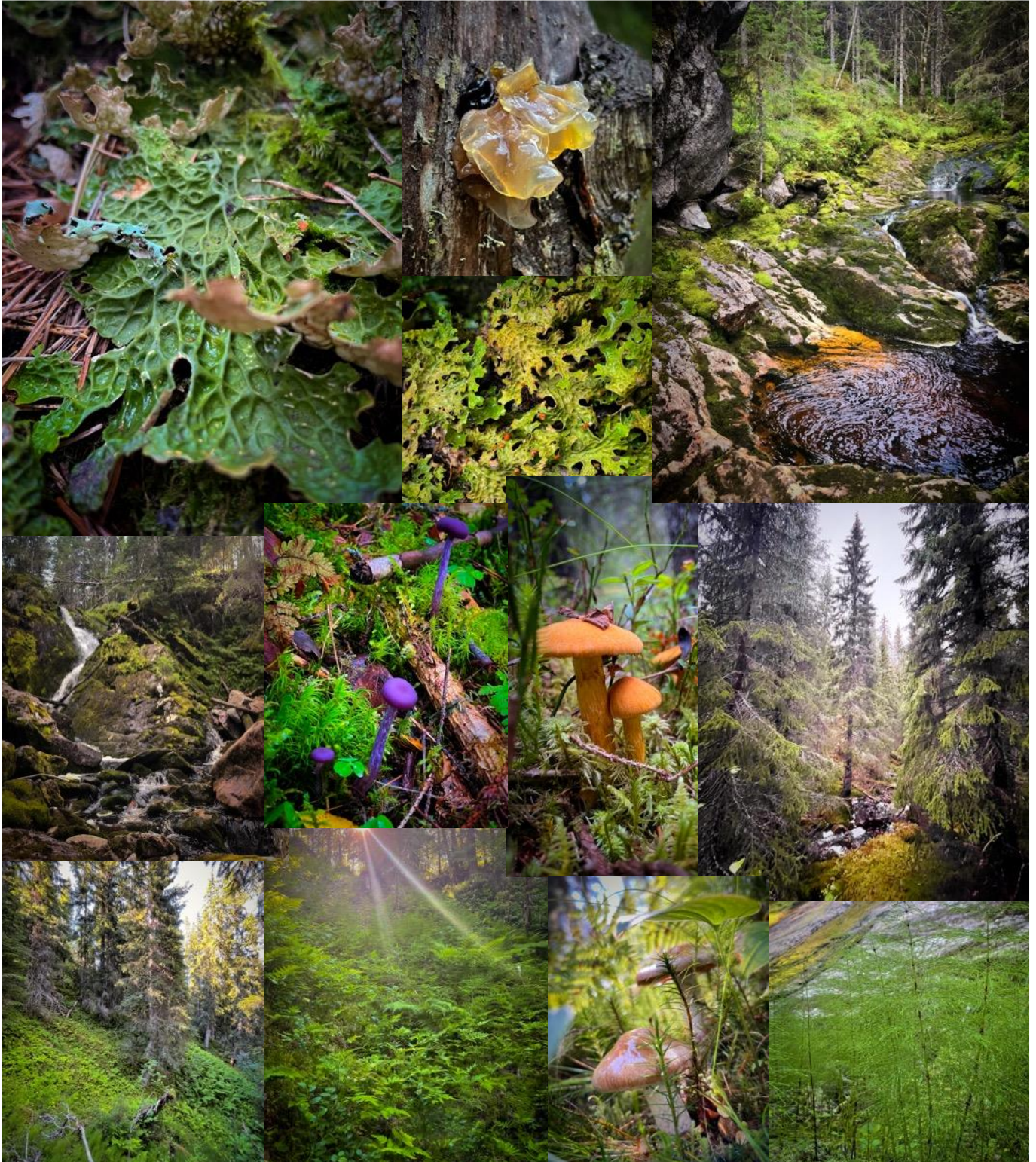# Clear-Cut Logging Edge Effects on Boreal Rainforest Remnants in Central Norway

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Abstract

Boreal rainforests in central Norway have been harvested to near depletion. Only small fragments remain today, where terrain such as ravines and steep mountain sides made harvesting unmanageable. Most of the oldest boreal rainforests in Norway are less than 150 years old. While many are protected, clear-cut logging practices still take place adjacent to protected rainforests. Buffer zones are a useful tool in nature management to mitigate edge-effects from anthropogenic disturbances such as clear-cut logging. The objective of this study was to provide region specific data about clear-cut logging edge effects on unharvested boreal rainforests in central Norway to potentially recommend an appropriate size for harvest-free buffer zones. Data was collected from five sites adjacent to clear-cut edges in northern Trøndelag from July to October 2021. Ninety circular plots (2.5 m radius) were studied within a distance of 200 m from the nearest clear-cut edge with 25 m intervals between each plot. Presence / absence of the lichen species *Lobaria pulmonaria* (L.) Hoffm., a commonly used indicator of biodiversity and continuity of boreal rainforests, was recorded for each plot. A standardized teabag method was used to investigate soil decomposition rates, and moisture / temperature sensors were also deployed. Tree species within each plot were recorded. Forest floor functional group diversity and canopy cover were also recorded. *L. pulmonaria* was present in 14 of 90 plots. Classification and regression trees revealed a relationship between soil moisture, fern abundance, and nearest clear-cut edge on the presence of *L. pulmonaria*, but a logistic regression model did not show a significant effect of nearest clear-cut edge distance on presence of *L. pulmonaria*. This is probably due to a minimal contrast in microclimates between edge area and forest interior, evidenced by the lack of significant effect from nearest clear-cut edge distance on the abiotic variables soil moisture, ground level temperature, canopy cover, and teabag decay rate. This is likely partly attributed to edge aspects, as previous studies have shown South and Southwest facing edge aspects have the most edge influence, and only 24 of 90 plots had edges facing Southwest. Also, wind has previously shown considerably more edge influence than light, and no edge faced the direction of prevailing winds. Logistic regression did however reveal fern abundance to have a significant positive influence on the presence of *L. pulmonaria*. Distance to clear-cut edge was Spearman rank correlated with abundances of graminoids (negatively) and bryophytes (positively), likely due to increased light in the area of edge influence but might also be a signal for increased nitrogen deposition near clear-cut edges. My data is unable to suggest buffer zone sizes based on the presence of ecological indicator *L. pulmonaria*, but my data does provide opportunities for future studies which could aid efforts to preserve the integrity of these last remaining boreal rainforests of central Norway.

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Title page photo: Collage of personal photos presenting the beauty of Norwegian boreal rainforests. All photos are from sites studied in this project, taken with iPhone 7 (©Apple Inc, 2016)

Chapter 1. Introduction

Tropical rainforests are well known for their importance for global biodiversity and climate change, and for being heavily threatened by anthropogenic disturbances such as agriculture, harvesting, and overpopulation (Zakaria et al. 2016; Laurance et al. 2012; Laurance, 2013; Brooks et al. 2002). However, smaller rainforest patches in different parts of the world are also important for contributing to global biodiversity and stabilizing the climate and are similarly threatened by deforestation pressures (Dinerstein et al. 2020; Yan et al. 2021).

In particular, Norwegian boreal rainforests include many rare and "red-listed" lichen species (IUCN; Huettmann, 2012; *Rødlista 2021 - Artsdatabanken*, 2021). These forests are rich in mosses, lichens, and ferns, mostly dominated by the spruce *Picea abies* but also include deciduous trees such as *Betula pubescens*, *Sorbus aucuparia*, and *Alnus incana*. These habitats are characteristically low in temperatures and high in humidity, with frequent precipitation, mostly occurring between 63 - 65° N (DellaSala, 2011). Much of Norway was formerly covered by these forests, but they have since been reduced to tiny remnant patches between 2 - 250 hectares due to over-harvesting through extensive clear-cut logging practices and conversion to agriculture fields, which is problematic for biodiversity because small fragmented forest patches have much lower species richness than larger forests, and also decreases over time (Turner, 1996; Holien & Prestø, 2008; DellaSala, 2011; Rybicki & Hanski, 2013). Most of these remaining patches are still in existence only due to their inaccessibility for tree harvesting, for example on steep mountainsides and in ravines (Holien & Prestø, 2008; DellaSala, 2011). Less than 10% of the remaining patches can be described as old growth. As of 2011, 300 Norwegian boreal rainforest patches remain, with less than 1% protected (DellaSala, 2011). Additionally, the protections in place for these small remnant patches may not be sufficient to preserve their biodiversity due to forest edge effects, defined as "changes in population or community structures that occur at the boundary of two or more habitats" (Levin, 2009), a key mechanism in the loss of species in rainforest fragmentation (Turner, 1996). While clear cut logging is not allowed within unprotected boreal rainforests with old growth characteristics, they are likely still susceptible to edge effects from clear-cut logging practices adjacent to their borders (Holien & Prestø, 2008; DellaSala, 2011).

A "whole earth" approach could potentially preserve more biodiversity within the borders of these remnant rainforest patches, by focusing not only on the area itself within the protected boundaries, but also integrating the neighboring land, people, and situations that are linked inherently with the condition of these rainforests (Pearce, 2018). Laurence et al. (2012) concluded that what happens outside protected areas is reflected within, and any serious attempts to conserve biodiversity must consider what is happening adjacent to their boundaries.

Since protected boreal rainforests potentially remain threatened due to nearby anthropogenic disturbance (Gauslaa, 1995; Wolsely & James, 2000; Kermit & Gauslaa, 2001), buffer zones may help mitigate some of these effects. If certain rare or threatened species living in these forests thrive only at far distances from clear-cut edges, this could advise a minimum area for harvest-free buffer zone sizes. Buffer zones have been recommended as a major priority for biodiversity conservation in

nature management (Diego, 2012). A report in 1997 by the former Directorate for Nature Management in Norway (replaced in 2013 by the Norwegian Environment Agency) recommended an implementation of buffer zones of 50-200m around boreal rainforests, citing research by Odin (1976) (Gaarder et al. 1997). In order to ensure long term success of these buffer zones, it may also be necessary to identify and involve the stakeholders associated with these forest edge areas, referring to the whole earth approach mentioned above (Pearce, 2018). For example, timber harvesters would see diminished profits if they are cutting down less trees, and local farmers might oppose government mandates about how to utilize their own property, especially if their income is similarly affected.

Landowners near Swedish boreal rainforests where buffer zones have been proposed have been asked their thoughts about the potential implementation (Götmark et al. 2000). The most opposition was due to fear of losing ownership of parts of their land in creation of new nature reserves under government ownership. However, most responded positively to the land being converted to buffer zones as long as it remained their private land, in addition to 100% compensation, not explicitly opposing the buffer zones themselves. Tscharntke et al. (2011) concluded that "biodiversity conservation measures aiming at more sustainable ways of [...] cultivation will be unlikely to be successful without creating economic incentives for [...] farmers," and also emphasized the necessity of educating farmers about the ecosystem services these rainforests provide. The success of protecting the last boreal rainforest remnants in central Norway may therefor depend on financial compensation for landowners in addition to inclusion and education during the planning, having open communication, and responding to and integrating feedback from locals.

As advised above (Gaarder et al. 1997), the size of potential buffer zones should be based on data, and ecological indicators are a useful tool in such situations. Della & Falkenberg (2019) defines an ecological indicator as "a species or group of species that readily reflects the abiotic or biotic state of an environment […] more easily measurable than other ecological variables of greater interest but difficult measurement […], or when budget and time are restricted." An example of such a species is the lichen *Lobaria pulmonaria* (L.) Hoffm., which requires dark, cool, and moist habitats (Barkman, 1958, Gauslaa & Solhaug, 1999), and thrives better in large undisturbed forests than in small disturbed fragmented patches (Gu et al. 2001, Skagerberg, 2011), as continuity allows for these favorable conditions (Kuusinen, 1996, Schei et al. 2013). Increased sunlight, heat, and wind exposure from large, newly created open areas will potentially damage these types of habitats. Furthermore, *L. pulmonaria* presence is recognized as being linked to the biodiversity of Norwegian boreal rainforests (Gauslaa, 1995). So, if their habitat is threatened or reduced, the overall biodiversity within these forests will likely suffer.

L. pulmonaria is a cyanolichen capable of both asexual and sexual reproduction (Denison, 2003). Asexual reproduction is through propagules called soredia, which are the algal symbiote cells encased within the fungal symbiote, or via detachable offshoots called isidioid soredia, but also through fragmentation (Denison, 2003). The less frequent sexual reproduction happens at the fruiting bodies (apothecia) which can jettison ascospores for many months up to a year after they form (Denison, 2003). Dispersal capacity is limited to short ranges (Öckinger et al. 2005; Jüriado et al. 2011). It is a foliose lichen, due to having dissimilar dorsal and ventral surfaces (Denison, 2003). Due to the three-party symbiotic relationship between cyanobacteria, green

algae (Dictyochloroposis), and the lichen-symbiotic fungus, it is known as a tripartite (Brodo, 2001). In Norwegian boreal rainforests, bark and branches of *Picea abies* trees with a pH between 4.2 - 4.8 create a suitable habitat for *L. pulmonaria*, in addition to providing shading for favorable light, moisture and temperature conditions (Kermit & Gauslaa, 2001; Hilmo et al. 2011). As mentioned above, *L. pulmonaria* is known as an indicator species of forest biodiversity and continuity, as it has been linked with rare macrolichens, bryophytes, and wood beetles (Gauslaa, 1995; Nilsson et al. 1995; Campbell & Fredeen, 2004). Populations of *L. pulmonaria* have been in widespread decline throughout Europe since the industrial revolution, attributed to extensive logging, transformed land use, and increased air pollution which lowers the pH of tree bark substratum below habitable (or establishable) levels (Gauslaa, 1995; Wolsely & James, 2000; Kermit & Gauslaa, 2001).

A recent study by Gauslaa et al. (2019) in British Columbian temperate rainforests focused on health parameters of three different *Lobaria* lichen species in relation to different distances from a recently formed logging edge. Photosynthetic performance and chlorophyll a content were lower in lichen nearest the edge, along with visual discoloration which reduced with an increase in distance from the edge. Nearest the edge was evidence of photoinhibition, defined as the "decrease in photochemical efficiency experienced in response to intense illumination due to radiation damages" (Giacometti and Morosinotto, 2013). All viability parameters measured suggested a distance of 120 meters from a clear-cut edge before they stabilized (Gauslaa et al. 2019).

Similarly, Aragón et al. (2015) observed *L. pulmonaria* only in the interior of a Mediterranean beech (*F. sylvatica*) forest in Spain. Distances investigated from edge were 5, 50, and 100 m. Most *L. pulmonaria* observed was at 100 m, with 2 observations at 50 m, only found at this distance from a soft contrast edge between Oaks (*Q. pyrenaica*) and the interior forest of beeches. They did not report any presence of *L. pulmonaria* at distances less than 100m from edges with hard contrasts such as shrubs. In forests of *Q. pyrenaica* also in Spain, *L. pulmonaria* was found to have a preference for the interior of the forest as opposed to road edges (Belinchón et al. 2007). Barry et al. (2015) also reported *Lobaria* species affected by edges in Atlantic Canadian forests, but they found epiphytes closer to the edges with an average first presence of 12.12m from the edge for all species tested, including *L. pulmonaria*. Another study in Switzerland in areas of historical intensive logging and logging/successive fire disturbance reported no significant influence on the abundance of *L. pulmonaria* (Kalwij et al. 2005). Additional studies are needed to detangle what may be leading to these varied results.

The aim of this project was to provide additional region-specific ecological data to advise in the potential creation of harvest-free buffer zones around the last boreal rainforest remnants in central Norway, through the use of ecological indicators. An investigation of *L. pulmonaria* presence in relation to distance from clear-cut edges satisfies the main criteria described by Della & Falkenberg (2019) for selecting a good ecological indicator in the following ways: by being logistically feasible within this masters project; by the lichen's aforementioned preferred habitat characteristics (Barkman, 1958; Gauslaa & Solhaug, 1999) which are common in undisturbed boreal rainforests (Rose, 1992; Gauslaa, 1994; Kuusinen, 1996; Schei et al. 2013); by the lichen's documented responses (Aragón et al. 2015; Barry et al. 2015; Gauslaa et al. 2019) to stressors expected from clear-cut edge effects; and by the lichen's unique

morphological characteristics (**Figs 1a - d**) which make identification in the field easy and fast, with a low likelihood of confusing it with other species.

Figures 1a - d. Examples of *Lobaria pulmonaria* observed throughout the project, personal photos taken with iPhone 7 (©Apple Inc, 2016).

The main objectives were to (1) identify a potential relationship between clear-cut logging specific edges and *L. pulmonaria* presence, (2) distinguish biotic and abiotic factors that influence this relationship, and (3) identify alternative potential indicators of clear-cut edge effects on the integrity of boreal rainforests, for example: understory functional group community composition and soil decomposition, measured by teabag decay rate.

I tested the hypotheses that (1) *L. pulmonaria* occurs significantly less near the edges of clear-cuts, an asymptotic relationship gradually increasing in abundance up to a stabilizing point around 120 m from the edges based on previous studies (Renhorn et al. 1996; Aragón et al. 2015; Gauslaa et al. 2019), (2) soil moisture, ground level temperature, and canopy coverage will significantly correlate with the distance to the

nearest clear-cut edge and *L. pulmonaria* presence, (3) teabag decay rate will positively correlate with distance to clear-cut edge (signaling faster soil decomposition furthest from edge), and (4) ground cover functional group composition will change in a gradient as the distance from clear-cut edges increases with a similar asymptote as mentioned above.

Chapter 2. Methods

2.1 Site selection

Potential study locations were boreal rainforests in Northern Trøndelag, Norway, as defined by the Norwegian Environment Agency's map database (Miljødirektoratet, 2019). Public access maps from NorgesKart (Norgeskart, n.d.) were used to determine study sites adjacent to clear-cuts less than 3 hours travel distance from Steinkjer, with priority given to the nearest sites for practicality. The forests chosen were Eldbrenna sør in Steinkjer municipality, Straumhyllbekken and Oksdøla S II in Namsos municipality, and Abrahammyra NV and Fuglsmoen S in Grong municipality (**Fig. 2 / Table 1**).
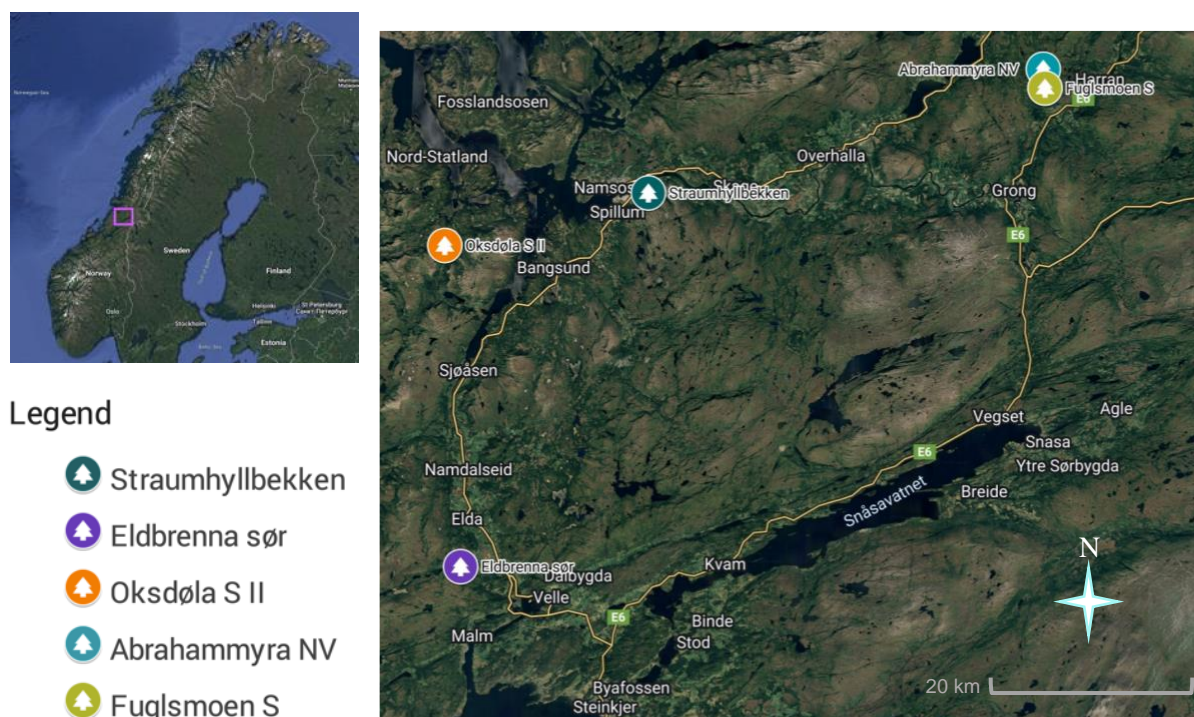
Figure 2. Study area with the 5 boreal rainforest site locations in northern Trondelag, Norway. (Map data ©2022 Google Imagery ©2022 TerraMetrics)

ArcGIS Pro software (ESRI 2002) was used to generate 90 plot locations (**see Appendix 1 Figs 1.1, 1.4, 1.7, 1.10, & 1.13**), horizontally spaced 25m, which corresponds with the height of a mature *Picea abies* in Central Norway (Hilmo & Holien, 2002; DellaSala, 2011; Portti, 2021). All plots were less than 200m from the nearest clear-cut edge, in accordance with previous studies about edge influence on *L. pulmonaria* (Renhorn et al. 1996; Aragón et al. 2015; Gauslaa et al. 2019). Distances from each plot to the nearest road were further than the distance to the nearest clear-cut edge to avoid confounding different edge influences. The upper age restriction for clear-cuts was that regenerating trees were not over 2 meters tall with no defined lower age limit.

Table 1. Boreal rainforest study sites with respective coordinates, direction from plots the edge faces towards a clear-cut (*Edge aspect*), number of plots, range of distances to the clear-cut edge from the plots within each site, and elevations in meters above sea level.

Rainforest ID	*Coordinates*	*Edge aspect*	*(n) Plots*	*Nearest clear-cut edge (m)*	*Elevation (m)*
Eldbrenna sør	64°08'15.3"N 11°12'26.2"E	SW, W	20	103 - 181	120
Straumhyllbekken	64°27'41.6"N 11°34'59.7"E	NW, W, SW	28	43 - 185	39
Oksdøla S II	64°24'58.2"N 11°10'32.5"E	NE	28	45 - 186	174
Abrahammyra NV	64°34'04.8"N 12°22'21.7"E	N, W	10	6 - 46	114
Fuglsmoen S	64°33'06.1"N 12°22'33.4"E	W	4	11 - 26	119

2.3 Field methods

Each plot was found by stopping at the first "0m to coordinates" encountered on a Garmin 62S gps unit which became the center of the plot. A palm-width blade was pushed into the nearest soil to form a pocket where a teabag (Lipton Indonesian Sencha Tradition: EAN 87 22700 05552 5) was placed inside. The paper tea label attached to the teabag string was wrapped with bright red duct-tape to help with visibility for return visits to the plots. The plot ID number was written on the red tape with a Sharpie permanent marker.

A moisture / temperature sensor (TOMST TMS-4; https://tomst.com/web/en/systems/tms/tms-4/) was placed into the soil as near to the center of the plot as possible without disturbing the teabag. In order to aid in relocating the plots during return visits, a photo was taken of the center of the plot with the red tape and plot ID number visible along with any distinctive surrounding features as a reference. In order to help orient the location the photo was taken, the Garmin GPS unit was also included in the photo with the antenna pointing north.

In order to create a circular 2.5 meter radius plot, one end of a rope measured and cut to 2.5 m was pinned down with a tent spike at the plot's center, and was fully extended toward each of the four cardinal directions, carefully stepping to avoid as much trampling as possible here and throughout the entire field work process. In order to visibly mark the plot for ground cover diversity inspection, tent spikes wrapped with bright red duct-tape were placed at the end of the fully extended rope at each cardinal directional point. An iPhone 7 (©Apple Inc, 2016) was used to take canopy photographs from heart-height at the North, East, South, and West borders of the plot.

These photos were later converted to binary data through unsupervised classification in R, and the average of the percentages of dark portions of the four photos was used as the canopy cover value for each plot.

All tree species within the plot were recorded. If a tree species was unknown or unsure, a photo of the tree was taken along with its leaf to be identified later. Ground cover functional group diversity was assessed using the DAFOR method specifying Dominant, Abundant, Frequent, Occasional, Rare, or zero for no presence. Functional groups recorded were bryophytes, dead wood, dwarf shrubs, ferns, graminoids, herbs, lichen, litter, stone, soil, trees taller than 2 m, and trees shorter than 2 m. A decision was made (incorrectly) in the field to treat Equisetum species as herbs. Presence / absence of *Lobaria pulmonaria* within the plot was noted. A final photo was taken of the entire plot, visibly showing the red tape from the teabag in the center, as well as at least one red taped tent spike from a directional point to inform about scale. Moisture / temperature sensors and teabags were retrieved approximately three months later before the first drop in local temperatures to 0 degrees Celsius.

2.3 Sample Processing

Total number of teabags retrieved were 56 out of the original 90. The rest were either missing upon relocation efforts or torn too greatly to be used. The retrieved teabags were placed in a freezer at the end of each day of collection. Teabags were dried using a VWR DL 112 Prime: 466-0449 at 70° C for 48 hours. All external debris was then removed from each dried teabag using forceps, and strings and tags were removed. Each tea bag was weighed on a Sartorius Lab Instruments QUINTIX224-1S scale. The ending dry weight of each teabag was subtracted from the initial weight of a fresh teabag. The natural logarithm of each difference was divided by days in the field. This was the final value used as decomposition rate (grams lost per day) for further analysis. This process was necessary because the tea bags were placed and retrieved on different days, and because the decay rate of tea bags is not linear but instead on a curve (Keuskamp et al. 2013).

Only 78 of 90 total sensors were relocated. The sensors recorded soil moisture over a 0-10cm depth along with temperatures at three different depths at 15 minute intervals for the entire duration. Since these were also placed and retrieved on different days, a common twenty day window was extracted, between September 7th - 26th, 2021, and the average of the raw moisture index values and temperatures at the middle depth were the values used for analysis.

2.4 Statistical Analyses

Classification and regression trees were used to describe the data as a reduction method to select explanatory variables for a logistic regression model with a response of *L. pulmonaria* presence, because this nonparametric method allows mixing different data types and does not assume linear relationships (Roff & Roff, 2003). This was done using the rpart() package (Therneau et al. 2015) in R. As the nearest clear-cut edge variable was the most relevant variable for my hypotheses, other variables with lesser importance values were sequentially eliminated from the original formula until nearest clear-cut edge was visible in the printed regression tree within the recommended number of splits indicated by the plotcp() function (Therneau

et al. 2015). The logistic regression model was then constructed including explanatory variables visible in the regression tree with *L. pulmonaria* presence as the response variable.

In order to test for collinearity, variance inflation factor (VIF) values were produced using the car() package in R (Fox et al. 2007). A k-fold cross validation was also performed to test for overfitting or selection bias (Stoltzfus, 2011). For each continuous variable, Shapiro-Wilk tests were used to determine if residuals were normally distributed, along with the generation of histograms of this distribution, and a test of linearity against log odds was also performed (**see Appendix 2 Figs A2.1 & A2.2**). The car() package was again used to identify potential outliers using the Bonferroni outlier test, and potential influential observations were checked against their Cook's distances (**see Appendix 2 Figure A2.3**) (Fox et al. 2007).

Spearman rank models with Benjamini & Hochberg (1995) corrections for multiple testing were constructed for all variables in relation to nearest clear-cut edge distance to inform about other potential effects of clear-cut logging edges, and scatterplots were also created for these relationships (**see Appendix 3 Figs A3.1 - A3.19**). Tree species with less than 10 observations were not included. In order to visualize potential collinearity with rainforest sites, boxplots were constructed for each explanatory variable in the logistic regression model in relation to each site (**see Appendix 4 Figs A4.1 - A4.3**).

Chapter 3. Results

L. pulmonaria was present in 14 of 90 sampled plots and occurred at every rainforest site except Abrahammyra NV (**see Appendix 5 Table A5.1**). Straumhyllbekken had 25% of plots with *L. pulmonaria* presence observed, the most of all sites. Fuglsmoen S also had 25%, but only four plots were studied there.

Soil moisture raw index values, fern abundance and nearest clear-cut edge distance were determined to be the most likely variables to describe presence of *L. pulmonaria* (**Fig. 3**). There was an implied unimodal relationship between soil moisture index values and *L. pulmonaria*. The lichen was present in 44% of the plots which had soil moisture index values less than 2696 combined with fern abundance greater than or equal to frequent (DAFOR scale), but the lichen was only present in 3% of the plots which had soil moisture index values greater than or equal to 2696. *L. pulmonaria* was completely absent from the plots which had soil moisture index values less than 2106 and fern abundance less than frequent. Although, when fern abundance was less than frequent and the nearest clear-cut edge distance was greater than or equal to 148 meters, with soil moisture index values between 2106 - 2696 (or equal to 2106), 43% of these plots included *L. pulmonaria*. The lichen was present in 15% of the plots where the nearest clear-cut edge was less than 148 meters with fern abundance less than frequent and soil moisture index values between 2106 - 2696 (or equal to 2106).
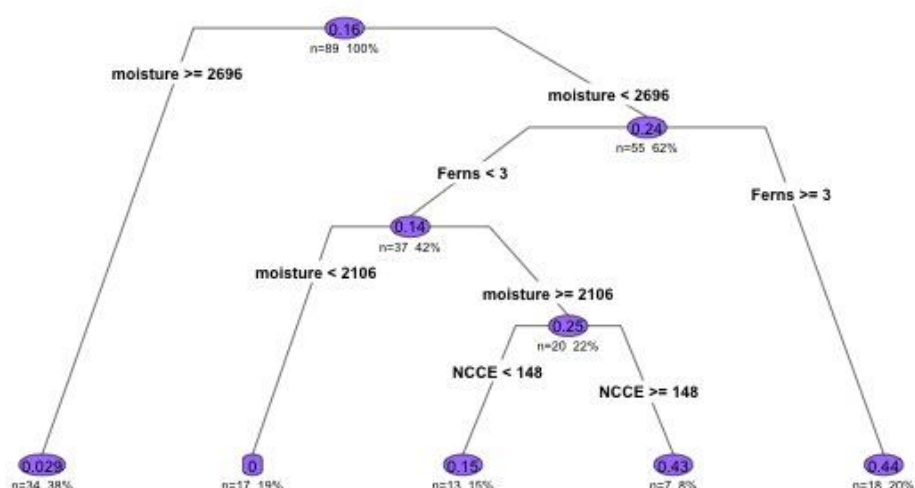
Figure 3. Classification and regression tree with variable combinations describing *L. pulmonaria* presence within each purple node.

A logistic regression test including the variables from the regression tree (**Fig 3**) did not show a significant effect of the nearest clear-cut edge on the presence of *L. pulmonaria* (**Table 2**). However, fern abundance did have a significant effect with a Mcfadden's Pseudo R^2 of 0.071.

Table 2. Results from logistic regression test with explanatory variables recommended from the classification and regression tree (**Fig 3**) tested against response variable *L. pulmonaria* presence.

Variable	(n) plots	Std. Error	Estimate	p - value
Ferns	89	0.311	0.624	0.045

Soil moisture	78	0.001	-0.001	0.278
Nearest clear-cut edge	89	0.007	0.003	0.684

Variance inflation factor (VIF) values were below the common threshold of 5, signifying low collinearity, with ferns: 2.007, moisture: 1.086, and nearest clear-cut edge: 0.408. Cross validation of the logistic regression models did not reveal any overfitting or sample bias. Shapiro-Wilk tests suggested normal distribution of residuals with soil moisture: W = 0.98509, p = 0.498; ferns: W = 0.90604, p = < 0.001, and nearest clear-cut edge: W = 0.95724, p = 0.005. Tests for linearity against log odds for continuous variables moisture and nearest clear-cut edge did not suggest nonlinearity (**see Appendix 2 Figs A2.1 & A2.2**). There were no outliers with a Bonferroni p - value less than 0.05, however observation 78 had p = 0.014 with Bonferroni p - value of NA. There were no influential observations with a Cook's distance greater than or approaching 1 (**see Appendix 2 Fig. A2.3**).

Due to the implied unimodal relationship between soil moisture index values and *L. pulmonaria* (**Fig. 3**), a quadratic term was included in a further logistic regression test. However, this did not improve the model validation with a nearly identical AIC value as the first logistic regression model. Therefor only the original model was included for maximum parsimony.

Spearman rank models with Benjamini & Hochberg (1995) corrections for multiple testing did not reveal significant correlations between nearest clear-cut edge distance and canopy cover, soil moisture, ground level temperature, or teabag decay rate (**Table 4**). However, the distance to edge correlated positively with mosses (bryophytes) and stones and correlated negatively with grasses (graminoids).

Table 4. Results from Spearman rank models. All variables were tested with explanatory variable nearest clear-cut edge, using Benjamini & Hochberg (1995) corrections.

Variable	*(n) plots*	*r*	*p - value (corrected)*
Soil moisture	78	-0.120	0.294
Ground levelre temperature	78	0.048	0.676
Canopy coverage	85	0.190	0.081
Teabag decay rate	56	0.160	0.239
Bare soil	89	0.078	0.467
Stone	89	0.247	0.020
Bryophytes	89	0.442	< 0.001
Deadwood	89	-0.065	0.545
Dwarf shrubs	89	0.0873	0.416
Ferns	89	0.0479	0.656
Graminoids	89	-0.236	0.026
Herbs	89	0.051	0.633
Lichen	89	-0.065	0.549
Litter	89	-0.076	0.481
Trees > 2m	89	0.021	0.846
Trees < 2m	89	-0.075	0.487
Betula pubescens	89	0.039	0.720

Sorbus aucuparia	89	0.019	0.862
Picea abies	89	-0.004	0.972

Chapter 4. Discussion
4.1 Presence of *L. pulmonaria*

The absence of significant relationships between nearest clear-cut edge distance and any of the microclimate variables such as ground level temperature, canopy cover, soil moisture, or soil decomposition rate, points to there not being enough difference in the microclimates between edges studied and the forest interiors as a main explanation for the observed lack of significant edge influence on the presence of *Lobaria pulmonaria*. This could also be partly due to the low total amount of *L. pulmonaria* observed.

However, during this study I began to realize based on literature reading that presence of *L. pulmonaria* might not actually be the most informative variable to investigate for edge effects (**Table 5**). For example, Barry et al. (2015) found *L. pulmonaria* to be the least affected by road edge influence out of three *Lobaria* species they studied. Kalwij et al. (2005) also suggested that dispersal capability of *L. pulmonaria* might not be limited enough to be an adequate ecological indicator of continuity after stand level disturbances. However, they only studied natural disturbances where regenerating trees create more potential hosts for re-establishment. Hilmo et al. (2011) suggested recolonization is not successful near such open areas until regenerating trees create dark enough conditions, and that logging areas specifically likely wouldn't be suitable for establishment of *L. pulmonaria,* because the period of time between harvests is often shorter than the time needed for diaspore production. They did however note that *L. pulmonaria* seemed more resistant to drought and high light compared to *Lobaria scrobiculata*. Renhorn et al. (1996) also found most *L. pulmonaria* transplants increased size near a clear-cut edge edge in northern Sweden, with the highest growth rates 6 meters next to the edge and lowest at 50 meters into the interior of the forest, while also noting that boreal rainforests have low microclimate contrast between edges and interiors. Coxson and Stevenson (2007) similarly found large *L. pulmonaria* thalli to increase in size near clear-cut edges in British Columbian forests. Gauslaa and Solhaug (1999) found light and heat to have additive effects on desiccated *L. pulmonaria* thalli, but wet conditions could mitigate this effect. Gauslaa et al. (2006) found *L. pulmonaria* grows better under open canopies, but with a trade-off of increased desiccation risk. This risk would likely be low in areas such as northern Trøndelag which have frequent precipitation (**see Appendix 1 Figs A1.2, A1.5, A1.8, A1.11, A1.14**) (DellaSala, 2011; Mafole et al. 2017). Increased light near clear-cut edges likely stimulates growth in mature thalli as long as there are not any prolonged dry periods. *L. pulmonaria* is able to filter out extra light by melanization and is capable of repairing photoinhibition damage under wet conditions, where metabolic rates are high (Mafole et al. 2017). Gauslaa et al. (2019) also concluded that frequent rainfall during short summers could be efficiently utilized because of the low water holding capacity of *L. pulmonaria*, which only needs about 16mm of rain to fill the lichen's internal water storage.

Table 5. Previous studies relevant to this study involving disturbance or specifically edge effects on *L. pulmonaria*.

Reference	Study species	Location	Latitude	Adverse effects found for L pulmonaria?	Distance
Renhorn et al. (1996)	*Platismatia glauca* & *L. pulmonaria* (transplanted)	Sweden	64°14' N	No (increased growth rates near edges)	(Distances studied: 2, 6.25, 12.5, 25, 50 and 100 m)
Kalwij et al. (2005)	*L. pulmonaria*	Switzerland	46°28' –34' N	No (community response to historical disturbance, spatial distribution)	NA
Belinchón et al. (2007)	Bryophytes & Lichens (including *L. pulmonaria*)	Spain	40°34' N	Yes - presence/abundance	"found at long distances to the edge", "preference for the interior." (otherwise unspecified, distances studied: 5, 15, 25, 35, 45, 55 and 100 m)
Coxson & Stevenson (2007)	*L. pulmonaria*	British Columbia, Canada	53°44' - 53°50' N	Yes - decreased growth rates only for small thalli - soft contrast edges (large thalli increased growth rates near edges)	Similar results up to 60 m (distances studied: 0, 7.5, 15, 30, 60 m)
Hilmo et al. (2011)	*L. pulmonaria* & *L. scrobiculata* (transplanted)	Northern Trøndelag, Norway	63°58' - 64°32' N	No - establishment was as successful in plantations as old forests (significant effect of locality found)	Distances from edges not investigated
Aragón et al. (2015)	Bryophytes & Lichens (including *L. pulmonaria*)	Spain	41°15'	Yes - presence	100m for hard contrast edges
Barry et al. (2015)	*L. pulmonaria, L. quercizans, L. scrobiculata*	New Brunswick, Canada	~ 46°60' - 47°59'	Yes - presence	Average distance from edge: 12.11 m (however, L. pulmonaria was the least affected of the three species studied)
Gauslaa et al. (2019)	*L. retigera, L. oregana, L. pulmonaria* (transplanted)	British Columbia, Canada	55°32'	Yes (photosynthetic performance, chlorophyll a content, photoinhibition)	Gradient up to 120m
Di Nuzzo et al. (2022)	*L. pulmonaria* (transplanted)	Italy	43°18'	Yes - minimal survival & decreased growth rates in logged vs. unlogged stands, but also the same for south facing vs. north facing specimens	Distances from edges not investigated
This study	*L. pulmonaria*	Northern Trøndelag, Norway	64°08' - 64°34'	No	(Distances studied were 6 - 186 m)

Lack of observed significant edge effect on *L. pulmonaria* presence could also be partly due to the direction each edge faces. Hylander (2005) found differences in edge influence between southern and northern edge aspects in northern Swedish boreal forests adjacent to clear-cuts. A recent study (Di Nuzzo et al. 2022) about edge effects on *L. pulmonaria* also revealed that growth of small fragments of the lichen facing north was nearly twice as much as those facing south, and closely similar to growth in unlogged stands. They concluded this could be due to protective shading of southern trees from sunlight in addition to nightly dew events that occur frequently on northern sides of forest gaps. Renhorn et al. (1996) mentioned above also attributed their lack of significant edge effect to be partly due to edge aspect, as their edges faced east. My study did not include a full range of edge orientations. The small sizes of these nearby remnant patches and their irregular shapes made this difficult. A compromise was necessary, and five sites were chosen which did not have a similar clear-cut edge aspect, and none facing directly south from the plots (**see Appendix 1 Figs A1.1, A1.4, A1.7, A1.10, & A1.13**). However, Eldbrenna sør and Straumhyllbekken had southwest facing edges for 15 of 20 plots and 9 of 28 plots respectively. This compromise also led to sites with differing annual precipitation (**see Appendix 1 Figs A1.1, A1.2, A1.4, A1.5, A1.7, A1.8, A1.10, A1.11, A1.13 & A1.14**). Hilmo et al. (2011) studied *L. pulmonaria* in three similar localities in Steinkjer, Namsos, and Grong, among others, and observed a significant effect of locality on the colonization of *L. pulmonaria*, with the highest establishment rates at the Steinkjer location, which they noted corresponds with the lowest amount of annual precipitation of all sites they studied. They also did not report significant differences between establishment success in logged stands versus unlogged stands for *L. pulminaria*. As suggested by Renhorn et al. (1996), it's possible that Norwegian boreal rainforests likely don't have enough microclimate contrast between edges and interiors to show an adverse edge influence on *L. pulmonaria*. This also seems to be indicated by most studies not showing a significant edge influence occuring above 60° N (**Table 5**), except in Switzerland (Kalwij et al. 2005), which was not actually an edge effect study.

Edge aspects in relation to the direction of the prevailing winds in the region is also important to consider, as distances of edge influence from winds can be up to 20 times more than from light (Chen et al. 1995; Davies-Colley et al. 2000; Harper et al. 2005,). However, for each study site the prevailing winds were mostly east-southeast (**see Appendix 1 Figs A1.1, A1.3, A1.4, A1.6, A1.7, A1.9, A1.10, A1.12, A1.13, & A1.15**). Since edge aspects in my project (**Table 1**) mostly face away from this prevailing wind (or towards low wind activity such as Oksdøla S II), the forest itself may have acted as a barrier, as above with sunlight, protecting from some of the worst potential edge influence from wind. This may be a way to reduce potential edge effects from clear-cuts, by positioning the felling with edges where intact forests shelter the edge areas from the directions of sunlight and prevailing winds.

Fern abundance was the only variable with a significant influence on the presence of *L. pulmonaria*. Since the presence of *L. pulmonaria* has previously been associated with many rare, endangered, and red listed species in Norwegian boreal rainforests (Gausla, 1995), certain fern species are likely to also correlate with such rare species. Della & Falkenberg (2019) investigated the use of pteridophytes as ecological indicators which included 32 studies as specific indicators of either environmental integrity or association with other groups of organisms, but none of

these were based in boreal rainforests. Future studies are recommended to distinguish which specific fern species correlate with *L. pulmonaria* as potential alternative ecological indicators for biodiversity of Norwegian boreal rainforests.

Soil moisture was expected to positively correlate with *L. pulmonaria* abundance, but logistic regression analysis did not reveal a significant relationship in this study. However, the regression trees suggested a potentially unimodal relationship between soil moisture and *L. pulmonaria*. Since fern abundance correlated with *L. pulmonaria* presence, and common fern species in the area (Alm 2016) have a preference for average or higher soil moisture content but avoid the highest Ellenberg soil moisture classifications (Ellenberg et al. 1991), this might also suggest a unimodal relationship between soil moisture and *L. pulmonaria*. Also, as mentioned above, the study by Hilmo et al. (2011) noted that the locations with the highest annual precipitation did not have the highest amount of establishment of *L. pulmonaria*, which also possibly indicates a unimodal relationship.

4.2 Alternative associations with nearest clear-cut edge distance

Stone functional group abundance on the forest floor was significantly positively related to the distance from nearest clear-cut edge. This likely reflects how the terrain in these last remnant forests makes it difficult for harvesting the areas furthest away from the clear-cut edges, which has played a role in their continued existence (DellaSala, 2011).

Bryophyte abundance also significantly correlated positively (Table 5) with the distance to clear-cut edge, which is likely due to being outcompeted by graminoids in potentially increased light conditions near the edge (see below) (Van der Wal et al. 2005). However, the only variable that measured light conditions for each plot was canopy cover, which did not significantly increase further away from the edges. The potentially increased light entering the forest in a more horizontal angle from the edge itself was not directly measured in this study. Since canopy photos were taken facing directly upwards, they were not able to capture this effect. Since the edges did not face the prevailing winds, it is possible that winds were not strong enough to fell trees during the time since the clear-cut edge was created, which might account for the lack of a significant relationship between canopy cover and distance to edge. The characteristics of the northern latitudes' sun also affects light conditions. Harper et al. (2005) found the magnitude of edge influence to be lower in boreal forests compared to temperate forests at lower latitudes as a result of reduced edge contrast from "a longer optical path and greater solar attenuation." However, they also suggest that the distance of edge influence could be longer because of a greater angle to the sun.

Straumhyllbekken had the highest percentage of plots with *L. pulmonaria* and was also the site with the lowest elevation (Table 1), corresponding with a study in Ukraine which found elevation to have an influence on the lichen's distribution (Nadyeina et al. 2014). They attributed the lack of higher elevation distribution to exposure to airborne pollution.

4.3 Possible increased nitrogen deposition

Increasing bryophyte ground cover away from the edges could also partly be due to potentially increased anthropogenic nitrogen deposition at the edges, as bryophytes are especially sensitive to airborne nitrogen (Lamers et al. 2000). Also, graminoids increased significantly (**Table 5**) towards the edges of clear-cuts. Increased light at the edges (see above paragraph about canopy cover) is probably the main cause, as they compete well in high light areas (Kull & Aan, 1997; Van der Wal et al. 2005), but this could also be an additional signal for increased nitrogen deposition near the edges (Rosén et al. 1992; Strengbom et al. 2002). This would be problematic because boreal rainforests are typically low in nitrogen (Tamm, 1991) with an understory mostly dominated by ericaceous dwarf shrubs (Walter, 1979).

An influx of nitrogen in boreal rainforests increases the abundance of grasses not only because increased nitrogen stimulates growth of the grasses themselves (Tamm, 1991), but another mechanism involving parasite - host interactions shown to quadruple the effects of nitrogen deposition on the growth of grasses. Increased nitrogen deposition increases the abundance of amino acids such as glutamine in the leaves of ericaceous shrubs, making the leaves more susceptible to parasitic fungal attacks by species such as *V. heterodoxa*. These increased attacks cause a reduction in leaves, allowing increased light penetration to the forest floor, facilitating increased abundance of fast-growing grasses below, in combination with the effects of the increased nitrogen itself (Strengbom et al. 2002). There were personal undocumented observations of many spotted leaves of ericaceous bushes in addition to many leafless bushes during the summer months of the field work.

However, fern abundance did not correlate with distance to nearest clear-cut edge. Since fern species common to the area (Alm, 2016) do not compete well in areas with high nitrogen (Soó, 1964-1980, Sonkoly et al. 2022), this might suggest there is not actually increased nitrogen deposition near the edges. Also, airborne nitrogen, particularly harmful for bryophytes (Lamers et al. 2000), is likely more influential at edges facing prevailing winds, which were not studied in my project. Norway has also taken steps to avoid nitrogen deposition problems, and the Norwegian government reports that nitrogen levels from fertilizers have remained stable over the past 70 years (Ministry of Climate and Environment, n.d.). These claims could be tested by investigating rainforest edges adjacent to clear-cuts for increased levels of nitrogen deposition, including inspections for increased occurrence of parasitic fungal attacks on the dominating ericaceous dwarf shrubs. If Nitrogen levels are indeed rising near clear-cut edges, buffer zones may help to avoid approaching critical load and prevent an understory community composition shift in these forests.

4.4 Soil decomposition

Teabag decay rate was not found to be significantly correlated with the distance to nearest clear-cut edge. The increase in bryophytes away from the edge might be a confounding influence, specifically wherever sphagnum species were present, as they are known to acidify soils (Van Breemen, 1995), which slows soil decomposition (Bardgett & Wardle, 2010). The presence of sphagnum bryophytes near teabag placements was later confirmed in 26 plots via photograph inspections (**see Appendix 6 Figs A6.1 - A6.3**). Future studies including these variables should account for this

relationship between the presence of soil acidifying species such as sphagnums and teabag decay rate.

4.5 Possible confounding edge influence

A maintained edge borders the north side of the Abrahammyra NV study site (**see Appendix 1 Fig. A1.10**). Plots for this site were within a short range from this maintained edge, and all of them were also close to the clear-cut edge (**Table 1**). It's possible that there were confounding effects from this different type of edge, as maintained edges have different effects, for example on the understory, than regenerating edges. If high competition along this long-term maintained edge created a forest wall of fast-growing light demanding species, it could have resulted in lower abundance of slower growing understory vegetation in the area of this maintained edge's influence, which is perpendicular to the expected gradient of edge influence from the neighboring clear-cut (Harper et al. 2005).

4.6 Additional future studies not already mentioned

In order to better understand the role of clear-cut edge influence on *L. pulmonaria* in Norwegian boreal rainforests, future studies would need more ideal study locations, for example in areas known for high *L. pulmonaria* presence, with a full range of edge orientations related to prevailing winds and the sun, full ranges of distances, and similar in annual precipitation, compared with a control forest which was not a clear-cut edge, but some other edge type, to help distinguish clear-cut edge type influence from the influence of the specific edge type of the control forest. It would also probably be preferable to investigate chlorophyll a content of present *L. pulmonaria* or growth rate of transplanted fragments along a potential edge influence gradient instead of presence / absence, as rercent studies have found pronounced edge influence on these variables (Gauslaa et al. 2019; Bianchi, 2020; Di Nuzzo et al. 2022).

Chapter 5. Conclusion

This study did not detect an influence from clear-cut edges on *L. pulmonaria* presence in northern Trøndelag. Only 14 plots included *L. pulmonaria*, which could be partly attributed to the lack of available study sites logistically available for this project. The absence of significant relationships between nearest clear-cut edge and abiotic variables such as ground level temperature, canopy cover, soil moisture, and soil decomposition rate, suggests there is not enough difference in microclimates between the studied edges and forest interiors as a main explanation for the observed lack of significant edge influence on the presence of *Lobaria pulmonaria*. Reasons for this are varied but likely involve study design, including edge aspect in relation to prevailing wind direction and the sun's position, as well as having numerous study locations without a full range of distances able to be sampled at each site, but also because Norwegian boreal rainforests may not have high enough contrast in microclimates between edge area and interior, due to consistent rain and low temperatures.

Although the data from this project is unable to inform about buffer zone sizes, it does help to develop new hypotheses to identify further research needs. Fern functional group abundance positively correlated with presence of *L. pulmonaria*, a commonly used indicator species for forest biodiversity. This implies certain fern species also have potential indicator value for biodiversity of Norwegian boreal rainforests. Therefor future studies are recommended to distinguish which specific fern species' presence significantly correlates positively with *L. pulmonaria* and perhaps with other rare species. Also, graminoids' increasing abundance near the edges combined with bryophytes' increasing abundance further from edges suggests increased light near the edges, but also might signal increased nitrogen deposition near the edges as well. Further studies are then recommended to investigate this possibility, with implications for the entire understory composition of the last remaining boreal rainforests in central Norway.

Chapter 7. Acknowledgements

Chapter 6. References

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Chapter 8. Appendices

Appendix 1

(A1.1)

N

200 m

(A1.2)

30 °C
20 °C
10 °C
0 °C
-10 °C
-20 °C
-30 °C

100 mm
75 mm
50 mm
25 mm
0 mm

-1 °C -1 °C -1 °C 6 °C 4 °C 8 °C 16 °C 18 °C 17 °C 13 °C 7 °C 2 °C -1 °C
-7 °C -7 °C -5 °C -1 °C 12 °C 10 °C 10 °C 6 °C 2 °C -2 °C -5 °C

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

● Precipitation — Mean daily maximum - - Hot days — Mean daily minimum
- - Cold nights — Wind speed

meteoblue ≡

(A1.3)

ESE
● 0 : **3 h/year**
● >1 : **101 h/year**
● >5 : **644 h/year**
● >12 : **459 h/year**
● >19 : **196 h/year**
● >28 : **111 h/year**
● >38 : **79 h/year**
● >50 : **53 h/year**
● >61 km/h: **33 h/year**

Appendix Figs A1.1 - A1.3: Eldbrenna sør study site with average temperatures and precipitation, and wind rose for the area, showing aspect of edge in relation to prevailing winds (clear-cut site is transparent green area). Map source: ArcGIS Pro software (ESRI 2002) Climate data source: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/

(A1.4)

(A1.5)

(A1.6)
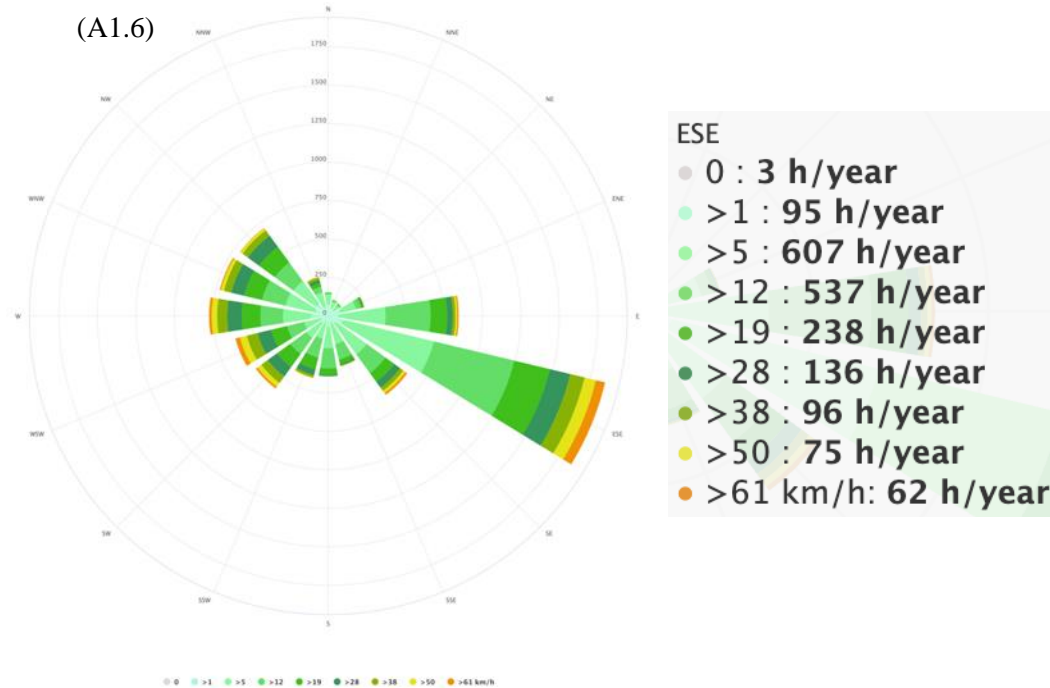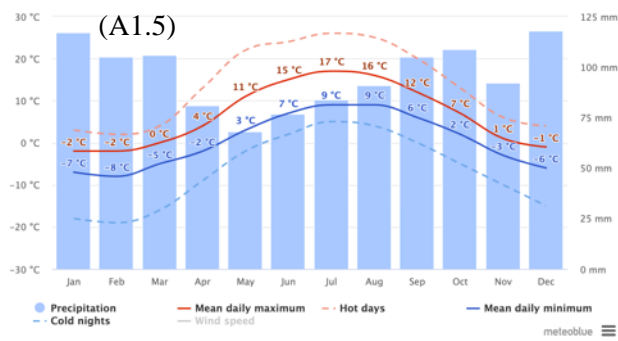
Appendix Figs A1.4 - A1.6: Straumhyllbekken study site with average temperatures and precipitation, and wind rose for the area, showing aspect of edge in relation to prevailing winds (clear-cut site is transparent green area). Map source: ArcGIS Pro software (ESRI 2002)

Climate data source: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/

(A1.7)

(A1.8)

(A1.9)
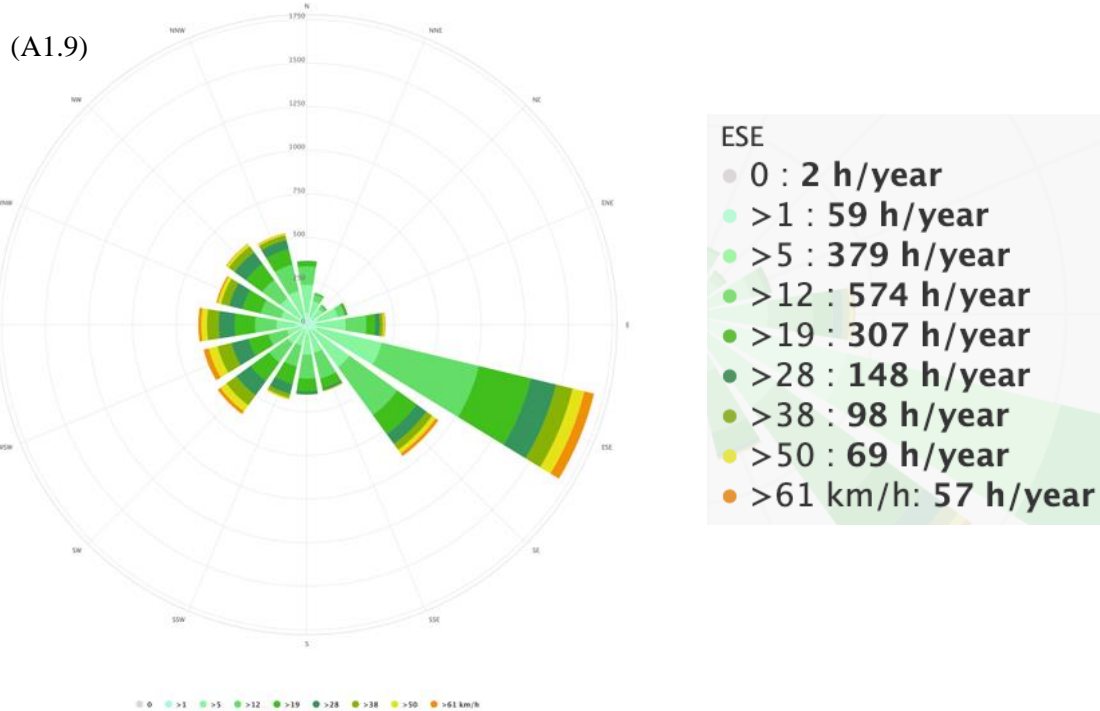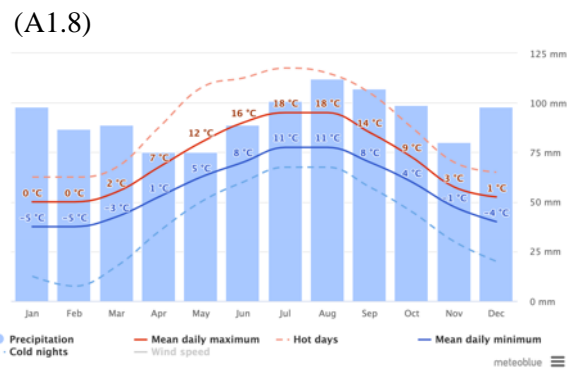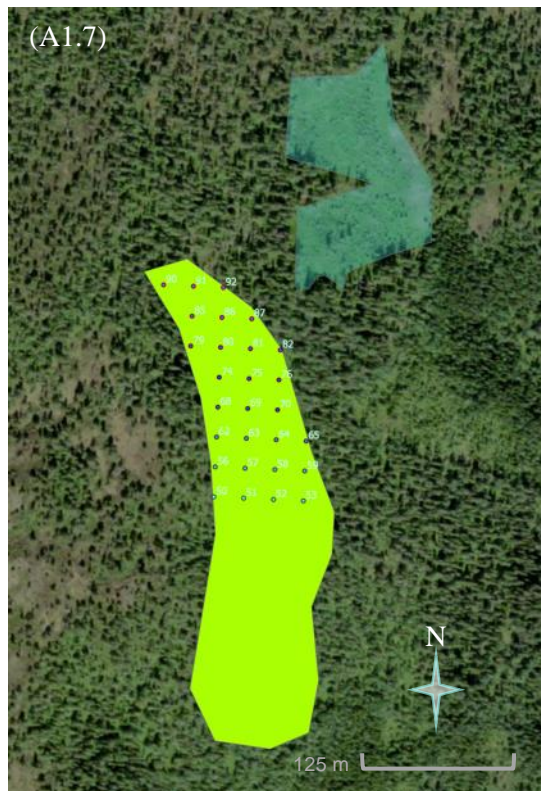
Figure A1.7 - A1.9: Oksdøla S II study site with average temperatures and precipitation, and wind rose for the area, showing aspect of edge in relation to prevailing winds (clear-cut site is transparent green area). Map source: ArcGIS Pro software (ESRI 2002)

Climate data source: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/

(A1.10)

(A1.11)
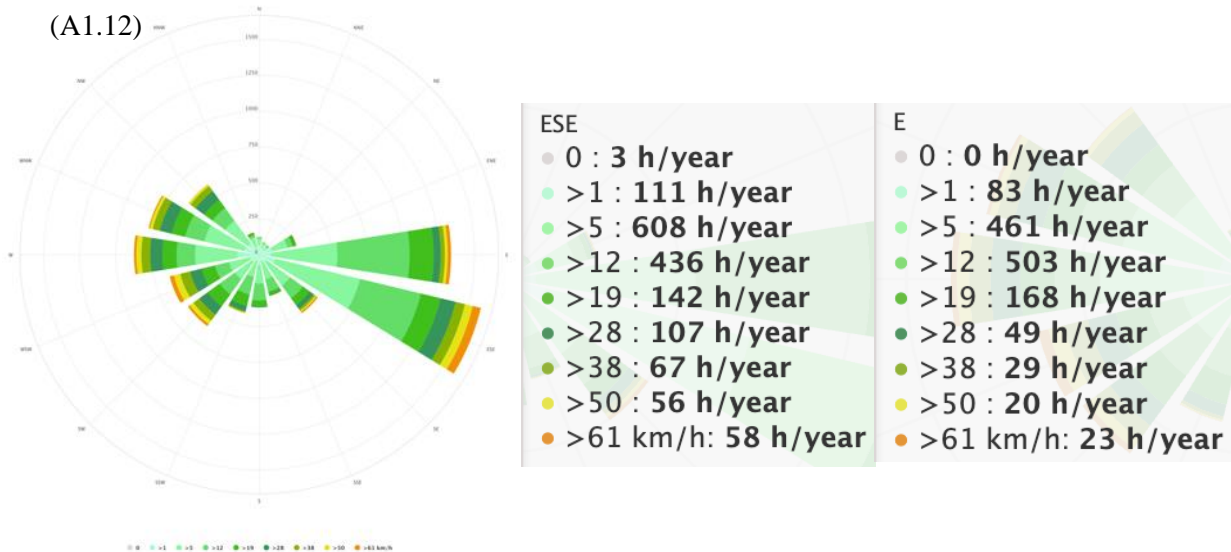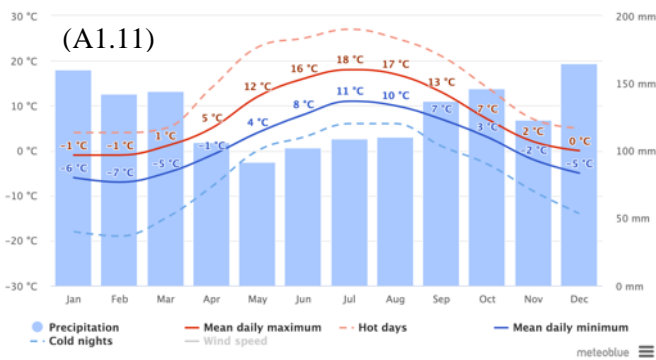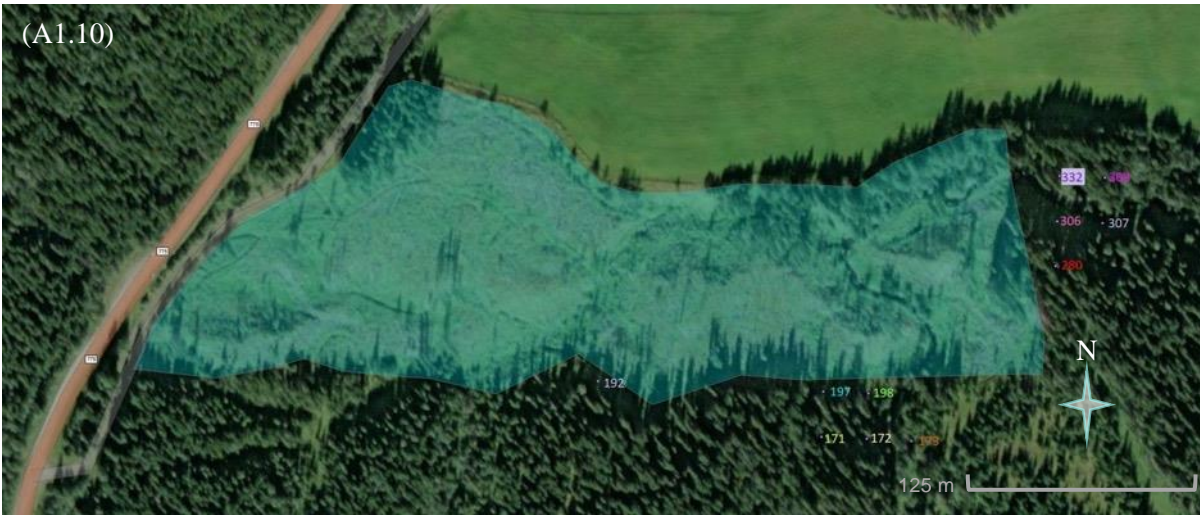
(A1.12)

Appendix Figs A1.10 - A1.12: Abrahammyra NV study site with average temperatures and precipitation, and wind rose for the area, showing aspect of edge in relation to prevailing winds (clear-cut site is transparent green area). Map source: ArcGIS Pro software (ESRI 2002)
Climate data source: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/

(A1.13)

(A1.14)

(A1.15)

ESE
- 0 : **3 h/year**
- >1 : **111 h/year**
- >5 : **608 h/year**
- >12 : **436 h/year**
- >19 : **142 h/year**
- >28 : **107 h/year**
- >38 : **67 h/year**
- >50 : **56 h/year**
- >61 km/h: **58 h/year**

E
- 0 : **0 h/year**
- >1 : **83 h/year**
- >5 : **461 h/year**
- >12 : **503 h/year**
- >19 : **168 h/year**
- >28 : **49 h/year**
- >38 : **29 h/year**
- >50 : **20 h/year**
- >61 km/h: **23 h/year**
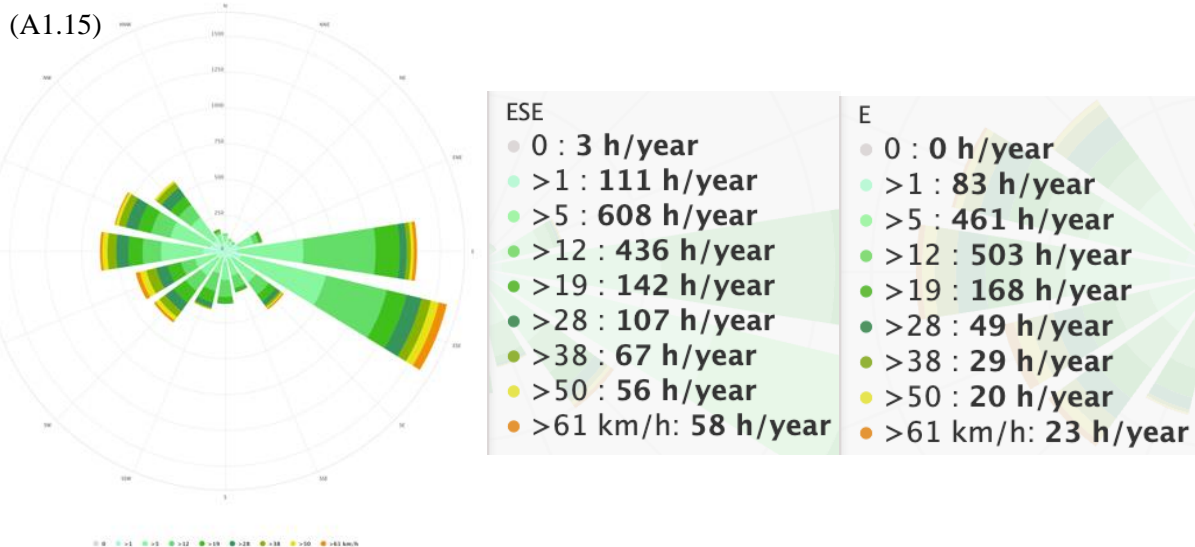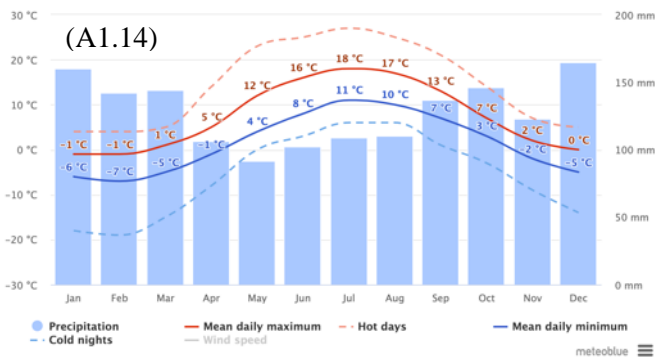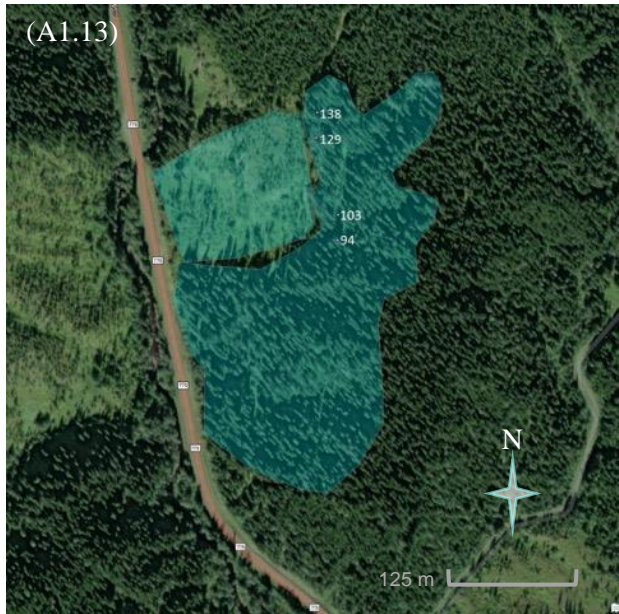
Appendix Figs A1.13 - A1.15: Abrahammyra NV study site with average temperatures and precipitation, and wind rose for the area, showing aspect of edge in relation to prevailing winds (clear-cut site is the top left transparent green area). Map source: ArcGIS Pro software (ESRI 2002)
Climate data source: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/

(A2.1)

(A2.2)
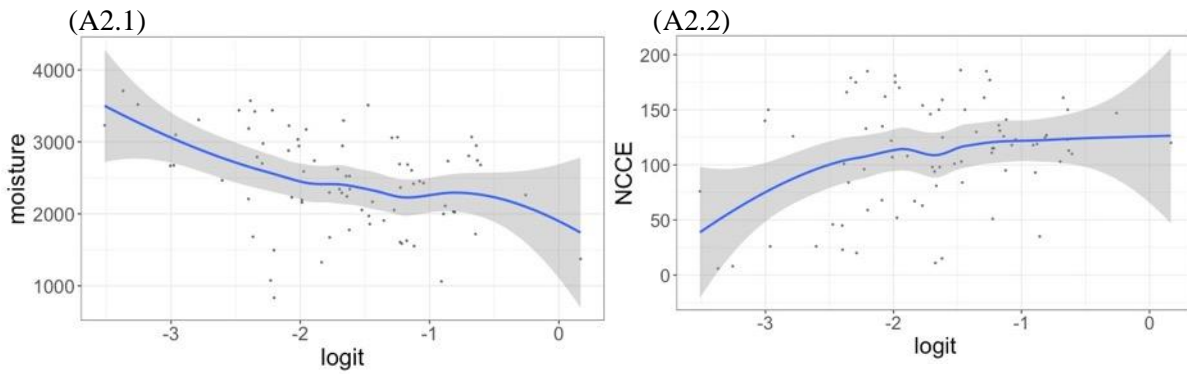
Appendix Figs A2.1 & A2.2: Tests for linearity against long odds for continuous variables moisture and nearest clear-cut edge, both showing relative linearity
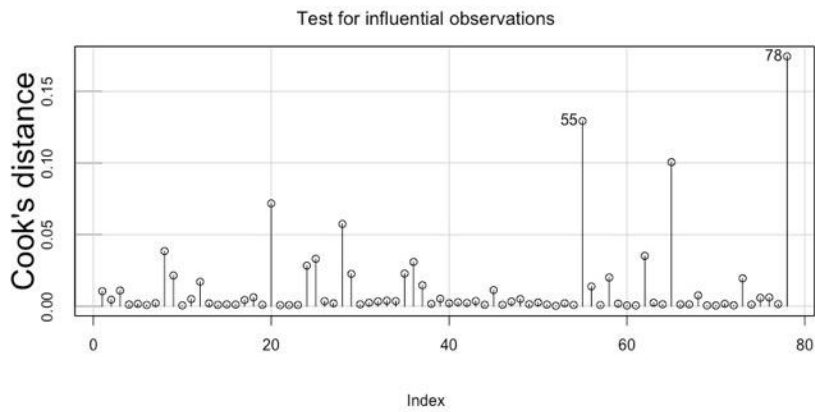
Appendix Figure A2.3: Influential observation test of residuals and their cook's distances, with none showing > 1, signaling no influential outliers.

Appendix Figure A3.1: Scatterplot of canopy coverage percentage in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.2: Scatterplot of soil moisture raw index values in relation to nearest clear-cut edge distance in meters.
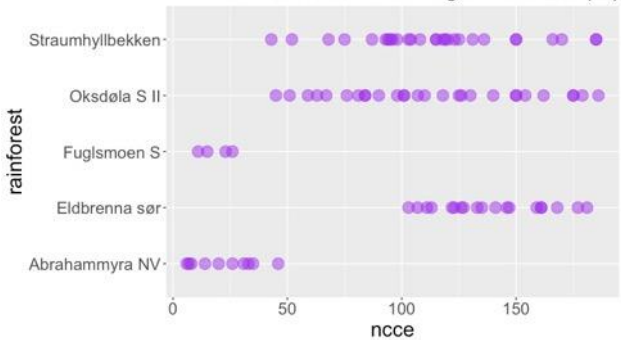
Appendix Figure A3.3: Scatterplot of plot distances in meters from nearest clear-cut edge for each site.

Appendix Figure A3.4: Scatterplot of bare soil functional group abundance (DAFOR scale: Dominant = 5, Abundant = 4, Frequent = 3, Occasional = 2, Rare = 1, and no occurrence = 0) on forest floor in relation to nearest clear-cut edge distance in meters.
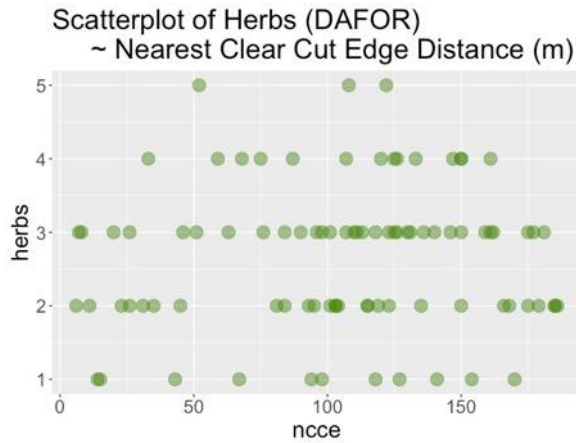

Appendix Figure A3.5: Scatterplot of stone functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
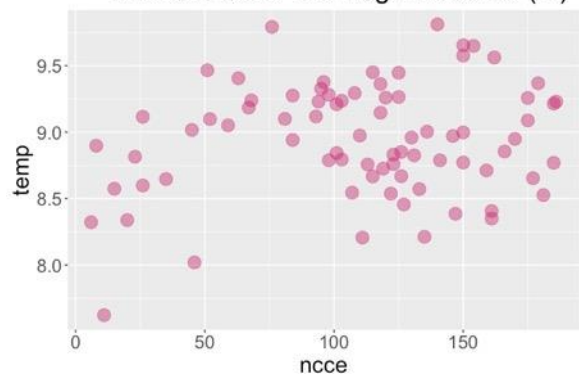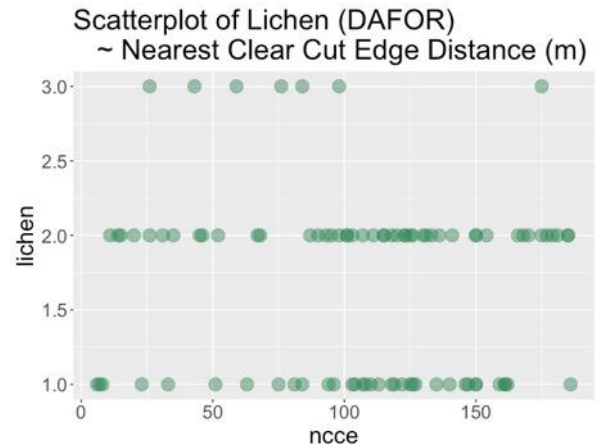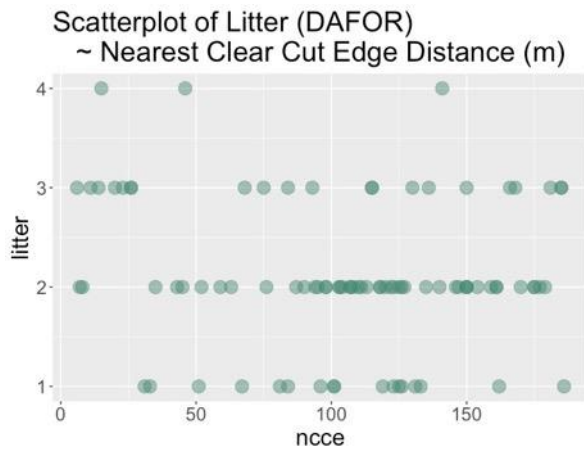

Appendix Figure A3.6: Scatterplot of temperatures (celcius) in relation to nearest clear-cut edge distance in meters.
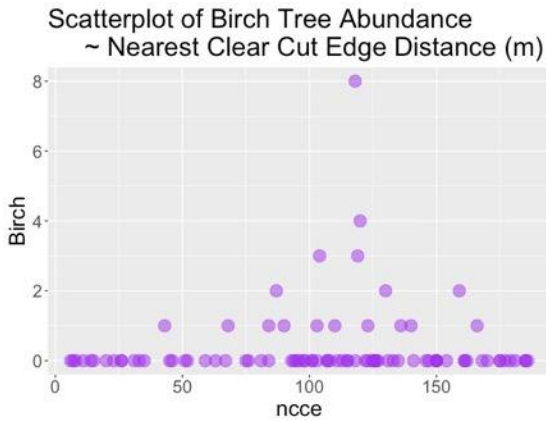
Appendix Figure 3.7: Scatterplot of *Betula pubescens* abundance (*n*) in relation to nearest clear-cut edge distance in meters.
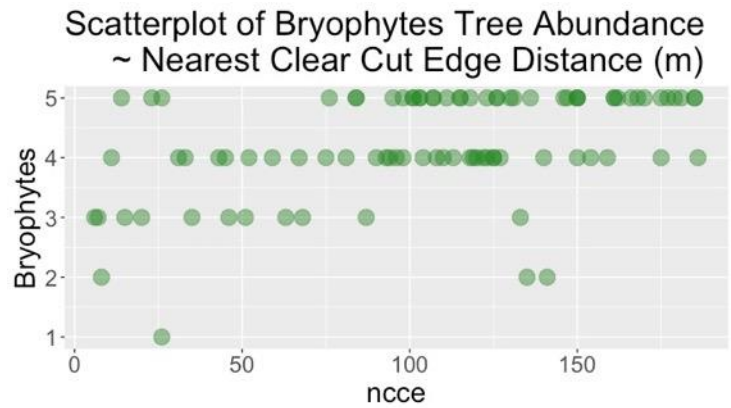
Appendix Figure A3.8: Scatterplot of *Bryophytes* abundance (DAFOR scale as above) in relation to nearest clear-cut edge distance in meters.
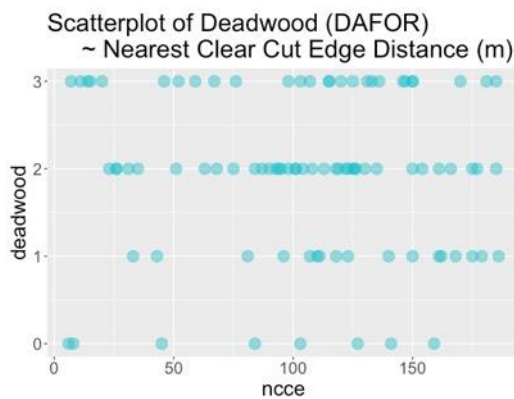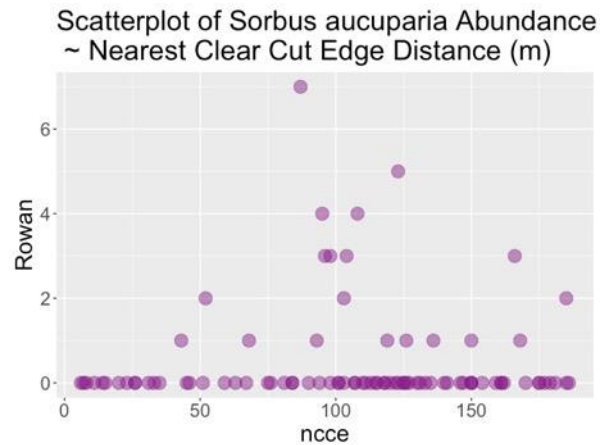

Appendix Figure A3.9: Scatterplot of deadwood functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
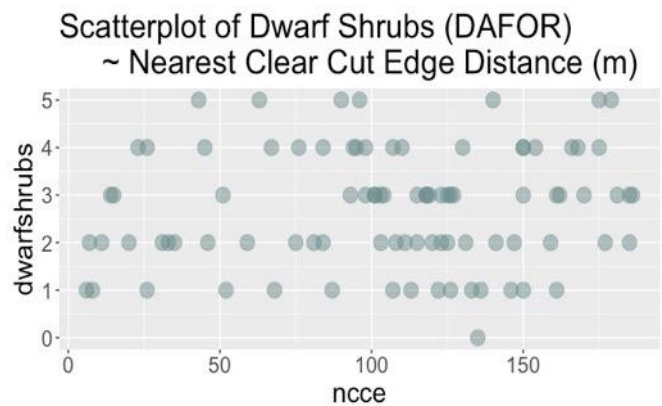
Appendix Figure A3.10: Scatterplot of dwarf shrubs functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
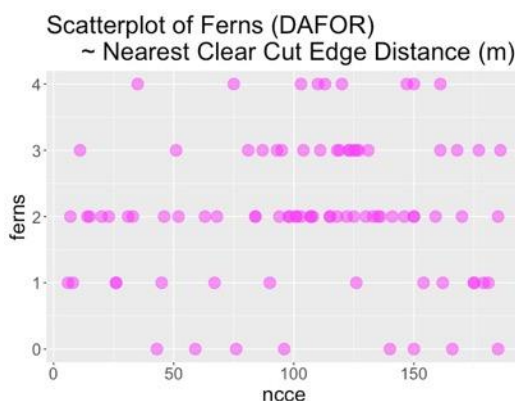
Appendix Figure A3.11: Scatterplot of fern functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
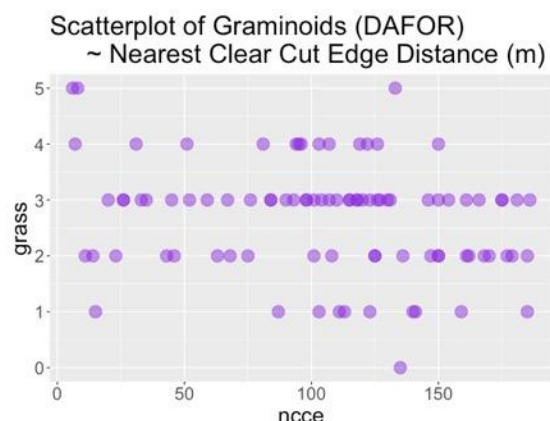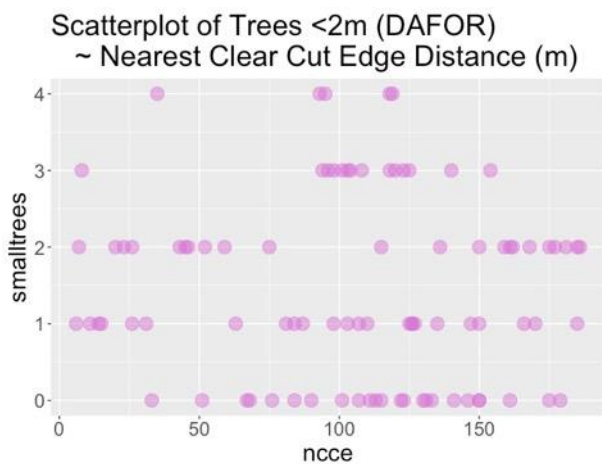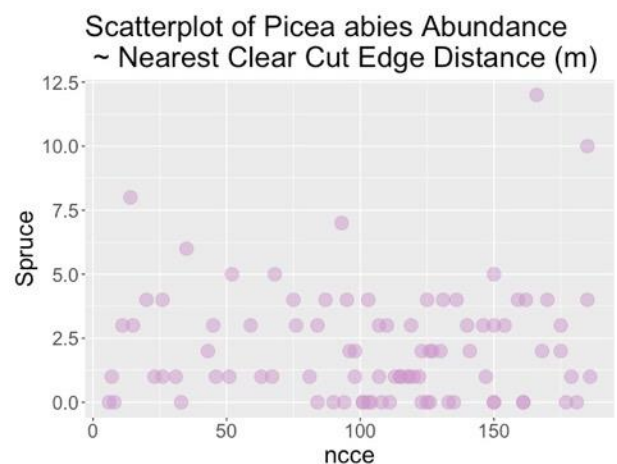

Appendix Figure A3.12: Scatterplot of graminoid (grasses) functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.13: Scatterplot of herbs functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.14: Scatterplot of lichen functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
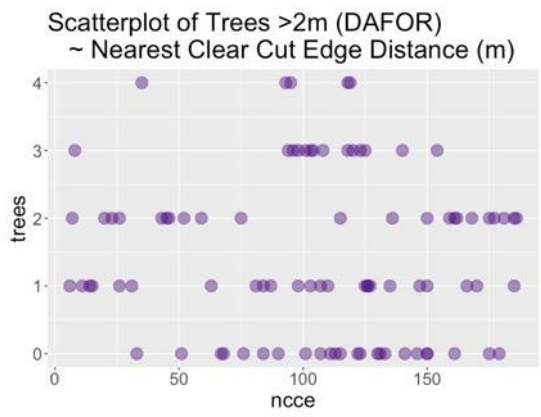

Appendix Figure A3.15: Scatterplot of litter functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.16: Scatterplot of *Sorbus aucuparia* abundance (*n*) in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.17: Scatterplot of trees <2m functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
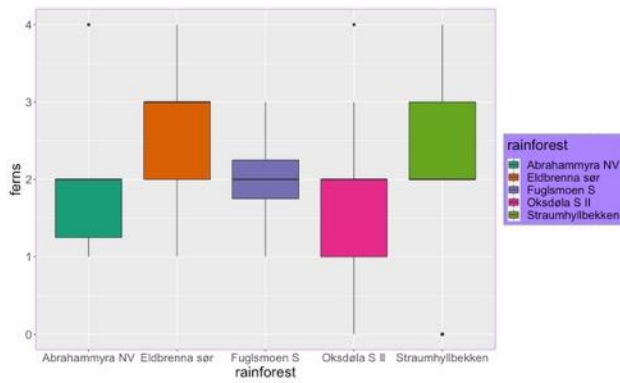

Appendix Figure A3.18: Scatterplot of *Picea abies* abundance (*n*) in relation to nearest clear-cut edge distance in meters.

Appendix Figure A3.19: Scatterplot of trees >2m functional group abundance (DAFOR scale as above) on forest floor in relation to nearest clear-cut edge distance in meters.
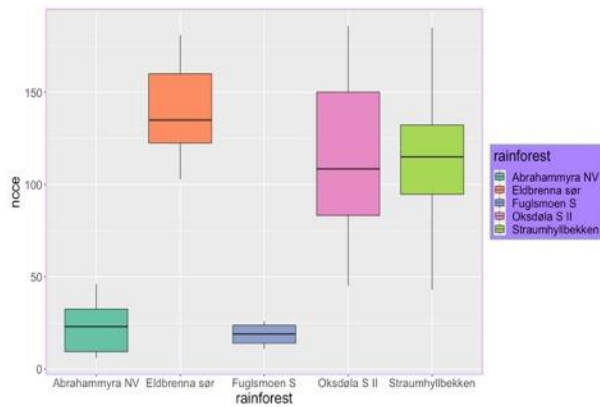
Appendix Figure A4.1: Box plot showing fern functional group abundance (DAFOR scale as above) in relation to each study site.
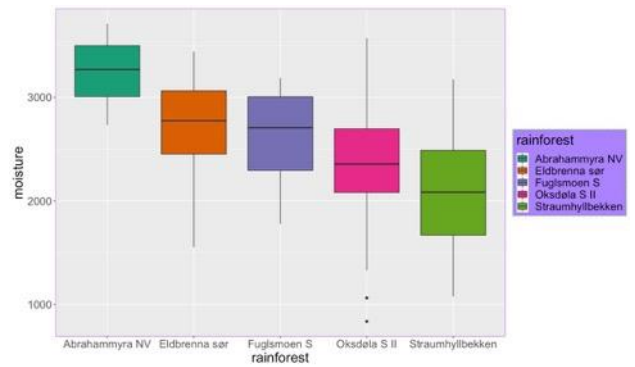
Appendix Figure A4.2: Box plot showing soil moisture raw index values in relation to each study site.

Appendix Figure A4.3: Box plot showing nearest clear-cut edge distance in meters related to each study site.

Appendix Table A5.1: Number of plots within each site with L. pulmonaria along with number of plots for each site, and percent of plots with L. pulmonaria presence per site.

Rainforest ID	(n) Plots with L. pulmonaria presence	(n) Plots	% plots occupied by L. pulmonaria
Eldbrenna sør	2	20	10 %
Straumhyllbekken	7	28	25 %
Oksdøla S II	4	28	14 %
Abrahammyra NV	0	10	0 %
Fuglsmoen S	1	4	25 %
Grong Sites Together	1	10	7 %
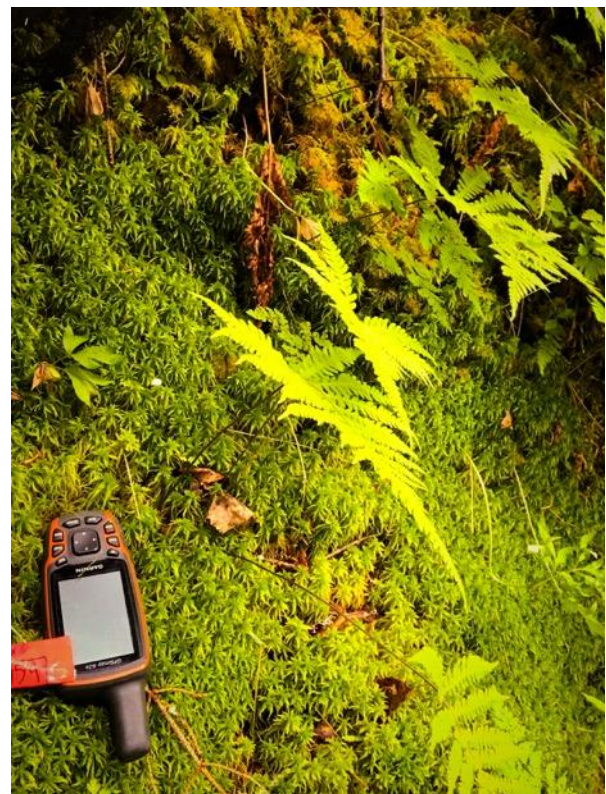
Appendix Figures A6.1 - A6.3. Photographs of *Sphagnum* bryophyte species as a possible confounding influence on teabag decay rate due to their soil acidification properties (Van Breemen 1995, Bardgett & Wardle, 2010). Buried teabags are connected to above ground red tapes in each photo.