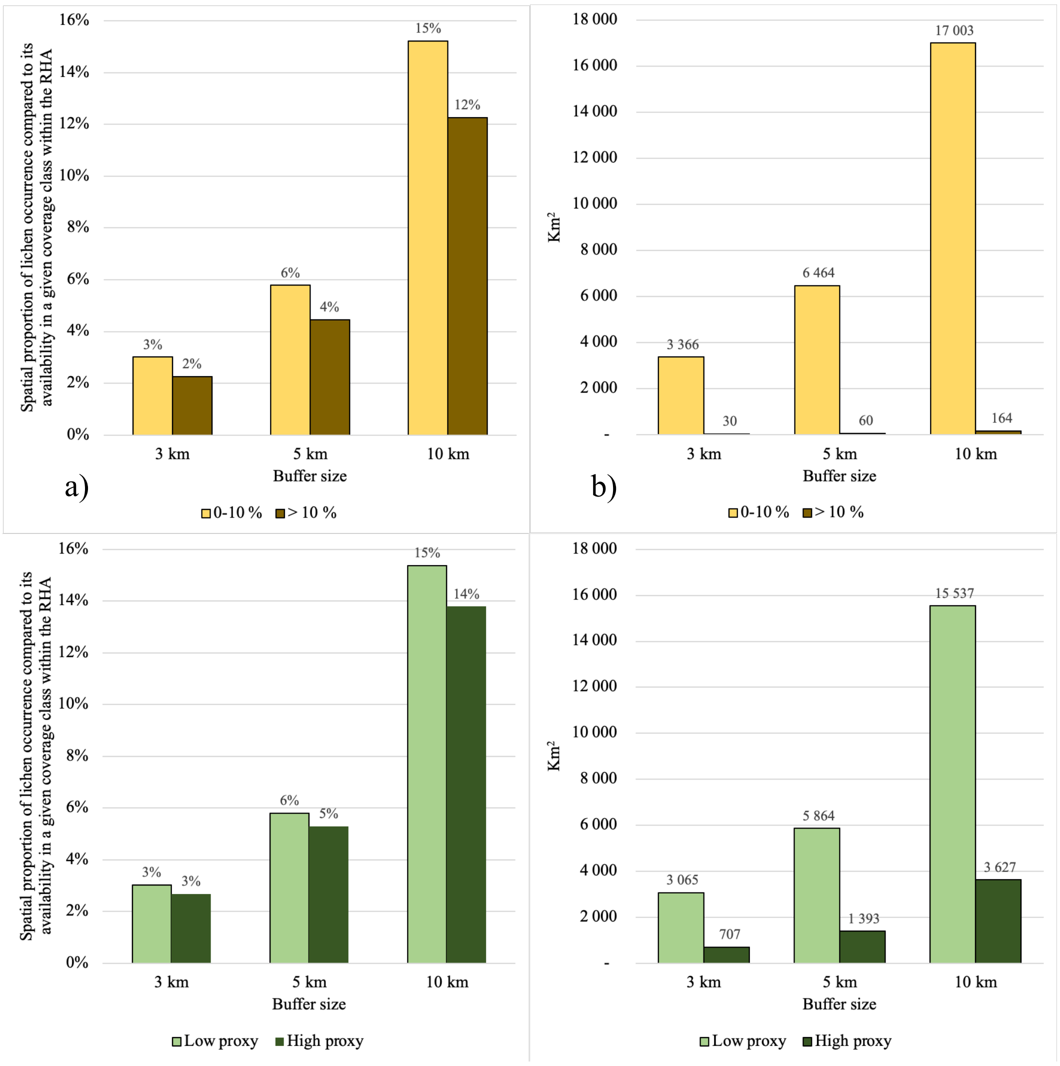


Figure 7. a) *Proportion of forests with low (0-10 %) or high (> 10 %) ground lichen occurrence within wind power sites at three spatial scales (3-5-10 km) compared to lichen availability in each class in the reindeer husbandry area.* **b)** *Spatial coverage [km^2] of lichen forests (0-10%, >10%) within wind power sites on three spatial scales.* **c)** *Proportion of forests with low proxy (no conifer continuity forest or conifer continuity forest < 5m) or high proxy (conifer continuity forest > 5m) of epiphytic lichen occurrence within wind power sites on three spatial scales (3-5-10 km) compared to lichen availability in each class in the reindeer husbandry area.* **d)** *Spatial coverage [km^2] of forests in the given classes within wind power sites on three spatial scales.*

Direct and indirect impact

Within and close to the wind power sites, forests with high ground lichen coverage constitutes a smaller proportion and area compared to the three spatial scales relevant for reindeer (*3-5-10 km*). Both within the site (*direct impact*) and planning areas (*indirect impact*), forests with high ground lichen coverage make up less than 1 % of all forests with high ground lichen coverage in the RHA (Figure 8a), which only account for a few square kilometers (Figure 8b). The difference between the concave and the convex approach indicates a rather small difference both regarding the proportion (Figure 8a) and area (Figure 8b) within the wind power sites. Forests with high ground lichen coverage only account for 1 % of the total site and planning areas, and thus represent a similar coverage as the entire RHA. Even though the difference is small, the share of forests with high ground lichen coverage is larger in the site areas than the planning areas, indicating that ground lichen coverage decreases with distance from the wind power establishment (Appendix 3).

Compared to ground lichen, both the proportion and size of forests with high probability of epiphytic lichen within the planning areas are larger and cover up to 1,5 % of all forests with high probability of epiphytic lichen in the RHA (Figure 8c). Since forests with high probability of epiphytic lichen generally are more common, these forests correspond to a much larger area (Figure 8d) within the wind power sites than forests with high ground lichen coverage. Consequently, the difference between the concave and concave approach also results in a larger difference in terms of area, compared to forests with high ground lichen coverage. In opposite to the forests with high ground lichen coverage, forests with high probability of epiphytic lichen are lower in proximity to the wind power sites (Appendix 4).

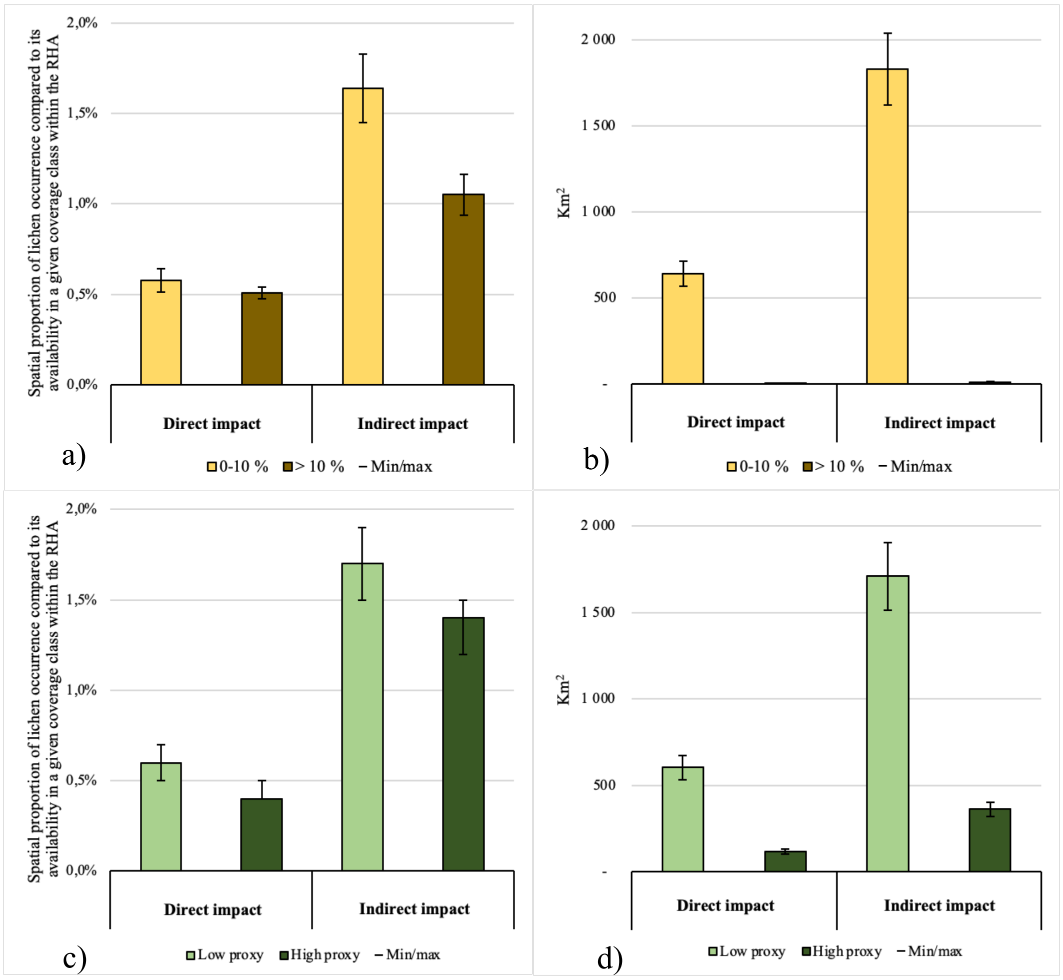


Figure 8. a) *Proportion of forests with low (0-10 %) or high (> 10 %) ground lichen occurrence within the wind power sites site areas (direct impact) and planning areas (indirect impact) compared to lichen availability in each class in the reindeer husbandry area.* **b)** *Spatial coverage [km^2] of lichen forests (0-10%, >10%) within the wind power sites site and planning areas.* **c)** *Proportion of forests with low proxy (no conifer continuity forest or conifer continuity forest < 5m) or high proxy (conifer continuity forest > 5m) of epiphytic lichen occurrence within the wind power sites site areas (direct impact) and planning areas (indirect impact) compared to the lichen availability in each class in the reindeer husbandry area.* **d)** *Spatial coverage [km^2] of forests in the given classes within the wind power sites site and planning areas.*

3.2. Expected reduction of reindeer winter forage in Jämtland, Västernorrland, Västerbotten and Norrbotten due to future wind power expansion (Q2)

The need for wind power expansion will lead to an increase between 1,4 to 5,1 times of the area of wind power sites today, depending on county and whether it is within the site or planning area. The planning areas in Västerbotten has the largest increase (Table 3). Within the four counties, the proportions for each lichen coverage class in future wind power sites is about same as today.

Table 3. *The proportional increase from current size of the wind power sites site areas (direct impact) and planning areas (indirect impact) if the energy production would increase to 80 TWh, 100 TWh or 120 TWh from today for a given county.*

	Production level		
	80 TWh	100 TWh	120 TWh
County	*Direct/Indirect*	*Direct/Indirect*	*Direct/Indirect*
Jämtland			
Increase from today	***1,84/1,82**	**2,30/2,27**	**2,76/2,72**
Västernorrland			
Increase from today	**1,50/1,56**	**1,88/1,95**	**2,25/2,34**
Västerbotten			
Increase from today	**3,29/3,37**	**4,11/4,21**	**4,93/5,05**
Norrbotten			
Increase from today	**1,35/1,41**	**1,68/1,77**	**2,02/2,12**

**E.g., if the energy production increase to 80TWh in Jämtland, the site areas in Västernorrland would increase 1,84 times current size.*

Ground lichen

Forests with high ground lichen coverage account for a rather small proportion within the wind power sites in all counties except from Västernorrland. Today, the site areas in Västernorrland comprise 1,3 % of all forests with high ground lichen coverage within the county. In the planning areas the proportion increases to more than the double. In both Jämtland and Västerbotten, site and planning areas have a proportion of 1% or less, based on all forests that are available with high ground lichen coverage in the county. In Norrbotten, the proportion is slightly larger than in Jämtland and Västerbotten (Figure 9a).

With an energy production of 80 TWh, the proportion of forests with high ground lichen coverage in Västernorrland would be larger than the corresponding proportions in the other three counties if the production level would reach 120 TWh. With increased production levels, Västerbotten would surpass the proportion in Jämtland and Norrbotten. In terms of area, forests with high lichen coverage within wind power sites accounts for a few km^2 today and increases with the production level. In future scenarios, Jämtland and especially Västernorrland has the smallest area of forests with high lichen coverage within the site and planning areas, while Västerbotten have close to equal size as Norrbotten for all productions levels in both the site and planning areas. Similar as previous results that take the entire RHA into account, the share of forests with high ground lichen coverage is largest in proximity to the wind power sites for all counties (Appendix 5).

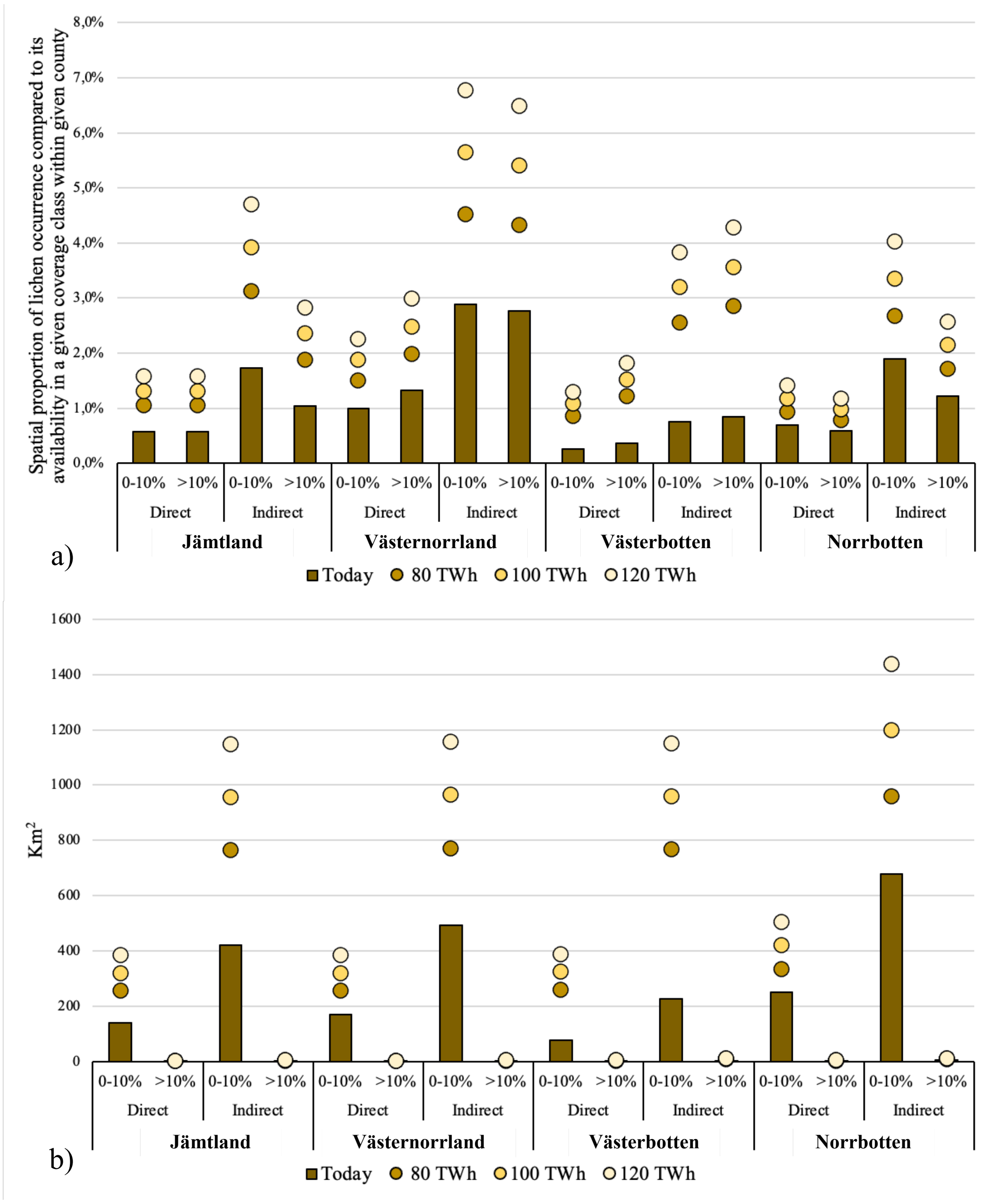
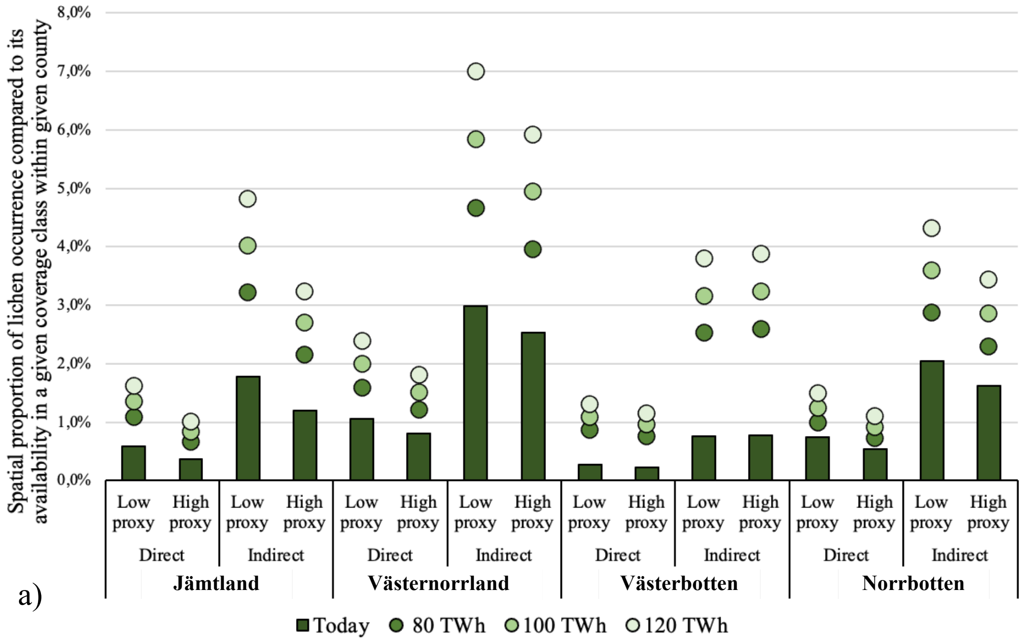


Figure 9. a) *Proportion of forests with low (0-10 %) or high (> 10 %) ground lichen coverage within the wind power sites site areas (direct impact) and planning areas (indirect impact) compared to lichen availability in each class in the given county today (bar) and in future scenarios with increased production levels (circles).* **b)** *Spatial coverage [km²] of lichen forests (0-10%, >10%) within the wind power establishments site and planning areas.*

Epiphytic lichen

The consequences of wind power expansion on forests with high probability epiphytic lichen have similar trends as the consequences on forests with high ground lichen coverage but highlights the difference between the counties in terms of which type of lichen that is more affected. Of all available forests with high probability of epiphytic lichen within each county, Västernorrland has the highest proportion today both within then site and planning areas, followed by Norrbotten, Jämtland and Västerbotten (Figure 10a). In all future scenarios, Jämtland would have the lowest proportion of forests with high probability of epiphytic lichen. The proportion of forests with high probability of epiphytic lichen within the planning areas in Jämtland and Norrbotten is larger than the proportions of forests with high ground lichen coverage, while it is the opposite in both the site and planning areas in Västernorrland and Västerbotten. Thus, the wind power sites have more negative consequences for the availability of epiphytic lichen in Jämtland and Norrbotten, while the consequences on the availability of ground lichen is larger in Västernorrland and Västerbotten.

Even though the proportions are similar to forests with high ground lichen coverage, forests with high probability of epiphytic lichen account for a larger area. Today, Västerbotten have the smallest area of forest with high probability of epiphytic lichen, followed by Jämtland, Västernorrland and Norrbotten, of which Norrbotten area corresponds to more than three times Västerbotten's area (Figure 10b). According to future scenarios, Västerbotten should exceed both Jämtland and Västernorrland on impacted area, whilst wind power sites in Norrbotten would cover the largest total impact area. Within the wind power sites in all counties, forests with high probability of epiphytic lichen increase with distance from the sites (Appendix 6).



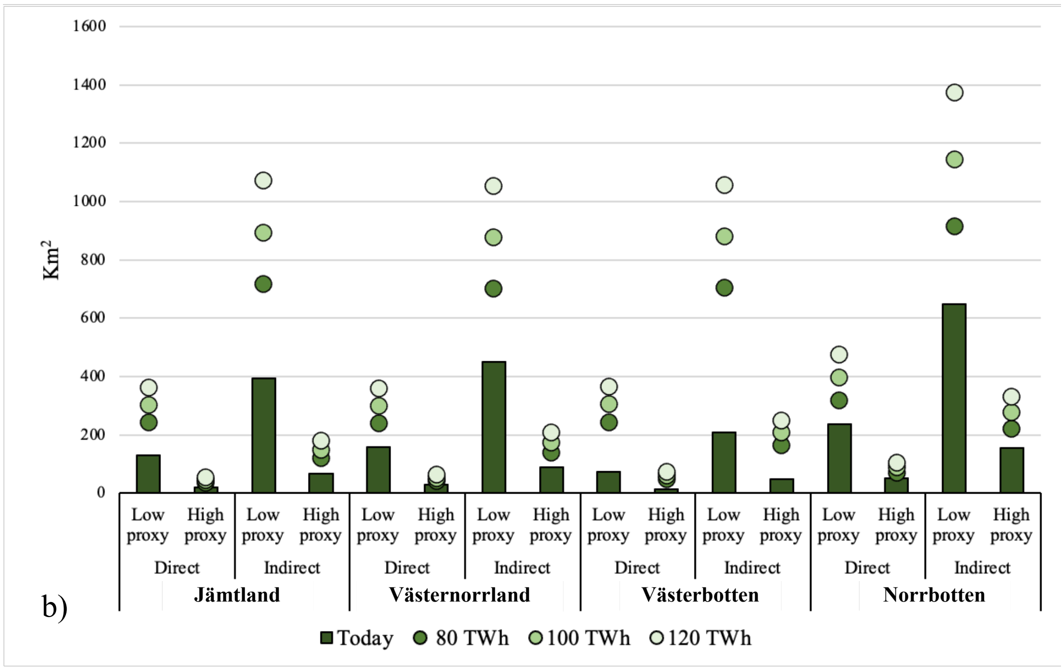


Figure 10. a) *Proportion of forests with low proxy (no conifer continuity forest or conifer continuity forest < 5m) or high proxy (conifer continuity forest > 5m) of epiphytic lichen occurrence within the wind power sites site areas (direct impact) and planning areas (indirect impact) compared to the lichen availability in each class in the given county today (bar) and in future scenarios with increased production levels (circles)* **b)** *Spatial coverage [km^2] of forests in the given classes within the wind power establishments site and planning areas.*

3.3. Spatial relationship between wind power sites and reindeer winter forage in Vilhelmina Södra and Östra Kikkejaure (Q3)

3, 5, 10 km buffers

Despite that the overall lichen occurrence is low in the RHA, there is a great variety between the RHCs. Importantly, RHCs also vary regarding how large area that is overlapping with another RHC. The nine largest RHCs, have a larger overlap with another RHC, than the part that is exclusively for them. The proportion of available forests with ground and epiphytic lichen also varies between the RHCs. Even though Idre is a small RHC in terms of size, it has a large proportion of forests with high ground lichen coverage in both the non-overlapping and overlapping area (Appendix 7). Several RHCs have a larger proportion within the overlapping area, than their non-overlapping area, while some have no, or a negligible, overlap, but a quite large proportion of forests with high occurrence of lichen. Many of the smaller RHCs, both with and without overlap, have a relatively large proportion of forests with high occurrence of ground and epiphytic lichen within their non-overlapping area, e.g., Sierri RHC with a large proportion of forests with high probability of epiphytic lichen (Appendix 8).

The in-depth analysis of the two RHCs, Vilhelmina Södra (Mountain-to-coast RHC) and Östra Kikkejaure (Forest RHC), show the importance of the size and location relationship between a RHC and its wind power sites. Close to a third of all forests with high ground lichen coverage in Östra Kikkejaure is affected by the wind power sites today, while the corresponding proportion is a fourth in Vilhelmina Södra (Figure 11a). Also, within all buffers, forests with high ground lichen coverage account for a larger in area in Östra Kikkejaure compared to Vilhelmina Södra (Figure 11b, Appendix 9). Further, if all forests within the wind power sites is compared to the size of each RHC, the wind power sites comprise a larger share of the total area in Östra Kikkejaure compared to Vilhelmina Södra.

Epiphytic lichen availability varies largely between the two RHCs. Based on the proportion of all forests with high probability of epiphytic lichen within each RHC, Östra Kikkejaure has a larger proportion within all buffer sizes compared to Vilhelmina Södra. The wind power sites in Östra Kikkejaure have a larger proportion of forests with high probability of epiphytic lichen (Figure 11c) than the proportion of forests with high ground lichen coverage as well, while it is the opposite way for Vilhelmina Södra, hence creating a larger difference between the RHCs compared to the impact on forests with high ground lichen coverage. With a 3 and 5 km buffer, forests with high probability of epiphytic lichen account for a larger area in Östra Kikkejaure, while the 10 km buffer comprises a larger area with high probability of epiphytic lichen in Vilhelmina Södra (Figure 11d; Appendix 10). However, the relative area of forests with high probability of epiphytic lichen is notably larger in Östra Kikkejaure within all buffer sizes (Figure 11d).

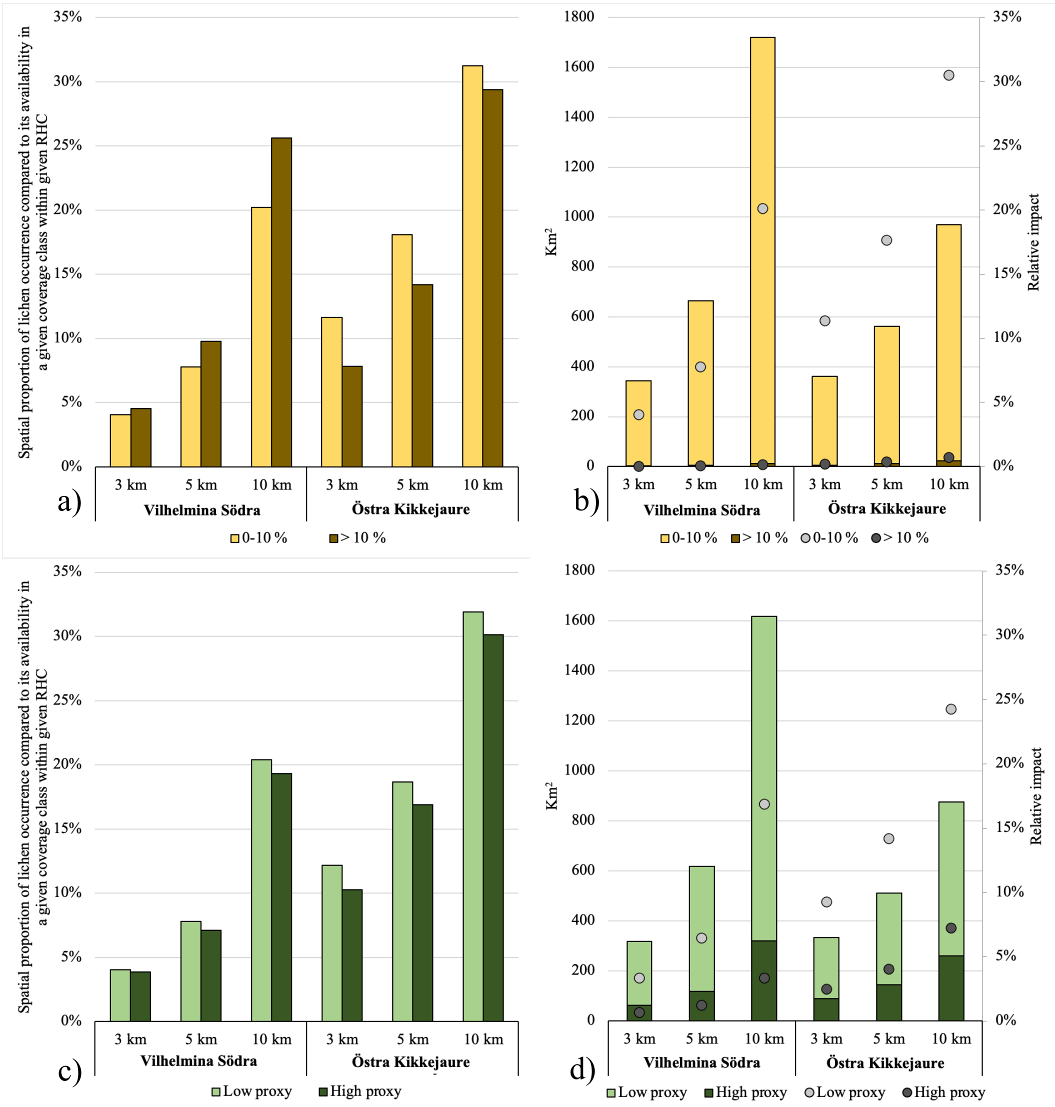


Figure 11. a) *Proportion of forests with low (0-10 %) or high (> 10 %) ground lichen coverage within wind power sites at three spatial scales (3-5-10 km) compared to lichen availability in each class in the given reindeer herding community (RHC).* **b)** *Left Y-axis: Spatial coverage [km^2] of lichen forests (0-10%, >10%) in the given classes within wind power sites three spatial scales. Right Y-axis: The spatial coverage in relationship to the size of the RHC.* **c)** *Proportion of forests with low proxy (no conifer continuity forest or conifer continuity forest < 5m) or high proxy (conifer continuity forest > 5m) of epiphytic lichen occurrence within wind power sites three spatial scales (3-5-10 km) compared to lichen availability in each class in the given reindeer herding community.* **d)** *Left Y-axis: Spatial coverage of forests [km^2] in the given classes (low proxy, high proxy) within given buffer size. Right Y-axis: The spatial coverage in relationship to the size of the community.*

Direct and indirect

The site and planning areas covers a smaller proportion and area with high ground lichen occurrence than the buffers. The wind power sites in Östra Kikkejaure comprises a larger proportion of all forests with high ground lichen coverage within the RHC, compared to the wind power sites in Södra Vilhelmina, that sums up to only a quarter the size of the proportion in Östra Kikkejaure (Figure 15a). Compared to the buffers, there is however a shift in the size relationship between Södra Vilhelmina and Östra Kikkejaure, where the total area within wind power sites is larger in Östra Kikkejaure compared to Vilhelmina Södra. Relative to the size of the RHC, the wind power sites represent an even larger area in Östra Kikkejaure compared to Vilhelmina Södra (Figure 15b; Appendix 11).

The difference between the two RHCs regarding forests with high probability of epiphytic lichen within the wind power sites is larger compared to the difference of forests with high ground lichen coverage. Except from the site areas in Vilhelmina Södra, the proportion of forests with high probability of epiphytic lichen is larger than the proportion of ground lichen coverage in both RHCs. However, the proportion of forests with high probability of epiphytic lichen within the planning areas in Östra Kikkejaure account for more than four times the corresponding proportion in Vilhelmina Södra (Figure 16a). The proportion of the forests with high probability of epiphytic lichen within the wind power sites also account for a larger area than the forests with high ground lichen coverage. The wind power sites in Östra Kikkejaure affect twice the area of forests with high probability of epiphytic lichen compared to Vilhelmina Södra (Appendix 12), and in relationship to the size of the two RHCs, the difference is even larger (Figure 16b).

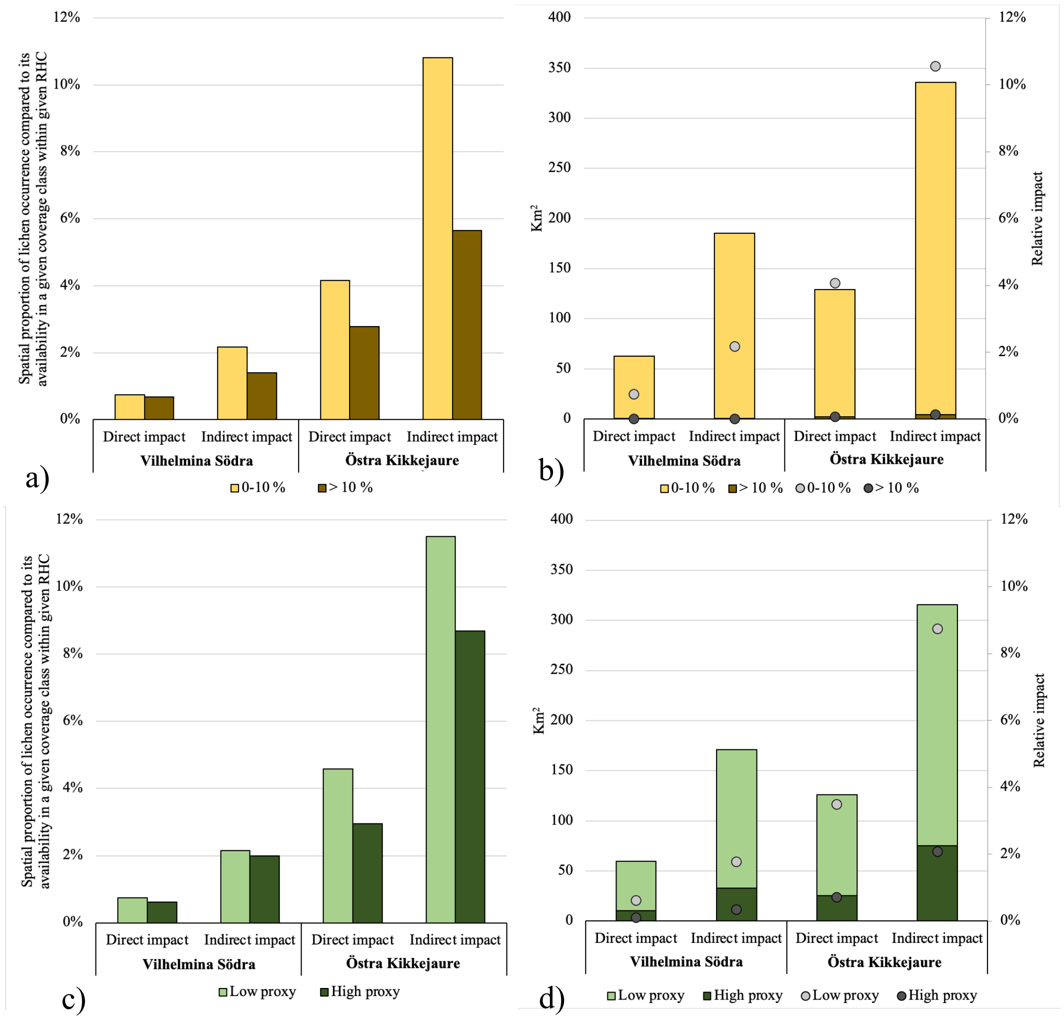


Figure 12. **a)** *Proportion of forests with low (0-10 %) or high (> 10 %) ground lichen coverage within wind power sites site areas (direct impact) and planning areas (indirect impact) compared to lichen availability in each class in the given reindeer herding community (RHC).* **b)** *Left Y-axis: Spatial coverage [km²] of lichen forests (0-10%, >10%) in the given classes within wind power sites site and planning areas. Right Y-axis: The spatial coverage in relationship to the size of the reindeer herding community.* **c)** *Proportion of forests with low proxy (no conifer continuity forest or conifer continuity forest < 5m) or high proxy (conifer continuity forest > 5m) of epiphytic lichen occurrence within wind power sites site areas (direct impact) and planning areas (indirect impact) compared to lichen availability in each class in the given reindeer herding community.* **d)** *Left Y-axis: Spatial coverage [km²] of forests in the given classes (low proxy, high proxy) within wind power sites site and planning areas. Right Y-axis: The spatial coverage in relationship to the size of the community.*

4. Discussion

I found that forests with high ground lichen coverage are uncommon compared to the availability of forests with high probability for epiphytic lichen in the RHA today. The proportion of forests with high ground lichen coverage within the landscape is similar to the proportions within wind power sites (around 1%). However, due to the low availability of ground lichen, the forests within the wind power sites comprise a substantial proportion (up to 12%) of all available forests with high ground lichen coverage in the RHA. In contrast, forests with high probability of epiphytic lichen, are more common on the landscape level (21%), resulting in a larger area within the wind power sites as well. Whether the impact on lichen rich forests is estimated based on the scientific buffers relevant for reindeer (*3-5-10 km*) or if it is based on the site and planning areas as suggested in the national wind strategy clearly have varying consequences for the availability of reindeer forage during winter. Wind power sites impact on reindeer' winter forage will develop differently between the counties in the RHA with future wind power expansion, where Västernorrland will experience the largest impact and Västerbotten the largest change from today. My in-depth analysis of two RHCs further highlighted that the consequences of wind power sites also vary at a local scale and that one single wind power site might cause a substantial loss of winter forage for the concerned RHC.

Spatial relationship between wind power sites and reindeer winter forage (Q1)

The scientific buffers relevant for reindeer (*3-5-10 km*), affects a much larger area of forests with high occurrence of ground and epiphytic lichen compared the site and planning areas in the national wind strategy (Skarin et al., 2016; Skarin et al., 2018; Swedish Energy Authority, 2021) and highlight the importance of accounting for large impact on reindeer when establishing wind turbines. There is risk that the site and planning areas are used as the estimation of lost reindeer forage by power companies, when the reality is much larger. Multiple studies on reindeer avoidance, habitat selection, movement and physiological responses emphasize thresholds close to 3-5-10 km (Strand et al., 2018; Eftestøl et al., 2021; Skarin et al., 2016, 2018, 2021). Importantly, several Swedish court cases considered distance of 3 km and 5 km as established thresholds at which reindeer are negatively impacted (Swedish Energy Authority, 2020). Consequently, future wind power sites should account for an avoidance and reduction of habitat selection within at least 3-5 km from the site, which represented a four times larger loss of winter forage compared to the planning areas in the national wind strategy. Next, Eftestøl et al. (2021) and Skarin et al. (2016) show that reindeer avoid wind power sites within 15 km^2 and 25 km^2, representing larger distances than my upper limit of 10 km. Even though the impact weakens with distance, it would mean that reindeer are affected to some degree, by only wind power, in a large part of the RHA.

The reindeer response to wind power implies a need for reindeer husbandry to adapt to the new conditions and change their use of the landscape outside the wind power sites. Today, there is no clear guidelines for how to make the environmental impact assessments when establishing a wind power site and how to deal with the cumulative effects that follow with a wind power site (Kløcker Larsen et al., 2016). The mining industry have together with two RHCs developed a method to better asses the cumulative effects of a mining project, which is divided in three spatial scales: local, county and RHC scale (LKAB, 2015). As such, it should describe better the overall impact on the reindeer, humans, and the landscape's function. Such methods are a step towards better estimations of the impact on reindeer and reindeer husbandry, especially with an increasing number of wind power sites in the landscape, resulting in more reindeer encounters adding to the cumulative effects. How often and what time at the year reindeer encounter a site, if the site affects one or several herds, are examples of factors that should be described in the assessments, hence giving a better understanding of the impact on both reindeer and reindeer husbandry. Therefore, avoiding negative ecological consequences should be important criteria in the initial stage of prospecting potential wind power sites.

Forests with high ground lichen coverage occurred more often close to wind power sites compared to forests with high probability of epiphytic lichen. Many turbines in the RHA are placed on highland areas (Skarin et al., 2021) to reach better wind conditions, which co-occurs with favorable conditions for ground lichen as well (Skarin et al., 2016), which may explain the high ground lichen occurrence in proximity to wind power sites. The favorable conditions for ground lichen with sparse forests and dry soils is less favorable for vascular plants (Heggberget et al., 2002). As such, forests close to the wind power sites may only have low productive forests below 5 meters which I defined as low probability of epiphytic lichen. Next, expansion of onshore wind power in Sweden clearly shows that the largest share of both existing and forecasted wind power sites are on forestlands, of which the largest shares are owned by private forest companies (Svensson et al, forthcoming). Landowners get both an economical compensation by the power companies while the area is also excluded from the forestry act (1979:429), and due to the increased accessibility, forests with epiphytic can been harvested (Skarin et al., 2021) without any restrictions in terrain that usually is less affected by forestry (Svensson et al., 2019). This may be a contributing factor to the low area of forests with high probability of epiphytic lichen in proximity to the wind power sites and indicate that more forests with epiphytic lichen will be removed with future wind power expansion.

I found a difference when estimating spatial wind power impact area based on concave or a convex approach, with the convex approach creating larger area whereas the concave approach appears as a more conservative approach. Both approaches have been used in previous studies to estimate wind power sites spatial extent (Reddy, 2020; Unnewher, 2021). Therefore, the impact on forests with lichen in my analysis could have been both larger and smaller if I would have chosen only one approach. The shape of the wind power site determines the size of the difference (Figure 5). Consequently, studies that cover smaller spatial scales and only analyze the impact of one wind power site could have large differences between the concave and convex approach and emphasize the importance of comparing the two.

Expected reduction of reindeer winter forage in Jämtland, Västernorrland, Västerbotten and Norrbotten due to future wind power expansion (Q2)

Wind power expansion will have varying consequences for reindeer forage in different counties, where some counties will face a larger change from today than others (e.g., Västerbotten versus Norrbotten), where both the available lichen and the spatial extent of wind power sites affect the consequences for the given county. It is important to remember that the future impact is based only on wind power establishments site and planning areas today, and not the scientific thresholds based on reindeer avoidance and habitat selection. Since the site areas are based on the area covered with turbines, the increase in scale should be similar for the buffers, which are based on individual turbines. If the buffers follow similar trend as the site areas, there would be large changes in the area and proportion of forests with high lichen occurrence that is impacted in the future, especially in Västernorrland where a relatively large share of the winter forage lies within the site and planning areas.

Advances in technology with larger turbines with better capacity are considered in the national wind strategy's future scenarios (Swedish Energy Authority, 2021; Svensk Vindenergi, 2021). This implies a better capacity to produce the same amount of energy in smaller areas. Therefore, it is possible that the site and planning areas might decrease for some wind power sites where old inefficient turbines are replaced. Yet, it does not ensure that the impact on reindeer would decrease since the visibility of turbines affect reindeer behavior (Skarin et al., 2018). If turbines increase in height, the visibility of turbines across the landscape could also increase, depending on the landscape's topography and turbine's placement. The increased height may therefore intensify the impact on reindeer forage, even if the site and planning areas got smaller.

Whether Sweden will go towards large and few, or small and many, wind power sites is of concern regarding how large areas of reindeer forage that will be affected with increased production levels. Today, the strategy aims towards large scale wind power sites, which result in a smaller impact on reindeer winter forage compared to if small wind power sites would be scattered across the landscape. Small wind power sites with only one turbine, with a 3, 5 or 10 km buffer affect an area with the corresponding radius, while the site and planning areas only affect an area 300 meters and 520 meters (3 times site area) around the turbine (Swedish Energy Authority, 2021). Consequently, several small wind power sites with overlapping buffers impact a larger area in total than if the turbines would be clustered in one large site. Even if the impact on reindeer forage within the entire RHA or a county may be smaller with large wind power sites, the local consequences for the concerned RHC may be severe, which create a difficult trade-off.

Spatial relationship between wind power sites and reindeer winter forage in Vilhelmina Södra and Östra Kikkejaure (Q3)

The lichen occurrence varies a lot between all RHCs. In total, 42 RHCs overlapped with another, even though the overlap is negligible for many. However, the lichen occurrence displays the importance of the overlap, as these areas include a relatively large proportion of forests with ground and epiphytic lichen. Since both, but especially ground lichen, are scarce resources, the overlap is an important contribution to other RHCs with even smaller forage grounds. My study shows the importance to analyze how forests with high lichen occurrence relate to wind power sites on a scale relevant for reindeer herders and how several factors decide the severity for concerned RHC. Many studies analyse how reindeer respond to wind power on a regional scale (Skarin et al., 2016; Skarin et al, 2018; Strand et al., 2018) but does not put it in relationship to the other factors that is relevant for concerned RHC. Thus, my in-depth analysis provides a rough understanding of the consequences of wind power expansion for the given RHC. The factors that need to be taken into account are (1) the available lichen, (2) size and number of wind power sites, (3) size of RHC, (4) whether it has overlapping borders with another RHC and need to share grazing grounds and (5) how the borders align with the county borders, since the demanded area for each county needed for wind power expansion (Swedish Energy Authority, 2021) lead to an uncertainty of expansion within a RHC if it lies within two or more counties.

Reindeer winter forage in both Vilhelmina Södra and especially Östra Kikkejaure, much due to Markbygden wind power site, are largely affected by wind power sites today which might have severe consequences for how reindeer and reindeer husbandry utilize the area. Such losses of forage reduce the buffers needed for winters with low lichen access due to worse snow conditions (e.g., rain-on-snow events), which could affect reindeer health and thus meat quality (Petäjä, 1383; Wiklund et al., 1996), and therefore increase the need of support feeding and transportation of reindeer by truck, which costs both time and money for the reindeer herders (Skarin et al., 2016; Rosqvist et al., 2021). Even if wind power companies can hand out economical compensation to concerned RHC, it reduces the herders' right of natural grazing grounds which contradicts the reindeer husbandry law (1971:437). Next, economical compensation puts a price tag on reindeer forage and gives a monetary value on reindeer husbandry for temporary land use. Potentially, off-setting of lichen-rich forests by the wind power companies could be the best option of compensation today, which could ensure no net loss of reindeer winter forage. However, both economical compensation and off-setting make reindeer husbandry inferior to the interests of wind power and therefore legitimize land exploitation, which increase the risk of losing the cultural value of reindeer husbandry. Wind power companies does however have the potential to contribute with important information regarding reindeer behavior within and close to wind power sites. By working together with the reindeer herding communities, the wind power companies have the possibility to contribute with e.g., monitoring of reindeer, hence providing the affected community with important information regarding their herds.

Wind power sites impact on reindeer forage may lower the maximum allowed number of reindeer for each RHC, which is based on the carrying capacity of the land. Quantifying the spatial loss of reindeer forage for each RHC generates valuable information of the carrying capacity within the RHC to ensure the wellbeing of reindeer and can contribute to an objective decision making regarding the conflict between reindeer husbandry and wind power. The wind power sites impact on reindeer grazing grounds could therefore have more severe consequences for Östra Kikkejaure than Vilhelmina Södra regarding the number of reindeer allowed, which potentially could result in a conflict within the RHC over how to distribute the reindeer between the herders. Yet only some RHCs have wind power sites within their community, which make the consequences of wind power highly varying for all RHCs. On top of the increased workload and costs for affected RHCs, wind power expansion could potentially lead to a situation where reindeer husbandry is impossible in some RHCs.

Comparison between the occurrence of ground and epiphytic lichen

Despite the varying occurrence of ground and epiphytic lichen, both resources are important for reindeer during winter. Today, the area with ground lichen occurrence is low and make up around 1 % within the RHA, which makes the remaining forests vulnerable for further land use changes. Even though the proportional impact is larger on forests with high probability of epiphytic lichen, it is a more common resource and thus make up a larger area outside of the wind power sites available for grazing. Yet, reindeer herders are dependent on the availability of resources within their own RHC rather than the entire RHA. My analysis showed a big variety of lichen occurrence among individual RHCs, where forests with high ground lichen occurrence account 1 % of the forested area in some RHCs, but 7% in another. Even though the wind power expansion might be more acute for forests with high ground lichen coverage than forests with high probability of epiphytic lichen in general, reindeer are dependent of spatial as well as temporal connectivity, of which both ground and epiphytic lichen are needed to provide sufficient forage across the landscape and with seasonal variations (Horstkotte et al., 2014).

Cumulative effects of land use within a changing climate

My analysis considers wind power sites as islands within the forest landscape, even though it is not the reality. Wind power sites need to be connected to the road network and the power grid as well. Even though reindeer avoidance of power lines mainly is affected by the construction phase rather than the operation phase (Colman et al., 2015; Eftestøl et al., 2016), Nelleman et al. (2001) show that reindeer are affected by the latter as well, especially in combination with roads. Nevertheless, such infrastructure creates a permanent removal of lichen, hence removing the available reindeer forage. Consequently, my result of the impact by wind power on reindeer forage is likely an underestimation due to the exclusion of the additional roads and powerlines. Cumulative effects of other land users such as forestry, mining, infrastructure, and human activity further affect availability of forage, causing reindeer avoidance, and hampers reindeer movement (Sandström et al. 2016; Esseen et al., 1996; Dettki & Esseen, 1998; Kløcker et al., 2016; Vistnes & Nelleman, 2008), which altogether create a difficult situation for reindeer husbandry as highlighted recently (Kløcker et al., 2016).

The climate change has direct consequences, which further cause indirect consequences, for reindeer husbandry. A milder climate with increased precipitation will likely increase vascular plants' productivity and create a hostile environment for ground lichen, thus removing their competitive advantage in dry conditions (Cornelissen et al., 2001; Heggberget et al., 2002). It is still unclear whether the reindeer can mediate the shrubification in such a scenario (Skarin et al., 2020). The shift in weather could also have other seasonal effects that affect the accessibility of ground lichen due to problems with a thick snowpack and formations of ice crusts above the lichen (Reimers, 1982; Miller & Gunn, 2003; Gates et al., 1986). A possible outcome of climate change is a more intense forestry with a maximized production, where old forest with epiphytic lichen is harvested to replace fossil-based products, as well as denser forests and shorter rotation periods, leading to suboptimal conditions for both ground and epiphytic lichen to establish (Horstkotte & Moen, 2019; Esseen et al., 1996). Forestry together with wind power is therefore an indirect consequence of climate change that threatens reindeer. This leads to a paradoxical situation, since both the direct consequences of climate change and possible tools to solve the problem have a negative outcome, which would lead to increased pressure of the remaining, available lichen (Helle & Säntti, 1982).

Limitations

My study is based on two differences methods of mapping ground lichen and epiphytic lichen which vary in quality. The mapping of ground lichen coverage is based on a model, resulting in a good predicative capacity (Adler et al., 2021). The preliminary lichen map I used does not have the same capacity as the final lichen map regarding the coverage of lichen, but still have a good predicative capacity regarding occurrence. Since I used a wide span for the areas considered as high lichen coverage (> 10%), it should not affect the result that much. The mapping of epiphytic lichen, however, is only a proxy based on variables that increase the probability, but not ensure, epiphytic lichen occurrence, which make it less predictive than the ground lichen model. Next, the mapping of continuity forest that I used in my analysis was made in 2016. Since then, Jämtland, Västerbotten and Västernorrland have made a new, more precise mapping (Ahlkrona et al., 2017b; 2019; 2021) to reduce previous overestimations. I used the previous mapping for my proxy to ensure that it was based on the same prerequisites for all counties, which likely overestimates the probability of epiphytic lichen, due to an overestimation of continuity forests.

Future studies

In this study, the proxy for epiphytic lichen is based on three variables even though several intercorrelated variables affects epiphytic lichen occurrence. The most explanatory variable, age, correlates rather poorly with forest variables such as tree height, especially for spruce (McCune, 1993; Price & Hochachka, 2001; Kuuluvainen et al., 2002) and low productive forest lands like in most of Northern Sweden. Therefore, creating a proxy only in GIS based on geodata is rather challenging. Hence, complementing the ground lichen model with an epiphytic lichen model would be helpful to reduce the uncertainty of the epiphytic lichen occurrence and consequently improve the landscape planning and studies regarding reindeer and reindeer husbandry. Next, technological development creates an uncertainty regarding the impact on reindeer due to the decrease in site and planning areas because of the increased turbine height, which therefore could affect reindeer negatively (Swedish Energy Authority, 2021; Svensk Vindenergi, 2021). Thus, a view shed analysis, analyzing the difference between the height of turbines today compared to possible future heights, likely reduce the uncertainty of how large extent of reindeer habitat that will be impacted.

4.1. Conclusion

The RHA is facing a large transformation of the landscape due to the expansion of wind power. Ground lichen is an especially scarce resource within the forest landscape that is crucial for the survival of reindeer and reindeer husbandry. The impact on reindeer forage by wind power sites is considerably larger within the buffers relevant for reindeer behavior compared to the suggested site and planning areas in the national wind strategy. Today, the physical wind power sites occupy a rather small area but indirectly affect a substantial proportion of the available reindeer forage. The consequences of wind power sites on reindeer forage in the entire RHA is not representative for individual RHCs, of which some are worse affected than others. Hence, wind power causes an uncertain future for reindeer husbandry in some RHCs, especially since more reindeer grazing grounds may be affected due increased turbine height with future wind power expansion. On top of the consequences caused by wind power, the cumulative effect of other land uses, and the climate change adds more pressure to the problem. Due to the exclusion of roads and powerlines of the wind power sites in my analysis, the estimated impact on reindeer forage is likely an underestimation. Therefore, my analysis is only one approach of many that is necessary to estimate and quantify the spatial impact of wind power expansion on lichen occurrence within RHA, which can contribute knowledge to a sustainable landscape planning and hence ensure the survival of reindeer husbandry.

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Appendix

Appendix 1. *The coverage of ground lichen occurrence within wind power sites at different spatial scales (3-5-10 km) and the corresponding proportion of that class within a given buffer size. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within given buffer differ from the corresponding proportion of that class within the whole RHA.*

Buffer size	**Class**	
3 km	*0-10%*	*>10 %*
Area (km^2)	**3366**	**30**
Proportion of impacted area	**99,11%**	**0,89%**
Difference from RHA (%)	**+0,29%**	**-0,29%**
5 km	*0-10%*	*>10 %*
Area (km^2)	**6464**	**60**
Proportion of impacted area	**99,08%**	**0,92%**
Difference from RHA (%)	**+0,27%**	**-0,27%**
10 km	*0-10%*	*>10 %*
Area (km^2)	**17003**	**164**
Proportion of impacted area	**99,04%**	**0,96%**
Difference from RHA (%)	**+0,23%**	**-0,23%**

Appendix 2. *The coverage of epiphytic lichen occurrence within the wind power sites at different spatial scales (3-5-10 km) and the corresponding proportion of that class within a given buffer size. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within given buffer differ from the corresponding proportion of that class within the whole RHA.*

Buffer size	**Class**	
3 km	*Low proxy*	*High proxy*
Area (km^2)	**3 065**	**707**
Proportion of impacted area	**81,26%**	**18,74%**
Difference from RHA	**+ 1,91%**	**- 1,91%**
5 km	*Low proxy*	*High proxy*
Area (km^2)	**5 864**	**1 393**
Proportion of impacted area	**80,80%**	**19,20%**
Difference from RHA	**+ 1,45%**	**- 1,45%**
10 km	*Low proxy*	*High proxy*
Area (km^2)	**15 537**	**3 627**
Proportion of impacted area	**81,07%**	**18,93%**
Difference from RHA	**+ 1,72%**	**- 1,72%**

Appendix 3. *The coverage of ground lichen occurrence within the wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of the given class. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area.*

	Direct impact		Indirect impact	
	0-10%	*>10 %*	*0-10%*	*>10 %*
Area (km^2)	**643**	**7**	**1 832**	**14**
Proportion of impacted area	**98,95%**	**1,05%**	**99,24%**	**0,76%**
Difference from RHA	**0,14%**	**-0,14%**	**0,42%**	**-0,42%**

Appendix 4. *The coverage of epiphytic lichen occurrence within wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of the given class. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area.*

	Direct impact		Indirect impact	
	Low proxy	*High proxy*	*Low proxy*	*High proxy*
Area (km^2)	**604**	**116**	**1 710**	**362**
Proportion of impacted area	**83,85%**	**16,15%**	**82,52%**	**17,48%**
Difference from RHA	**4,50%**	**-4,50%**	**3,18%**	**-3,18%**

Appendix 5. *The coverage of ground lichen occurrence within wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of the given class, today and in future scenarios with increased production levels. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area. Future scenarios have the same proportions and difference to the proportion in the reindeer husbandry area as today, since both classes are multiplied with the same factor for a specific energy production.*

County	**Direct impact**		**Indirect impact**	
Jämtland	*0-10%*	*>10 %*	*0-10%*	*>10 %*
Area today (km^2)	141	*1*	*422*	2
Area 80 TWh (km^2)	257	2	766	4
Area 100 TWh (km^2)	321	3	957	5
Area 120 TWh (km^2)	385	4	1148	6
Impact	**99,09%**	**0,91%**	**99,45%**	**0,55%**
Difference from RHA	+ 0,27%	- 0,27%	+ 0,63%	- 0,63%
Västernorrland	*0-10%*	*>10 %*	*0-10%*	*>10 %*
Area today (km^2)	171	1	494	3
Area 80 TWh (km^2)	257	2	771	4
Area 100 TWh (km^2)	321	2	964	5
Area 120 TWh (km^2)	385	3	1 157	6
Impact	**99,25%**	**0,75%**	**99,46%**	**0,54%**
Difference from RHA	+ 0,44%	- 0,44%	+ 0,64%	- 0,64%
Västerbotten	*0-10%*	*>10 %*	*0-10%*	*>10 %*
Area today (km^2)	79	1	228	3
Area 80 TWh (km^2)	260	4	768	9
Area 100 TWh (km^2)	325	5	960	11
Area 120 TWh (km^2)	390	5	1 152	13
Impact	**98,61%**	**1,39%**	**98,89%**	**1,11%**
Difference from RHA	-0,20%	+ 0,20%	+ 0,08%	- 0,08%
Norrbotten	*0-10%*	*>10 %*	*0-10%*	*>10 %*

Area today (km^2)	250	3	678	6
Area 80 TWh (km^2)	336	4	959	9
Area 100 TWh (km^2)	420	5	1 198	11
Area 120 TWh (km^2)	504	6	1 438	13
Impact	**98,80%**	**1,20%**	**99,07%**	**0,93%**
Difference from RHA	- 0,02%	+ 0,02%	+ 0,26%	- 0,26%

Appendix 6. *The coverage of epiphytic lichen occurrence within wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of the given class, today and in future scenarios with increased production levels. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area. Future scenarios have the same proportions and difference to the proportion in the reindeer husbandry area as today, since both classes are multiplied with the same factor for a specific energy production.*

County	**Direct impact**		**Indirect impact**	
Jämtland	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	131	20	394	66
Area 80 TWh (km^2)	242	37	716	119
Area 100 TWh (km^2)	302	46	895	149
Area 120 TWh (km^2)	362	53	1 073	179
Impact	**86,74%**	**13,26%**	**85,71%**	**16,47%**
Difference from RHA	+ 7,39%	- 7,39%	+ 6,36%	- 6,36%
Västernorrland	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	160	28	450	89
Area 80 TWh (km^2)	240	42	703	139
Area 100 TWh (km^2)	300	53	879	173
Area 120 TWh (km^2)	360	64	1 054	208
Impact	**84,99%**	**15,01%**	**83,53%**	**16,47%**
Difference from RHA	+ 5,64%	- 5,64%	+ 4,19%	- 4,19%
Västerbotten	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	74	15	209	49
Area 80 TWh (km^2)	244	49	705	166
Area 100 TWh (km^2)	305	61	881	207
Area 120 TWh (km^2)	366	73	1058	249
Impact	**83,27%**	**16,73%**	**80,97%**	**19,03%**

Difference from RHA	+ 3,92%	- 3,92%	+ 1,62%	- 1,62%
Norrbotten	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	236	52	647	156
Area 80 TWh (km^2)	318	71	915	221
Area 100 TWh (km^2)	397	88	1 143	276
Area 120 TWh (km^2)	476	106	1 372	332
Impact	**81,80%**	**18,20%**	**80,53%**	**19,47%**
Difference from RHA	+ 2,45%	- 2,45%	+ 1,18%	- 1,18%

Appendix 7. *The coverage of forests with low (0-10 %) or high (> 10 %) ground lichen coverage and the corresponding proportion of the given class within the reindeer herding communities (RHCs) today and whether it lies within the non-overlapping or overlapping area. I.e., how large area that is shared with another reindeer herding community.*

	No overlap				**Overlap**			
	Km^2		Proportion		Km^2		Proportion	
Name	*0–10 %*	*> 10 %*	*0–10 %*	*> 10 %*	*0–10 %*	*> 10 %*	*0–10 %*	*> 10 %*
Lainiovuoma	16	0	99,0%	0,7%	0	0	0,3%	0,0%
Ängeså	1 576	13	68,8%	0,6%	696	5	30,4%	0,2%
Liehittäjä	1 068	6	99,4%	0,6%	0	0	0,0%	0,0%
Handölsdalen	2 137	57	65,9%	1,8%	1 016	34	31,3%	1,0%
Kall	427	1	88,7%	0,2%	53	0	11,1%	0,0%
Tåssåsen	3 594	28	81,9%	0,6%	757	8	17,3%	0,2%
Mittådalen	1 383	42	64,1%	1,9%	702	30	32,6%	1,4%
Voernese	10 319	74	46,9%	0,3%	11 560	75	52,5%	0,3%
Ruvhten sijte	874	43	60,9%	3,0%	480	38	33,5%	2,6%
Girjas	902	13	88,8%	1,3%	99	2	9,8%	0,2%
Baste cearru	514	7	96,9%	1,3%	9	0	1,7%	0,0%
Unna Tjerusj	473	4	58,8%	0,5%	324	3	40,3%	0,4%
Jåhkagaska tjiellde	5 150	89	25,8%	0,5%	14 463	260	72,5%	1,3%
Sierri	464	4	92,1%	0,9%	35	1	6,9%	0,1%
Udtja	5 408	106	26,7%	0,5%	14 449	260	71,5%	1,3%
Vittangi	508	5	63,2%	0,6%	289	2	35,9%	0,3%
Östra Kikkejaure	3 106	76	97,6%	2,4%	0	0	0,0%	0,0%
Västra Kikkejaure	1 804	49	97,4%	2,6%	0	0	0,0%	0,0%
Mausjaure	2 395	63	97,4%	2,6%	0	0	0,0%	0,0%
Pirttijärvi	685	4	99,5%	0,5%	0	0	0,0%	0,0%
Kalix	1 859	17	82,0%	0,8%	389	3	17,1%	0,1%
Tärendö	1 256	3	68,0%	0,2%	588	1	31,8%	0,1%
Sattajärvi	859	2	99,8%	0,2%	0	0	0,0%	0,0%
Korju	1 628	6	99,6%	0,4%	0	0	0,0%	0,0%
Muonio	2 130	15	86,7%	0,6%	310	2	12,6%	0,1%
Ståkke	1 221	37	58,3%	1,8%	807	28	38,6%	1,4%
Könkämä	216	2	99,3%	0,7%	0	0	0,0%	0,0%
Talma	294	4	93,6%	1,3%	16	0	5,0%	0,1%
Vilhelmina Norra	8 062	54	88,1%	0,6%	1 031	7	11,3%	0,1%
Vapsten	5 190	36	86,0%	0,6%	803	6	13,3%	0,1%
Vilhelmina Södra	8 513	45	71,3%	0,4%	3 369	18	28,2%	0,2%
Ubmeje tjeälddie	3 266	34	90,0%	1,0%	328	2	9,0%	0,1%
Gällivare	5 923	62	75,6%	0,8%	1 833	21	23,4%	0,3%
Saarivuoma	806	9	56,2%	0,6%	615	4	42,9%	0,3%
Idre	2 087	179	80,3%	6,9%	300	34	11,6%	1,3%
Raedtievaerie	10 268	42	29,3%	0,1%	24 597	105	70,3%	0,3%
Jijnjevaerie	15 270	68	35,2%	0,2%	27 966	128	64,4%	0,3%
Jovnevaerie	6 124	22	31,5%	0,1%	13 218	53	68,1%	0,3%

Ran	3 818	42	89,7%	1,0%	393	3	9,2%	0,1%
Gran	2 099	25	81,9%	1,0%	432	8	16,9%	0,3%
Svaipa	1 281	18	90,8%	1,2%	112	1	7,9%	0,0%
Malå	4 708	57	89,4%	1,1%	493	9	9,4%	0,2%
Maskaure	1 492	10	92,4%	0,7%	111	1	6,9%	0,0%
Njaarke	2 823	12	74,2%	0,3%	964	6	25,3%	0,2%
Laevas	948	6	59,5%	0,4%	637	3	40,0%	0,2%
Gabna	520	5	88,9%	0,9%	59	0	10,2%	0,0%
Semisjaur-Njarg	1 765	39	93,1%	2,1%	91	1	4,8%	0,1%
Luokta-Mávas	1 315	41	62,6%	2,0%	717	27	34,1%	1,3%
Tuorpon	5 039	90	25,4%	0,5%	14 449	260	72,8%	1,3%
Sirges	5 145	89	25,7%	0,5%	14 498	261	72,5%	1,3%
Ohredahke	14 797	69	35,3%	0,2%	26 949	126	64,3%	0,3%

Appendix 8. *The coverage of forests with low (low proxy) or high (high proxy) probability of epiphytic lichen occurrence and the corresponding proportion of the given class within the reindeer herding communities (RHCs) today and whether it lies within the non-overlapping or overlapping area. I.e., how large area that is shared with another reindeer herding community.*

	No overlap				**Overlap**			
	Km^2		Proportion		Km^2		Proportion	
Name	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Lainiovuoma	11	7	60,7%	39,0%	0	0	0,2%	0,1%
Ängeså	1 434	388	54,2%	14,7%	656	169	24,8%	6,4%
Liehittäjä	1 005	200	83,4%	16,6%	0	0	0,0%	0,0%
Handölsdalen	1 982	479	54,5%	13,2%	928	248	25,5%	6,8%
Kall	364	98	70,2%	19,0%	44	12	8,5%	2,3%
Tåssåsen	3 103	922	63,5%	18,9%	673	190	13,8%	3,9%
Mittådalen	1 219	348	51,1%	14,6%	667	149	28,0%	6,2%
Voernese	8 966	2 296	37,7%	9,7%	9 984	2532	42,0%	10,7%
Ruvhten sijte	839	198	51,7%	12,2%	481	106	29,6%	6,5%
Girjas	792	261	67,9%	22,4%	81	32	7,0%	2,8%
Baste cearru	403	174	68,6%	29,7%	8	2	1,4%	0,3%
Unna Tjerusj	455	120	46,7%	12,3%	333	67	34,1%	6,9%
Jåhkagaska tjiellde	4 440	1 406	19,9%	6,3%	12 678	3803	56,8%	17,0%
Sierri	359	157	64,9%	28,3%	16	21	3,0%	3,9%
Udtja	4 781	1 390	21,1%	6,1%	12 669	3798	56,0%	16,8%
Vittangi	510	115	51,0%	11,5%	314	62	31,4%	6,2%
Östra Kikkejaure	2 745	866	76,0%	24,0%	0	0	0,0%	0,0%
Västra Kikkejaure	1 587	505	75,9%	24,1%	0	0	0,0%	0,0%
Mausjaure	2 233	604	78,7%	21,3%	0	0	0,0%	0,0%
Pirttijärvi	660	152	81,3%	18,7%	0	0	0,0%	0,0%
Kalix	1 687	426	65,9%	16,6%	372	77	14,5%	3,0%
Tärendö	1 241	340	53,4%	14,6%	585	157	25,2%	6,8%
Sattajärvi	830	238	77,7%	22,3%	0	0	0,0%	0,0%
Korju	1 522	368	80,5%	19,5%	0	0	0,0%	0,0%
Muonio	1 998	533	68,5%	18,3%	327	59	11,2%	2,0%
Ståkke	1 035	324	46,0%	14,4%	683	207	30,4%	9,2%
Könkämä	182	74	71,0%	29,0%	0	0	0,0%	0,0%
Talma	253	89	70,0%	24,6%	16	3	4,5%	0,9%
Vilhelmina Norra	7 384	1 627	72,6%	16,0%	954	200	9,4%	2,0%
Vapsten	4 782	1 077	70,7%	15,9%	743	158	11,0%	2,3%
Vilhelmina Södra	7 935	1 659	59,8%	12,5%	2 969	701	22,4%	5,3%
Ubmeje tjeälddie	2 912	727	72,6%	18,1%	296	74	7,4%	1,9%
Gällivare	5 203	1 663	57,8%	18,5%	1 668	471	18,5%	5,2%
Saarivuoma	856	163	47,6%	9,1%	657	124	36,5%	6,9%
Idre	2 041	612	67,3%	20,2%	305	75	10,1%	2,5%
Raedtievaerie	9 043	2 241	23,7%	5,9%	21 653	5206	56,8%	13,7%
Jijnjevaerie	13 694	3 144	28,9%	6,6%	24 599	5936	51,9%	12,5%

Jovnevaerie	5 735	1 297	26,7%	6,1%	11 694	2737	54,5%	12,8%
Ran	3 479	852	72,9%	17,9%	352	90	7,4%	1,9%
Gran	1 904	486	66,0%	16,8%	412	84	14,3%	2,9%
Svaipa	1 121	345	70,5%	21,7%	92	32	5,8%	2,0%
Malå	4 505	954	74,8%	15,8%	464	100	7,7%	1,7%
Maskaure	1 367	339	74,7%	18,5%	92	32	5,0%	1,7%
Njaarke	2 556	729	57,8%	16,5%	892	244	20,2%	5,5%
Laevas	854	291	44,2%	15,1%	604	185	31,2%	9,6%
Gabna	514	120	73,3%	17,1%	47	20	6,7%	2,9%
Semisjaur-Njarg	1 479	493	71,5%	23,8%	78	21	3,8%	1,0%
Luokta-Mávas	1 093	357	48,8%	15,9%	605	186	27,0%	8,3%
Tuorpon	4 375	1 368	19,7%	6,2%	12 669	3798	57,0%	17,1%
Sirges	4 430	1 423	19,8%	6,4%	12 694	3824	56,7%	17,1%
Ohredahke	13 008	3 090	28,7%	6,8%	23 581	5703	52,0%	12,6%

Appendix 9. *The coverage of forests with low (0-10 %) or high (> 10 %) ground lichen coverage within wind power sites in Vilhelmina Södra and Östra Kikkejaure at different spatial scales (3-5-10 km) and the corresponding proportion of that class within a given buffer size. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within a given buffer differ from the corresponding proportion of that class within the reindeer husbandry area.*

County	**3 km**		**5 km**		**10 km**	
Vilhelmina Södra	*0-10 %*	*>10 %*	*0-10 %*	*10 %*	*0-10 %*	*>10 %*
Area (km^2)	**345**	**2**	**664**	**4**	**1 721**	**11**
Proportion of impact	**99,42%**	**0,58%**	**99,35%**	**0,65%**	**99,34%**	**0,66%**
Difference from RHA	**+ 0,60%**	**- 0,60%**	**+ 0,53%**	**- 0,53%**	**+ 0,52%**	**- 0,52%**
Östra Kikkejaure	*0-10 %*	*>10 %*	*0-10 %*	*>10 %*	*0-10 %*	*>10 %*
Area today (km^2)	**361**	**6**	**562**	**11**	**971**	**22**
Impact	**98,38%**	**1,62%**	**98,12%**	**1,88%**	**97,75%**	**2,25%**
Difference from RHA	**- 0,44%**	**+ 0,44%**	**- 0,69%**	**+ 0,69%**	**- 1,06%**	**+ 1,06%**

Appendix 10. *The coverage of forests with low (low proxy) or high (high proxy) probability of epiphytic lichen occurrence within wind power sites in Vilhelmina Södra and Östra Kikkejaure at different spatial scales (3-5-10 km) and the corresponding proportion of that class within a given buffer size. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within a given buffer differ from the corresponding proportion of that class within the reindeer husbandry area.*

County	**3 km**		**5 km**		**10 km**	
Vilhelmina Södra	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area (km^2)	**319**	**64**	**618**	**118**	**1 617**	**320**
Impact	**83,36%**	**16,64%**	**84,00%**	**16,00%**	**83,47%**	**16,53%**
Difference from RHA	**+ 4,01%**	**- 4,01%**	**+ 4,66%**	**- 4,66%**	**+ 4,13**	**- 4,13%**
Östra Kikkejaure	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	**334**	**89**	**512**	**146**	**875**	**261**
Impact	**78,96%**	**21,04%**	**77,79%**	**22,21%**	**77,04%**	**22,96%**
Difference from RHA	**-0,39%**	**+ 0,39%**	**- 1,55%**	**+ 1,55%**	**- 2,31%**	**+ 2,31%**

Appendix 11. *The coverage of forests with low (0-10 %) or high (> 10 %) ground lichen coverage within Vilhelmina Södra and Östra Kikkejaure's wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of that class. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area.*

County	Direct impact		Indirect impact	
Vilhelmina Södra	*0-10%*	*>10 %*	*0-10%*	*>10 %*
Area (km^2)	**63**	**0,3**	**185**	**0,6**
Impact	**99,52%**	**0,48%**	**99,66%**	**0,34%**
Difference from RHA	**+ 0,70%**	**- 0,70%**	**+ 0,85%**	**- 0,85%**
Östra Kikkejaure	*0-10%*	*>10 %*	*0-10%*	*>10 %*
Area today (km^2)	**129**	**2,1**	**336**	**4,3**
Impact	**98,39%**	**1,61%**	**98,74%**	**1,26%**
Difference from RHA	**-0,43%**	**+ 0,43%**	**- 0,07%**	**+ 0,07%**

Appendix 12. *The coverage of forests with low (low proxy) or high (high proxy) probability of epiphytic lichen occurrence within Vilhelmina Södra and Östra Kikkejaure's wind power establishments site areas (direct impact) and planning areas (indirect impact) and the corresponding proportion of that class. The difference from the reindeer husbandry area (RHA) explain how many percentage units the proportion of a class within the establishments differ from the corresponding proportion of that class within the reindeer husbandry area.*

County	Direct impact		Indirect impact	
Vilhelmina Södra	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area (km^2)	**60**	**10**	**171**	**33**
Impact	**85,39%**	**14,61%**	**83,80%**	**16,20%**
Difference from RHA	**+ 6,04%**	**- 6,04%**	**+ 4,45%**	**- 4,45%**
Östra Kikkejaure	*Low proxy*	*High proxy*	*Low proxy*	*High proxy*
Area today (km^2)	**126**	**26**	**316**	**75**
Impact	**83,16%**	**16,84%**	**80,75%**	**19,25**
Difference from RHA	**+ 3,81%**	**- 3,81%**	**+ 1,41%**	**- 1,41%**