Response to referee #1

Below are the comments of the referee #1 in black and our responses in blue font and changes to manuscript *italicized and gray*.

Soil nutrients and stoichiometry is an important topic in forest ecosystems. The manuscript studied the relationships between understory vegetation species abundance in a boreal forest and soil /leaf nutrients. However, there are several major concerns about the statistical methods, the data presented in the figures and tables and shortage of basic information regarding the study site. Additionally, there are also grammatical issues and inappropriate descriptions of the results. The discussion cannot fully support their hypotheses and results.

Response: We thank anonymous referee #1 for the time they have spent revising our manuscript. We found the comments very helpful and sincerely appreciate all the detailed and concrete suggestions on how to proceed with the manuscript. As both referees brought up points about the role of tree species in soil nutrient content, we have added analyses and discussion about this topic in our manuscript.

Statistical analysis:
One-way ANOVA were chosen in the manuscript, it implies that the plot was the only factor. However, tree species plays an important role in soil nutrients as well, thus tree species should be considered as a confounding factor. Due to high spatial heterogeneity in soil samples, when you determine the difference in different plots, the block effects also should be considered in the statistical analysis.
Considering the relationships between species composition and soil nutrients, besides the species, the authors also should treat age classes as the second factor. For the same reason, soil layer also should be considered in the analysis.

Response: We agree with these comments. Unfortunately, we do not have exact knowledge of the age of the trees at each plot, as we did not core the trees. We know the approximate age of trees at plot A6 and have used this as help, when we estimated the tree ages based on their dbh and put the trees in three different classes (young trees 1-9.9 cm, mid-aged 10-14.9 cm and old > 15 cm). We added information about the tree age classification to materials and methods. We tested the effect of dominant tree species, tree age, soil parent material/bedrock type, and soil horizon on soil P, N and C:N with linear mixed-effect models and have added the following description to section 2.4:

"We tested the effects of environmental variables on soil P, N and C:N with linear mixed-effect models. We used dominant tree species, estimated tree age, rock parent material and soil horizon as fixed effects and plot as random effect. Soil P needed to be log-transformed while for N and C:N the visual inspection of residual plots did not reveal obvious deviations from homoscedasticity or normality. We obtained p-values for the fixed effects by likelihood ratio tests, where the full model with all the fixed effects was tested against model where each fixed effect was removed in turn. We used package lme 4 (Bates et al. 2015) in R programme 3.4.3 (R Development Core Team, 2017) for building the models. Pseudo R2-value for the models were calculated by using package r2glmm (Jaeger 2017)The models took the form:

$$SC_{P,N,CN} = B_0 + B_{dt} + B_{ta} + B_g + B_h + \in, \quad (1)$$

where $SC_{P,N,CN}$ is the soil nutrient content (P, N or C:N ratio), B_0 denotes a fixed intercept parameter, B_{dt} denotes the fixed unknown parameters associated with the dominant tree species, B_{ta} denotes the fixed unknown parameters associated with the age of the dominant tree species, B_g denotes the fixed unknown parameters associated with the rock parent material, B_h denotes the fixed unknown parameters associated with soil horizon. The random effect $\in$ is assumed to take the form:

$$\epsilon = \propto_p + u\,, \qquad (2)$$

where $\propto_p$ *denotes the random parameters related with the research plot and u is an unobservable error term. Random-effect parameters and random-error term are assumed to follow normal distributions* $\propto_p \sim N(0, \sigma_p^2)$ *and* $u \sim N(0, \sigma_u^2)$*."*

We made a new subsection for the results of mixed effect models under section 3 and added a table, which includes the fixed effects and their Chisq values, p-values and pseudoR2 values. To the appendices we added figures of the fitted vs. residuals, q-q plots and histograms of the residuals and removed the unnecessary tables of the previous one-way ANOVAs.

While we agree that the within-plot variation of soil element content is important, it could not be added to this same model, as the other factors were on the plot scale. We made box plots about the within plot variation of soil total P, N and C:N ratio.

In order to more precisely study the relationship of tree species and understory vegetation, we added the volume of birch per plot to the ordination and to Fig. 7d. We also added the cover (% of surface area) of species in the same species groups to the ordination and Fig. 7d.

Shortage of basic information: the authors provided the basic tree and other species composition in the Table 3. The tree age and biomass also affects the soil nutrients. The author should provide the mean basal area, leaf area index and mean DBH. These basic information would be useful to estimate the effects of tree species on the understory species composition and on soil nutrients.

Response: Yes, we agree. We redid this table (now Table 2) so that it includes the following information in their own columns: plot, trees/ha, basal area, total volume of trees, volume of pine, volume of spruce, volume of birch, mean dbh of pine, mean dbh of spruce and mean dbh of birch. Unfortunately, we have no information of LAI.

As to the weather information, the min and max temperature should also be provided in Table 1.

Response: Agreed, we added the min and max temperature to the table.

Authors should add a new table/Figure to show the mean soil nutrients in the birch, scots pine and spruce plots in each layer and make stat analysis.

Response: We agree. We made such a table and did the statistical analysis related to that. We marked the stat. differences between tree species to the table. We added the following piece of text to section 2.4:

"We grouped the plots based on their dominant tree species into pine, birch and spruce plots and calculated the average soil nutrient contents in each horizon in these plots. We then compared the nutrient contents in each soil horizon with one-way ANOVA.

We also added explanation of the results of the ANOVA to section 3.1.

In Fig 5, there were no adj-R2 value to show which factor possessed the most weight. At the same time, these correlations could be better presented in Table not in fig.

Response: We corrected the unclear figure caption in Fig 5 to include the following information:

“Positive correlations are displayed in blue and negative correlations in red. Colour intensity and size of the circle are proportional to the correlation coefficients..”

The confusing plot numbers in table A2/A3 /A4 and Table B2. In the Table A, the plot number was in alphabetical order while the Arabic number was adopted in table B2.

Response: We corrected the confusing and incorrect plot numbering in Table B2.

We cannot find the stats evidence support the data. For example: “Foliar N:P ratio did not show any differences in either species between plots.. . .. . .green leaves
compared to other species.” (3.2)

Response: We changed this piece of text to:

“On the other hand, N and C contents, as well as the C:N ratio of the conifers showed some between-plot variation ($p < 0.05$), but no significant variation was found in the foliar N:P ratio in either species.”

In the results section, the first sentence in each sub section provides meaningless information for the data and these sentences can be deleted. For example: “ The average contents. . . .. In fig 4” (3.1 soil element contents). The same was also found in each paragraph.

Response: Agreed, we deleted the sentences including meaningless information.

There were some grammatical issues in each paragraph. There was no deep discussion to support the hypotheses and results.

Response: We thank the referee for pointing out these issues. A native English speaker has checked our revised manuscript.
We have revised the discussion section based on the comments from both referees. We synthesized and shortened the part of text where we compare our total nutrient contents to previous studies as well as reorganized the sections so that the main results become clear in the first paragraph of the discussion section. We wrote more about the role of tree species in soil P content and highlight how and why our results are important and relate with the previous findings.

Response to referee #2

Below are the comments of the referee #2 in black and our responses in blue font and changes to manuscript *italicized and gray*.

We thank anonymous referee #2 for the time they have spent revising our manuscript. We found the comments very helpful and sincerely appreciate all the detailed and concrete suggestions on how to proceed with the manuscript. As both referees brought up points about the role of tree species in soil nutrient content, we added analyses and discussion about this topic in our manuscript.

Title: rephrase; “understory vegetation” is not precise, that are the species composition and abundance that were studied. Why to focus on the understory since the tree cover was also studied? You could also focus on what you consider as your main result, for example “Soil total P explains vegetation community composition in a northern boreal forest ecosystem”.

Response: We appreciate the suggestion, but feel that the title example by the referee would be too strong of a statement. Our study is more of a case study about a very special area surrounding a phosphate massif and, thus, it would be rather risky to generalize the results to cover also other northern boreal forest ecosystems. Thus, we changed the title to: “Soil total phosphorus and nitrogen explain vegetation community composition in a northern forest ecosystem near a phosphate massif”. We feel that it is important to mention the phosphate massif in the title to make it clear that our study area has some special features.

Abstract: needs a sentence on sampling design (the way the relationship were addressed)... In the present case, the reader have no idea what the “plots” refer to and what to conclude from that information. Here and in the materials and methods section, you need to state clearly that you described vegetation, and sampled tree leaves and soil, at different distances from the P ore. Revise this abstract after clarifying the objectives and re-analyzing/discussing the results.

Response: Agreed. We have added information about how the study plots and measurements were arranged.

Introduction: could be simplified and shortened. Also needs to better formulate the objective(s) and hypotheses, and/or to provide all the information that lead to such hypotheses. In particular, it is not very clear why the hypotheses focus on the humus layer.

Response: Agreed. We have simplified the introduction according to the suggestions and focused on re-formulating the aims and hypotheses.

By comparing the title, abstract and introduction, it is not clear if the objective if finally (1) to explain the understory species composition and abundance with environmental parameters, and particularly soil total P content, or (2) to predict soil/environment nutrient status by surveying understory vegetation. One option should be chosen and the whole article built around.

Response: This is a very good point and helped us to clarify the “common thread” of the manuscript. We originally started with option 1) and it is still valid. We aim to explain the understory species composition and abundance with environmental parameters, and see if soil total P and N content have an effect on them. In addition, we want to figure out what environmental parameters could explain soil N and P contents.

Material and methods: The site selection process is not clear; in particular, what is the basis for selecting those transects? I did not get if there is any gradient, for example.

Response: We have added the following sentences to materials and methods (after "We established 16 study plots…):

" The plots were located different distances from the phosphate ore in four transects, enabling evaluation of the possible effects of the mine in the future."

Are all the study sites located at a similar elevation with similar climate conditions?

Response: Yes they are.

As the study sites were located on different geological units (Fig. 1), did the authors tried to include such factor in their analysis?

Response: We have now included the geological unit to the analyses.

Do we know anything about the P contents of those rocks? Are these rocks essential parent material for the soils developed at the sites? Any idea of the age/development stage of the soils?

Response: The Sokli phosphate ore has been carefully sampled and studied, but the surrounding area lacks such detailed information. We added to the figure caption of Fig 1. that this map shows the bedrock in the region, which is essential parent material for the soil. The bedrock in Finland is among the oldest in Europe but the soils have been modified by the latest ice age. Sokli is different from the surrounding soils also because it is located in a sheltered depression and has not been affected by the erosion caused by latest ice age.

Are all the soils studied haplic podzols?

Response: Yes they are.

As for the statistical analyses, it seems the forest stand composition could be better taken into account by accounting for the species % of volume or by grouping sites according to their dominant species. As raised by reviewer 1, stand age could also be a confounding factor.
I think the authors could try to better explain the variations they observe in soil values. Also, why did the authors focused in the elemental contents of the O horizon (humus) in their analysis? Do we have an idea of the distribution of fine roots (and vegetation uptake zone) in the soil profile?

Response: We agree with these comments. We originally chose humus as the roots of understory vegetation are mainly in this layer, but we have now done more stat. analyses including other layers as well.
Unfortunately, we do not have exact knowledge of the age of the trees at each plot, as we did not core the trees. We know the approximate age of trees at plot A6 and have used this as help, when we estimated the tree ages based on their dbh and put the trees in three different classes (young trees 1-9.9 cm, mid-aged 10-14.9 cm and old > 15 cm). We added information about the tree age classification to section 2.2.1. We tested the effect of dominant tree species, tree age, soil parent material/bedrock type, and soil horizon on soil P, N and C:N with linear mixed-effect models and have added the following description to section 2.4:

"We tested the effects of environmental variables on soil total P and N contents and C:N with linear mixed-effect models. We used dominant tree species, estimated age class, rock parent material (Fig. 1) and soil

horizon as fixed effects and plot as random effect. Soil total P needed to be log-transformed, while for N and C:N the visual inspection of residual plots did not reveal obvious deviations from homoscedasticity or normality. We obtained p-values for the fixed effects by likelihood ratio tests, where the full model with all the fixed effects was tested against a model where each fixed effect was removed in turn. We used package lme4 (Bates et al. 2015) in R programme 3.4.3 (R Development Core Team 2017) for building the models. Pseudo R2-values for the models were calculated by using package r2glmm (Jaeger 2017). The models took the form:

$$SC_{P,N,CN} = B_0 + B_{dt} + B_{ta} + B_g + B_h + \in , \qquad (1)$$

where $SC_{P,N,CN}$ *is the soil nutrient content (P, N or C:N ratio),* B_0 *denotes a fixed intercept parameter,* B_{dt} *denotes the fixed unknown parameters associated with the dominant tree species,* B_{ta} *denotes the fixed unknown parameters associated with the age of the dominant tree species,* B_g *denotes the fixed unknown parameters associated with the rock parent material,* B_h *denotes the fixed unknown parameters associated with the soil horizon. The random effect* $\in$ *is assumed to take the form:*

$$\in = \propto_p + u \, , \qquad (2)$$

where $\propto_p$ *denotes the random parameters related with the research plot and u is an unobservable error term. Random-effect parameters and random-error term are assumed to follow normal distributions* $\propto_p \sim N(0, \sigma_p^2)$ *and* $u \sim N(0, \sigma_u^2)$*.”*

We made a new subsection for the results of mixed effect models under section 3 and added a table, which includes the fixed effects and their Chisq values, p-values and pseudoR2 values. To the appendices we added figures of the fitted vs. residuals, q-q plots and histograms of the residuals and removed the unnecessary tables of the previous one-way ANOVAs.

In order to more precisely study the relationship of tree species and understory vegetation, we added the volume of birch per plot to the ordination and to Fig. 7d. We also added the cover (% of surface area) of species in the same species groups to the ordination and Fig. 7d.

Additionally (based on a suggestion from referee #1), we grouped the plots based on their dominant tree species and calculated the means of soil nutrients and ratios in each soil horizon in pine, birch and spruce plots. We made a table of these and compared the nutrient contents in each soil horizon with one-way ANOVA.

The use of understory species is interesting, would it be possible to go further by narrowing down the number of species, by detecting indicator species (of the P status for example), and building a “simple” prediction model?

Response: Indeed, this would be interesting. However, we feel that building such a model would require a lot more study plots and data.

Results: I feel some results are not presented in the way that best help to address the questions of interest. I think in particular about the Fig. 3 and 4 or Table A2–A4, where we don’t have any clue about what could lead the variability and differences (forest stand composition? rock parent material? other?).

Response: Agreed. We have replaced Fig. 3 and 4. with box plots which show the within plot variation in these soil nutrients. We have also deleted Tables A2-A4, as the new table of fixed effects and figures of residuals and q-q plots (described above) are more useful in this context.

Discussion: The authors have put honorable efforts in comparing the data they obtained with known ranges of values for similar areas published in the literature. However, this part of the discussion could be better synthesized and written in a simpler and shorter style. The discussion lacks development on the results obtained in regard to the objectives of the study. What is the functional significance of these results? When focusing on key results, the Fig. and/or Tables where they are presented should be reminded to help the reader.

Response: We thank the referee for this comment. We have revised the discussion section based on the comments from both referees. We synthesized and shortened the part of text where we compare our total nutrient contents to previous studies as well as reorganized the sections so that the main results become clear in the first paragraph of the discussion section. We wrote more about the role of tree species in soil P content and highlight how and why our results are important and relate with the previous findings. We have also paid more attention on referring to the Figs and Tables.

Conclusions: potentially revise according to modifications in the introduction and discussion.

Response: We have modified the conclusions.

Technical corrections
Whole text: refer to Fig., Tables, and Appendix when appropriated, and order and number them following their first apparition in the text.

Response: Done.

p. 1, l. 8: “We studied the relationship of forest understory vegetation with nutrient contents of soil and tree leaves...”: write something which fits with your objectives and title. Again, “understory vegetation”is not precise, add “species composition and abundance”, which appears only at l. 12–13.

p. 1, l. 9–10: add a comma: “At most study plots, boreal...”

p. 1, l. 11–12: here and elsewhere, change “abundance and species composition of the vegetation” to “species composition and abundance of the understory vegetation”.

p. 1, l. 13–14: what is the information you want to raise?

p. 1, l. 19: some fixes: “... controlling the species compositions of tree stand and understory...”

Response: The previous comments were related to the abstract, which has now been revised.

p. 1, l. 21: what do you mean by “modified”? I would rather say that those ecosystems are “characteristically cold, have a short growing season, and are nutrient-poor”.

Response: Agreed and changed.

p. 1, l. 21–22: “affects” is not precise, and the sentence could be shorter and simpler.
Suggestion: “Organic matter decomposition and nutrient release are usually slow in cold climates”.

Response: Agreed and changed

p. 1, l. 22–24: not very informative.

Response: Agreed, we deleted this sentence.

p. 1, l. 25: change “tree species affect” by “tree cover affects”, unless you want to precise “different tree species affect differently understory...” (if this fits to the references cited).

Response: Agreed, and changed to tree cover.

p. 1, l. 26: again, “understory vegetation” is not precise, which parameters? Focus on what you study here (i.e. species composition and abundance).

Response: Agreed, we changed “understory vegetation” to “species composition and abundance in the understory”

p. 1, l. 27: “litterfall” is sufficient since it also includes branches, etc.

Response: Agreed and deleted the word “leaf”.

p. 1, l. 29: N and P “are generally the main growth-limiting nutrients...”

Response: Ok, we added the word “main”.

p. 1, l. 29–p. 2, l. 16: this whole paragraph convey interesting information but is not enough focused for the present study. It can be shortened and simplified by synthesizing the main ideas.

Response: Agreed, we have revised the text.

p. 2, l. 3–4: useless information. In the context of vegetation growth, available N mostly derives from organic matter decomposition (unless the plant is a N-fixer), and available P both from weathering and organic matter decomposition.

Response: Agreed and deleted.

p. 2, l. 4–6: not necessary in the context of this article.

Response: Agreed and deleted.

p. 2, l. 8–9: N–P interaction is a bit cryptic (is that a statistical term?), can you say something more functional? I think the idea is that the coupling between the N and P cycles drives nutrient limitation.

Response: Agreed. We changed the sentence to:

”The ratio of soil N to soil P is significant for forest growth on a global scale.”

p. 2, l. 11: move the comma: “In boreal N-limited forests, ...”

Response: Ok, done.

p. 2, l. 18: replace “soil nutrients” by “soil nutrient content” or “soil total N and P”.

Response: We have revised this part of text.

p. 2, l. 27–31: this is not related to your study and could be considered as a confounding factor hindering potential interesting relations. Move the information to the material and methods, and state clearly that you assume reindeer pressure (grazing, trampling, but also nutrient exports or inputs) is not such a confounding factor for this study. Of course, it has to be the case! Did you evaluate somehow the reindeer pressure at your study sites? How? Was it important? Was it typical for the region? Was it constant across sites?

Response: Agreed, we moved the information to the material and methods. We have not evaluated the reindeer pressure anyhow in this study.

p. 2, l. 32: what do you mean by “undisturbed”? The current (steady) state? A baseline status?

Response: We added baseline status after the word undisturbed.

End of the introduction: rephrase and clarify objective(s).
p. 3, l. 1: move this (= method) after the effects of mining.

Response: Done.

p. 3, l. 3–4: too much! Focus on mining and keep reindeer and/or climate change for an opening in the discussion. Other option: start the last paragraph of the intro saying that several disturbances such as mining, grazing (is there a change in grazing in the region? why?), and climate change could affect nutrient status of the ecosystem and you aim at establishing a baseline to monitor the effects of those disturbances. In that case, keep something on reindeer and/or add something on climate change, but keep it short and focused (effects on nutrient status of ecosystem).

p. 3, l. 4–5: simplify and shorten! It is not very clear why you did this... Did you want to establish a relatively simple and cheap protocol of monitoring? For example, surveys of key understory species abundance that would be indicative of the ecosystem nutrient status?

Response: As a common response to the previous comments. We have reformulated the last paragraph of the introduction section based on these comments, and it now says:

“The general aim of this study was to determine the undisturbed baseline status of the forest ecosystem in terms of soil, understorey vegetation and tree layers in the Sokli area in case there is a need to monitor the effects of phosphate mining. Phosphate mining can cause, for instance, aerial deposition of heavy metals and phosphate onto the surroundings of the mine (Reta et al. 2018), which can lead to changes in the

abundance and species composition of the understorey. Vegetation, soil and foliage chemistry surveys provide data on the current state of the ecosystem (from the year 2015) that can be used as a reference level for the changes. Our specific aim was to identify which factors in the soil and tree layer explain the composition and abundance of plant species. In addition, we studied which environmental variables could explain soil nutrient contents, especially total P content."

p. 3, l. 6–7: this sentence does not justify these hypotheses. Delete and replace by something like "We hypothesized: a)... b)...", and move that at the end of the preceding paragraph.

p. 3, l. 9–11: are these hypotheses justified with the preceding text of the introduction? Do they really relate to the objective? Why to focus suddenly on "humus"? I feel some pieces of the reasoning are missing.

p. 3, l. 11: wouldn't it be rather the humus layer that reflects the nutrient content of the leaves? Unless you assume most of the tree uptake occurs in this layer.

Response: We agree with the comments above and have reformed the hypotheses in the following way:

"We hypothesize that there are positive relationships between:

a) N and P contents of the soil humus layer and the abundance and species composition of the understory vegetation

b) N and P contents in the topmost soil layers and the N and P contents of needle and leaf biomass

c) N and P contents in the topmost soil layers and the occurrence of birch trees in the research plots"

p. 3, l. 14: what are these transects? Are they organized along a gradient? Which one? It seems on the map that it would be the distance to the carbonatite massif.

Response: We have changed this so that it says:

"The plots were located different distances from the phosphate ore in four transects, enabling evaluation of the possible effects of the mine in the future."

p. 3, l. 15: "No plots were located inside the mining district", why?

Response: Accessing and doing research at the mining district would have required a permit from the mining company. We found it easier to have our plots on the surrounding land, which is owned by the state of Finland. We now shortly mention this in the materials and methods in the following way:

"No plots were located inside the mining district, as accessing and doing research at the mining district would have required a permit from the mining company."

p. 3, l. 19: needs reference, but isn't that what you want to study? Consider moving this info to the discussion.

Response: Agreed, we corrected the place of the reference, as it was by mistake in the end of the following sentence. We also moved this info to discussion.

p. 3, l. 22: start the sentence with “Thus,”

Response: Done.

p. 3, l. 23–24: delete “, but they were not on any Natura area”.

Response: Done.

p. 3, l. 26: what is the gradient?

Response: The gradient of how far from the mining district all the dust and dirt go. Currently there is no gradient, but in the future there might be.

p. 3, l. 32: add a comma after “5◦C”.

Response: Ok, done.

p. 4, l. 1: change subsection title to “Plot setup and vegetation characterization”.

Response: Agreed and changed.

p. 4, l. 5: change subsection title to “Sampling of soil”.

Response: Agreed and changed.

p. 4, l. 6–10: move this to the preceding section.

Response: Agreed and moved.

p. 4, l. 6: cite Table 3 and add to the table tree height and diameter info.

Response: Agreed and done. We redid this table (now Table 2) so that it includes the following information in their own columns: plot, trees/ha, basal area, total volume of trees, volume of pine, volume of spruce, volume of birch, mean dbh of pine, mean dbh of spruce and mean dbh of birch.

p. 4, l. 7: precise “cover (% surface area)”.

Response: Agreed and done.

p. 4, l. 8: cite appendix C.

Response: Agreed and done (now appendix A).

p. 4, l. 10: add comma after “Altogether”.

Response: Done.

p. 4, l. 11: provide diameter of the soil corer.

Response: Added here that the dimeter of the corer is 5 cm.

p. 4, l. 11: change to “The soil was sampled within one meter from the subplots”.

Response: We changed this to:

” The soil was sampled within a 1m distance from the subplots”

p. 4, l. 12: change “The samples” to “The soil cores”.

Response: Agreed and changed.

p. 4, l. 14–15: simplify and shorten.

Response: Agreed. The text now says:

“The rocky soil and shallow humus layer made it impossible to sample the mineral soil layers in some clusters.”

p. 4, l. 16: remove “already”.

Response: Done.

p. 4, l. 18: remove “samples from”.

Response: Ok, done.

p. 4, l. 20–21: two first sentences useless, delete and add “2015” after “September” in the third sentence.

Response: Agreed and changed.

p. 4, l. 30: remove “, totalling of 100 leaves per plot”.

Response: Ok, done.

p. 5, l. 2: replace “in a similar way than needles” by “at 65◦C for 48 h”.

Response: Ok, done.

p. 5, l. 2: concretely, how did you clean the leaves? With a brush? Deionized water? Other?

Response: We have now added the following information here:

“The needles and the few soil particles attached on the litter leaves, were removed with tweezers. The green leaves did not need cleaning. The litter leaves were also rather clean, as it had rained at the time of sampling”

p. 5, l. 11: fix: “two to three mg of sample were...”

Response: We changed this to:

“Samples of 2–3 mg were measured and analysed…”

p. 5, l. 11: “VarioMax analyser” is a machine, what is the method behind?

Response: We have changed this so that it says:

”…with an element analyzer, which uses high temperature combustion method with subsequent gas analysis of CN (VarioMax, Elementar Analysensysteme GmbH, Germany).”

p. 5, l. 12: idem, replace “MilliQ water” by “ultrapure water”.

Response: Ok, changed.

p. 5, l. 21: “Ordination pattern of the study plots and weighted averages of plant species”, not clear, I thought you ordinated the weighted averages.

Response: We changed this to:

” Ordination pattern of the plots based on the Bray-Curtis dissimilarity indices in floristic composition was analysed to find the main environmental gradients behind the vegetation variation. ”

p. 5, l. 23: state why you did not present results for dim 2 vs dim 3.

Response: The text now says:

“We analysed the data in three-dimensional space but present the results in 1 vs 2 and 1 vs 3 dimensions (the results in 2 vs 3 dimensions did not give any new information).”

p. 5, l. 24: “some other environmental variables”, list them.

Response: We replaced “some other environmental variables” with the environmental variables that we used in the analyses.

p. 6, l. 5: “... imply rather high variation between and within plots”, isn’t that what you want to study? Maybe a deeper analysis, including tree species, forest stand age, and/or geology could help explaining a bit the variability observed.

Response: Yes it is. And now we have more analyses as well.

p. 6, l. 5–6: “Other soil elements...”, precise which ones or delete the sentence.

Response: Agreed and deleted.

p. 6, l. 11–12: the higher P content in young needles may indicate reallocation processes, which could be discussed shortly in regard to P availability for example.

Response: Agreed and done

p. 6, l. 12: replace “Unlike the expectations” by “Unlike our expectations”.

Response: We changed this to “against our expectations”.

p. 6, l. 15–23: refer to the Table or Fig. these informations are presented (if you go back to Table 2 after referring to Table B2, for example).

Response: Thanks for pointing this out!

p. 6, l. 19: replace “discovered” by “detected”.

Response: Ok, done.

p. 6, l. 22: “Number of species”, is this a good variable for your objectives? Could the total % cover of different species groups (the ones of Fig. 5, for example) be more informative?

Response: Number of species was originally chosen so that it would be easy to follow if new species start growing or if the variety of species declines in the plots. Sometimes the total % cover might very small, if there is for example only a couple of plants belonging to the group of grasses and sedges in the plot. The % cover was estimated visually and human eyes can make mistakes, especially if the % cover is small and the possible changes are also small. However, if one species starts spreading so that its % cover increases, counting the number of species cannot take this into account. We have now added the total % cover (same groups than for the number of species) and redone the ordination and the figure 7d.

p. 6, l. 27: how do you define the left and right sides of the plots? Is there a threshold or is this empirical?

Response: We clarified this in the text in the following way:

“Plots positioned more on the left-hand side in the figure had a higher number of forbs and grasses growing on them than the plots positioned on the right-hand side in the figure (Fig.6a,b).”

p. 6, l. 28: do you mean Fig. 6b? Or 6a–b?

Response: 6a-b, this is now correcred

p. 6, l. 30: no need to cite Table 3 here.

Response: Ok, deleted.

p. 7, l. 10: Start the paragraph by citing the Fig.: “In Fig. 7c–d, ...”

Response: We have changed the first sentence of the paragraph.

p. 7, l. 18: did you analyze soil samples by plot or by cluster? Did you quantify both within- and between-plot variabilities?

Response: We analyzed the soil samples by cluster, but have used averages of the whole plot and quantified the between-plot variabilities only. This sentence is now corrected.

p. 7, l. 19: refer to Fig. 3 where the soil P contents are presented. Also, this is a huge variability: is mainly due to between- or within-plot variation? If this is between plots, you might be able to explain it somehow by additional exploration of environmental factors, but if it is within plot there is no hope tree species will help, for example...

Response: This variability is due to between-plot variation. As mentioned in earlier responses, tree species is now also included.

p. 7, l. 24: “implying that decaying plant parts were a major source of P”, for what? The soil organic layers or plants?

Response: As an addition of P to the soil organic layer. This has now been clarified.

p. 7, l. 24–27: would it be possible to find a pattern of P content in the deep soil layers according to the soil rock parent material/geology? Do you think that high P content in the humus layer is important for plant nutrition (recycling) or is that just high litter production coupled with slow decomposition rates?

Response: We included soil parent material to the linear mixed effect models, but it seemed to have very little importance compared to the other fixed effects. According to our results, high P content in the humus is related with increased coverage of grasses and sedges, which means it is important for plant nutrition. It is also a result of high litter production (from birch) and slow decomposition rates.

p. 7, l. 28: what is the context of the study by Köster et al (2014)?

Response: They conducted their study in the same region, although not at the same plots. We have now added a sentence about this.

p. 8, l. 2: and so? Can you say something concrete for your study area?

Response: We ended up deleting this from the discussion, as it did not seem relevant anymore.

p. 8, l. 4: replace “similar than” by “similar to”.

Response: Ok, done.

p. 8, l. 18–19: Which analysis/which Fig. or Table? Table 4? But is it species richness or ordination pattern which was regressed? What do you mean exactly by “species richness”? The number of species?

Response: We are talking about the % cover and number of species in the group of grasses and sedges. We have now replaced the word richness with the previous explanation and otherwise revised this part of text.

p. 8, l. 19–20 and l. 30: which soil layer(s) are you considering? The hypotheses were about humus.

Response: This was about humus, we have now changed these.

p. 8, l. 32–p. 9, l. 2: “needles were sampled at different time of year than soil...”, this should be mentioned in, and even might only be part of, the materials and method section. If you sampled the needle at a right moment, it should be quite integrative of nutrient availability across the growing season.

Response: We have moved this information to the materials and methods section, as suggested.

p. 9, l. 4–8: why not such an opening but right now it is not well connected to what precedes. You could also talk about the coupling between N and P cycles and how this could be affected by climate change or disturbances and in turn affect ecosystem status and processes.

Response: Agreed, we have changed the last paragraph of the discussion so that it is more connected to what is discussed in the earlier paragraphs. We added discussion "about the coupling between N and P cycles and how this could be affected by climate change or disturbances and in turn affect ecosystem status and processes", as suggested.

p. 9, l. 6: "variation in the vegetation", be more precise (which parameter, sense of variation).

Response: Agreed and changed to "changes in plant species composition"

p. 9, l. 10 and 17: "vegetation dynamics", this is not what you study here, change to "vegetation community composition" or something like that.

Response: Agreed and changed.

p. 9, l. 12: change "has been discovered" to "was found".

Response: Agreed and changed.

Fig. 2: draw or remind in the title where tree cover was described.

Response: We have now added to the caption that trees were measured from the whole 30 x 30 m area that the clusters delineate. We also drew marks to the figure to make it clearer where the outer borders of the 30 x 30 m area were.

Fig. 3: would it be possible to also represent tree cover species (or different groups based on dominant species)? or age? or geology? Is this graph representing between- plot variability (i.e. you first calculated the mean for each plot and made the boxplots with those means) or a mix between within- and between-plot variability (i.e. you took all sub-plots values to make the boxplot)? It would be interesting to compare between- and within-plot variabilities.

Fig. 4: same comments as for Fig. 3.

Response: We have replaced these figures with box plots, which show the variation of soil nutrients between and within plots grouped based on their dominant tree species.

Fig. 5: What is the correlation coefficient calculated? (Pearson? Other?) Precise what is the "bottom layer". Why not to call this layer "moss lichen"? It would be clearer.

Response: We added that Pearson correlations were used. The bottom layer includes mosses and lichen, so we re-named this layer "moss lichen" and redid the figure.

Fig. 6: what is the criteria to define "the most abundant species"?

Response: We added here that most abundant species here means those species, which have the highest % coverage.

Fig. 6, l. 8: replace “generic” by “genera”. Start the last sentence of the figure legend by “In (a),”

Response: Agreed and done.

Fig. 7: remind which soil layer was considered for this analysis (I am assuming it’s O).

Response: Yes, it is O layer and we added this information to the figure caption.

Table 1: “degree days”, shouldn’t that be called “sum of degree days”? What is the unit?

Response: Degree days here mean the growing degree days, whose unit is GDD or °C days. We changed it to “growing degree day sum” as well added how it is calculated:

“Growing degree day sum was calculated as the average daily temperature (average of daily maximum and minimum temperatures) above 5 °C base temperature, accumulated on a daily basis over the year. Negative values are treated as zeros and ignored.”

Table 2: the classical ordering would be C, N, P, K, C:N, N:P. For numbers (mean and sd), provide the same number of digits after the dot for each column (one is enough) and align the numbers to the right to ease comparison of lines. Why not to put K in the same unit as the others?

Response: Agreed, we have made these changes.

Table 3: did you estimate the whole aerial volume of trees or just the trunk volume? Make three sub-columns for each species abundance. Add in this table tree height, diameter,...

Response: We estimated the trunk volume. We made the suggested changes.

Table 4: remind the first seven lines are soil values.

Response: Agreed and done.

Tables A2–A4: From which statistical test are these table issued? These tables hardly help to address your objectives.

Response: We have deleted these tables and replaced them with a table which includes the fixed effects (from the linear mixed effect models) and their Chisq values, p-values and pseudoR2 values.

Table B1: title: change to “Statistically significant differences between needle age group by species”. From which test?

Response: We changed the title and added that these are from the one-way ANOVA, with Tukey’s HSD for post hoc. We will add this information to the caption.

Appendix C: precise “(% of surface area)”.

Response: Agreed and done.

~~Understory vegetation relationships with soil element contents in a northern boreal forest ecosystem near a phosphate massif~~ Soil total phosphorus and nitrogen explain vegetation community composition in a northern forest ecosystem near a phosphate massif

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Abstract. ~~We studied the relationship of forest understory vegetation with nutrient contents of soil and tree leaves near Sokli phosphate ore in northern Finland, where the soil contains naturally high variation in phosphorus (P) contents.~~ We studied how the dominant tree species, tree age, rock parent material and soil layer affect soil nutrient contents, and how the community composition of forest vegetation relates to soil nutrient contents near Sokli phosphate ore in northern Finland. For this purpose, we established 16 study plots on different distances from the phosphate ore along four transects. Phosphate mining may take place in Sokli in the future, and the vegetation surveys and soil sampling that we conducted at the plots can be used as a baseline status for following the possible changes that the mining may cause to the surrounding ecosystem. We found, that ~~At most study plots boreal dwarf shrubs, bryophytes and lichen formed a dense mat under a mixture of sparsely growing *Pinus sylvestris, Picea abies* and *Betula pubescens*. However, some plots were dominated by *B. pubescens* and had a higher variety and number of forbs and grasses in the understory.~~ the total phosphorus (P) and nitrogen (N) contents of the soil humus layer were positively related with species number and abundance of the understorey vegetation, and the correlation was slightly higher with P than N. ~~The total P content in the soil humus layer explained the abundance and species composition of the vegetation slightly better than the total nitrogen content~~This is interesting as usually N has the most important growth-limiting role in boreal ecosystems. The spatial variation in the content~~s~~ of soil elements was high both between and within plots, emphasizing the heterogeneity of the soil. Dominant tree species and the soil layer were the most important environmental variables affecting soil nutrient content. High contents of P in the humus layer (maximum~~.~~ 2.60~~00~~ ~~m~~g kg^{-1}) were measured from the birch-dominated plots.~~.~~ As the P contents of birch leaves and leaf litter were also rather high (2.58~~0~~ ~~m~~g kg^{-1} and 1.28~~0~~ ~~m~~g kg^{-1}, respectively), this may imply that the leaf litter of birch forms an important source of P ~~to~~ for the soil.

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1 Introduction

Climate and availability of soil nutrients are important factors controlling the species composition of tree stand~~s~~ and understorey vegetation in boreal forests (Cajander 1909, 1949, Kuusipalo 1985, Økland and Eilertsen 1996). High latitude forest ecosystems are characteristically cold, have a short growing season, and are nutrient poor~~characteristically nutrient-poor and modified by low temperatures and short growing season~~. Organic matter decomposition and nutrient release are usually slow in cold climates ~~Cold climate affects decomposition rate of detritus and the amount of nutrients released from organic material~~ (Hobbie et al. 2002). ~~The availability of nutrients in soil, and utilization of nutrients by plants play a critical role in many functions of forest ecosystems (Merilä and Derome 2008).~~ The edaphic conditions are reflected in the growth and chemical composition of plant species, as well as in species composition of vegetation (Vinton and Burke 1995, Salemaa et al. 2008). In addition, tree ~~species~~ cover affects the ~~understory vegetation~~species composition and abundance in the understorey by shading (Verheven et al. 2012, Tonteri et al. 2016) and regulating nutrient input in throughfall precipitation (Salemaa et al. 2019) and ~~leaf~~ litterfall (Ukonmaanaho et al. 2008).

Nitrogen (N) and phosphorus (P) are generally the main growth-limiting nutrients for plants (Koerselman and Meuleman 1996). Boreal forests are mostly N-limited (Tamm 1991), and ~~fertilizing~~ fertilization with N usually speeds up forest growth (Saarsalmi and Mälkönen 2001). Nitrogen is bound in organic material, and only a little is directly available for plants as inorganic ammonium (NH^{4+}) and nitrate (NO^{3-}) (Marschner 1995) or as organic forms like amino acids (Näsholm et al. 2008 and references within). ~~The primary source of N is the atmosphere, while P originates from the weathering of bedrock (Walker and Syers 1976, Vitousek et al. 2010). Phosphorus is tightly bound in the soil (Marschner 1995, Hinsinger 2001), and plants take up P directly only as ortophosphates, which are compounds formed from inorganic and organic P in processes requiring specific phosphatase enzymes (Jackman and Black 1952, Deiss et al. 2018).~~ Phosphorus deficiency occurs in temperate and tropical forest ecosystems, but P is rarely a limiting factor in boreal ~~upland~~ forests on mineral soil (Augusto et al. 2017). However, P can be growth-limiting on boreal peatlands (Moilanen et al. 2010, Brække and Salih 2002). ~~It has been demonstrated, that t~~The ~~interaction~~ ratio of soil N ~~and~~ to soil P is significant for forest growth on a global scale (Augusto et al. 2017). –Hedwall et al. (2017) found that the species richness of vascular plants in a temperate forest doubled with combined NP fertilization in southern Sweden~~,~~ but not when either of the nutrients was added alone. This positive effect was strongest in grass species. In boreal~~,~~ N-limited forests, the number of vascular plant species (grasses and forbs) increased with increasing N concentration of the organic layer (Salemaa et al. 2008). Hofmeister et al. (2009) noticed that in a temperate forest the species richness of the herb layer ~~diversity~~ was higher ~~at~~in ~~P~~ P-rich than ~~P~~ P-poor soils~~,~~ but only if strong N limitation occurred simultaneously ~~at~~ in the ~~P~~ P-rich soils. However, in many regions~~,~~ where humans have enhanced atmospheric N deposition~~,~~ the number of plant species has decreased (Dirnböck et al. ~~2016~~2014). For instance, high soil N was related to decreased herb layer species richness in deciduous forests in Sweden (Dupré et al. 2002).

In this study, we analysed whether plant species composition and nutrient levels of tree leaves indicate soil ~~nutrients~~ total N and P in a ~~research site in~~ northern boreal ~~zone~~ (Hämet-Ahti 1981) research site in Sokli, Finland. At this site, the soil contains naturally large variations in P content~~s~~. In Sokli, there is a large deposit of phosphate rock, a carbonatite complex mainly consisting of apatite ~~[~~($Ca_5(PO_4)_3F$)~~]~~, which was discovered by the Mining and Steel Company of Rautaruukki Oy in 1967 (Vartiainen and Paarma 1979). Plans to open a phosphate mine in Sokli have been on display for decades and will possibly be realized in the future. The vegetation at the carbonatite complex differs from that of the typical forests of the region (Talvitie 1979, Pöyry Environment 2009). Downy birch (*Betula pubescens*) is dominating and often the single tree species, whereas the more typical forests of the region are dominated by Scots pine (*Pinus sylvestris*) or Norway spruce (*Picea abies*). Understorey vegetation at Sokli is ~~somewhat~~ slightly richer in herb and grass species compared ~~to~~ with ~~the typical~~surrounding forests, where dwarf shrubs, bryophytes and lichen dominate the understorey. However, ~~Similar~~ vegetation similar to that~~as~~ in Sokli ~~grows~~ can be found as patches elsewhere in the region.

~~An additional factor affecting vegetation composition at our research site is reindeer herding. Bryophytes have replaced many lichen species (Väre et al. 1995, Susiluoto et al. 2008, Akujärvi et al. 2014, Köster et al. 2018), and the number of seedlings of broadleaved trees has been found to decrease (Kreutz et al. 2015) in forests where reindeer trampling and grazing occurs. All our plots were located in areas where reindeer roam freely.~~

The general aim of this study was to ~~investigate~~ determine the undisturbed ~~undisturbed state~~baseline status of the forest ecosystem in terms of soil, understorey vegetation and tree layers in the Sokli area~~, for the possible situation~~in case there is a need ~~to~~ to monito~~r~~r the effects of phosphate mining~~. Vegetation, soil and foliage chemistry surveys provide data on the current state of the ecosystem (from the year 2015) that can be used as a reference level for the changes~~. Phosphate mining can cause, for instance, aerial deposition of heavy metals and phosphate onto the surroundings of the mine (Reta et al. 2018), which can lead to changes in the abundance and species composition of the understorey. Vegetation, soil and foliage chemistry surveys provide data on the current state of the ecosystem (from the year 2015) that can be used as a reference level for the changes. Our specific aim was to identify which factors in the soil and tree layer explain the composition and abundance of plant species. In addition, we studied which environmental variables could explain soil nutrient contents, especially total P content.

We hypothesize that there are positive relationships between ~~The combined effects of mining activities, reindeer grazing and climate change can lead to unpredictable changes on the element cycles. Particularly, we investigated the relationship between the understory vegetation and soil chemical composition in the study area and how the element compositions of tree leaves are related with soil chemistry.~~

~~Because N and P are known to be important limiting elements for biomass production of plants (Vitousek et al. 2010) we hypothesize, that~~

a) ~~N and P contents of the soil humus layer correlate with t~~N and P contents of the soil humus layer and the abundance and species composition of the understory vegetation ~~he abundance and species composition of the understory vegetation~~

b) ~~N and P contents of needle and leaf biomass reflect total N and P contents of the soil humus layer~~N and P contents in the topmost soil layers and the N and P contents of needle and leaf biomass

c) N and P contents in the topmost soil layers and the occurrence of birch trees in the research plots

2 Material and methods

2.1 Site description

We established 16 study plots along four transects (A–D) around the planned Sokli mining district (67° ~~48'~~48´ N, 29° ~~16'~~16´ E) in Savukoski, eastern Lapland in 2014 and 2015 (Fig. 1). The plots were located different distances from the phosphate ore in four transects, enabling evaluation of the possible effects of the mine in the future. No plots were located inside the mining district, as accessing and doing research at the mining district would have required a permit from the mining company. The carbonatite massif of Sokli belongs to the Devonian Kola Alkaline Province ~~(KAP)~~ (Tuovinen et al. 2015). Nine of the plots were located in Natura 2000 conservation areas. Plots A4, A5 and A6 were ~~on~~ in Värriö, A1 and A2 ~~on~~ in Yli-Nuortti, B1, B2 and B3 ~~on~~ in Törmäoja and D5 ~~on~~ in the UK-puisto – Sompio – Kemihaara Natura area. ~~The Törmäoja and Yli-Nuortti Natura areas have carbonatite in the soil, which explains the occurrence of grass species in understorey vegetation and the sparse, birch-dominated tree cover. By~~In terms of topography, Törmäoja is a valley, ~~reminding~~ reminiscent of the form of a kettle (*kattilalaakso* in Finnish) (NATURA 2000 - Standard Data Forms FI1301512 and FI1301513). The ~~mid~~ mid-parts of the valley are treeless, or the trees are at sapling stage, because cold winds blowing through the valley kill the new buds in the spring. Thus, ~~O~~our plots at Törmäoja were on the edge of the less steep western part, where some mature trees ~~grew~~grow. ~~Plots A3 and D2 were also birch-dominated with grass species in the understory, but they were not on any Natura area. Majority~~ The majority of the plots had a mixed composition of at least two tree species, ~~but some~~while in some plots the tree cover consisted of ~~were dominated by~~ only one species. An additional factor affecting vegetation cover and species composition at our research site is reindeer herding. ~~Bryophytes have replaced many lichen species (Väre et al. 1995, Susiluoto et al. 2008, Akujärvi et al. 2014, Köster et al. 2018), and the number of seedlings of broadleaved trees has been found to decrease (Kreutz et al. 2015) in forests where reindeer trampling and grazing occurs.~~ Since ~~A~~all ~~our~~the plots were located in areas where reindeer roam freely, we assume that the pressure caused by grazing and trampling is equal in all plots.

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The plots of this study together with ~~the~~ SMEAR 1 ~~station~~ (Station for Measuring Ecosystem-Atmosphere Relations) at the Värriö Subarctic Research Station (67° 46~~'~~´ N, 29° 35´ ~~'~~E) (Hari et al. 1994) serve as a gradient type network for monitoring the current status and the possible, mining-induced, changes of the environment in the future.

Meteorological parameters from the years of data collection and for the climatological normal period of 1980–2010 are presented in Table ~~-~~1. The ~~W~~wind blows almost equally from the south-west and north-east during spring and summer, whereas in winter and autumn the prevailing wind direction is south-west (Ruuskanen et al. 2003). ~~Growing~~ The growing season, when daily average temperature exceeds 5 ~~-~~°C, lasts from June to September. Soils are haplic ~~podzols~~ Podzols with sandy tills (FAO 1988).

2.2 Plot setup and vegetation characterization~~Plot and sub-plot set-up and field work~~

The distance between two plots depended on the topography and existing roads, but generally~~,~~ it was about ~~two kilometres~~2 km. A plot consisted of four clusters, each including three square-shaped sub~~-~~plots sized 1 ~~-~~m^2 for observations and sampling (Fig. ~~-~~2). The size of the whole plot was 30 ~~x~~× 30~~-~~m. We recorded all tree species growing on the plots, measured their heights and diameter at breast height (dbh) (equivalent to a height of 1.3 m) (Table 2). Stem volumes were estimated using the equations of Laasasenaho (1982). We estimated tree age by measuring dbh and examining the existing approximated tree age from plot A6 at SMEAR1, where the mature trees are about 70 years old. We considered trees with dbh 1–9.9 cm to be young, 10–14.9 cm as middle-aged and >15 cm as old. We visually assessed the cover (% surface area) and counted the number of plant species in the understorey vegetation in all 12 subplots per plot in the summers of 2014 and 2015 (Appendix A). We used a 1 m^2 square frame to delineate the subplot (Salemaa et al. 1999). All species in the bottom layer (bryophytes and lichens) and field layer (dwarf shrubs, tree seedlings, grasses, sedges and forbs, height < 50 cm) were included.

2.2.1 Sampling of ~~vegetation and~~ soil

~~We recorded the species of all trees growing on the plots and measured their heights and diameters (at height 1.3 m). Stem volumes were estimated using the equations of Laasasenaho (1982). We assessed visually the cover (%) and counted the number of plant species in the understory vegetation in all 12 sub-plots per plot in summers 2014 and 2015. We used a 1 m^2 square frame to delineate the sub-plot (Salemaa et al. 1999). All species in the bottom layer (bryophytes and lichens) and field layer (dwarf shrubs, tree seedlings, grasses, sedges and forbs) were included.~~ Altogether, ~~sixteen~~ 256 soil samples were collected from ~~each~~ sixteen plots using a soil corer (inner diameter 5 cm) in June 2015. The soil was sampled within a 1m distance from the subplots~~The soil samples were taken close to the vegetation, the maximum distance being approximately one meter~~ (cf. Liski 1995). The soil ~~samples were~~cores were separated by visual criteria into four soil horizons~~;~~ : the top layer, which is a mixture of litter and decomposing organic layer (F), the humus layer (O), the el~~l~~uvial layer (A), and the illuvial layer (B) (cf. Köster et al. 2014). The rocky soil and shallow humus layer made it impossible to sample the mineral soil layers in some clusters.~~The actual humus layer was very shallow and the soil rocky, which made the sampling difficult in some plots. In some plots it was, thus, possible to sample only the upper soil layers.~~ The soil samples from each horizon were combined into composite samples in each cluster ~~already~~ in the field. The composite samples were air-dried except for the organic F and O horizons, which were dried at 60 ~~-~~°C for 48 ~~-~~hours. Dried mineral soils were sieved with a 2 ~~-~~mm sieve and the ~~samples from~~ F and O horizons were milled before storing ~~them~~ in a dry place for further analyses.

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2.2.2 Sampling of needles and leaves

~~We collected foliar samples from all plots in 2015. We sampled both pine and spruce needles, as well as green birch leaves and birch leaf litter lying on the ground.~~ Five pines and five spruces per plot were chosen for needle sampling in September 2015, when the needle growth had ended. ~~-~~If less than five trees per species were present, all of them were chosen. Three branches (length approximately 50 ~~-~~cm) were taken from the upper third of the canopy~~,~~ using a branch saw. We took only second order branches because cutting of first order branches would have been too destructive to the trees (cf. Helmisaari 1990). Needle age classes (C = current year, C+1 = one-year-old needles, C+2 = two-year~~s~~-old needles) were separated from each branch and dried at 65 ~~-~~°C for 48 ~~-~~hours, milled and stored in a dry place for further analyses. The samples were combined so that there was one C, one C+1 and one C+2 composite needle sample per tree.

We sampled green birch leaves in July and leaf litter in September 2015. Approximately 10 green leaves from 10 different trees were picked and combined~~, totalling of 100 leaves per plot~~ (Rautio et al. 2010). Only mature, undamaged leaves were chosen. Birch litter was collected under the same tree canopies~~s~~ ~~where~~ from which the green ~~leaf samples~~leaves ~~were~~ had been taken and in approximately the same number as the green leaf samples. We aimed to take litter leaves shed in the current year, so that they were decomposed as little as possible. Green and litter leaves were dried at 65 °C for 48 h ~~in a similar way than needles~~ and manually cleaned ~~from~~ of extra material, such as soil particles and needles. The needles and the few soil particles attached on the litter leaves were removed with tweezers. The green leaves did not need cleaning. The litter leaves were also rather clean, as it had rained at the time of sampling. ~~-~~After ~~that,~~cleaning, the~~y~~ leaves were milled and stored in a dry place for further analyses. Needles and leaves were sampled at a different time than the soil. Both needle (e.g. Helmisaari 1990) and soil nutrient contents vary between the seasons. However, as all soil and all needle sampling was conducted at the same time of the season, the comparison between the plots was not hindered.

2.3 Laboratory analyses

Total element contents of potassium (K) and P were analysed from ~~all~~ soil and foliar samples by inductively coupled plasma optical emission spectrometry ~~(ICP-OES)~~. For this analysis, the samples were first wet combusted. One gram of mineral soil samples and 0.3 ~~-~~g of organic samples were combusted with 1 ~~-~~ml of H_2O_2 and 10 ~~-~~ml HNO_3~~,~~ and heated in a microwave oven. The samples were then filtered with Whatman Grade ~~-~~589/3 filter paper and stored in plastic bottles in a cooler until analysed.

Total carbon (C) and N were analysed directly from dried and milled foliar samples as well as from the F and O soil layers. Samples of 2–3 ~~Two to three~~ mg ~~of sample was~~ were measured and analysed with an Element Analyser, which uses a high temperature combustion method with subsequent gas analysis of CN (VarioMax, Elementar Analysensysteme GmbH, Germany) ~~analyser~~. Soil pH was measured from two O layer samples per plot and their ~~mean~~ average value used. 20 ~~-~~mg of dried sample was mixed together with ~~MilliQ~~ ultrapure water (50~~0~~ ml). The suspension was covered and left standing for 24 hours, and pH was measured with a glass electrode.

2.4 Statistical analyses

We used one-way analysis of variance (ANOVA) and Tukey's honestly significant difference post-hoc test for analysing the plot-wise differences in ~~the soil and~~ needle element contents. ~~In the latter case, p~~Plot-averages of needle elemental contents were calculated across all needle age classes and both conifer species. One-way ANOVA was also used in analysing differences between the needle age classes. We grouped the plots based on their dominant tree species into pine, birch and spruce plots and calculated the average soil nutrient contents in each horizon in these plots. We then compared the nutrient contents in each soil horizon with one-way ANOVA.

We tested the effects of environmental variables on soil total P and N contents and C:N with linear mixed-effect models. We used dominant tree species, estimated age class, rock parent material (Fig. 1) and soil horizon as fixed effects and plot as random effect. Soil total P needed to be log-transformed, while for N and C:N the visual inspection of residual plots (Fig. B1) did not reveal obvious deviations from homoscedasticity or normality. We obtained *p*-values for the fixed effects by likelihood ratio tests, where the full model with all the fixed effects was tested against a model where each fixed effect was removed in turn. We used package lme4 (Bates et al. 2015) in R programme 3.4.3 (R Development Core Team 2017) for building the models. Pseudo R^2-values for the models were calculated by using package r2glmm (Jaeger 2017). The models took the form:

$$SC_{P,N,CN} = B_0 + B_{dt} + B_{ta} + B_g + B_h + \in, \qquad (1)$$

where $SC_{P,N,CN}$ is the soil nutrient content (total P, N or C:N ratio), B_0 denotes a fixed intercept parameter, B_{dt} denotes the fixed unknown parameters associated with the dominant tree species, B_{ta} denotes the fixed unknown parameters associated with the age of the dominant tree species, B_g denotes the fixed unknown parameters associated with the rock parent material, and B_h denotes the fixed unknown parameters associated with the soil horizon. The random effect $\in$ is assumed to take the form:

$$\in = \propto_p + u, \qquad (2)$$

where $\propto_p$ denotes the random parameters related to the research plot and *u* is an unobservable error term. Random effect parameters and the random error term are assumed to follow normal distributions $\propto_p \sim N(0, \sigma_p^2)$ and $u \sim N(0, \sigma_u^2)$.

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We calculated plot-wise averages ~~of~~ from the percentage covers of the plant species ~~plant species coverages~~ in the sub~~-~~plots. We ordinated this vegetation data by global non-metric multidimensional scaling ~~(NMDS)~~ (Minchin 1987) using the Vegan package (Oksanen et al. 2018) in R programme 3.4.3 (R Development Core Team~~,~~ 2017). Ordination pattern of the plots based on the Bray-Curtis dissimilarity indices in floristic composition was analysed to find the main environmental gradients behind the vegetation variation. ~~Ordination pattern of the study plots and weighted averages of plant species were analysed to find the main environmental gradients behind the vegetation variation.~~ We analysed the data in three-dimensional space~~,~~ but present the results in 1 vs~~.~~ 2 and 1 vs~~.~~ 3 dimensions (the results in 2 vs 3 dimensions did not give any new information). We then fit the plot-~~averages~~ wise data of soil elements (~~contents from~~ O horizon), ~~some other environmental variables~~needle element contents, volume of birch (% of total tree volume),~~ as well as species~~ ~~numbers~~ species cover (% of the surface area) as well as plot distance from the phosphate ore as linear vectors to the ordination pattern of the ~~sample~~ plots. The correlation between the environmental variables and the ordination was calculated by a linear vector procedure (envfit in Vegan). The ~~soil~~ total P in the soil O horizon was also fitted as a smooth surface ~~on~~ to the ordination pattern in order to analyse the form of the relationship (linear or non-linear). The fit was done by a generalized additive model (~~GAM,~~ Gaussian distribution error).

3 Results

3.1 Soil element contents

~~The average contents of total P in different soil horizons are presented in Fig. 3. and the average N and C:N in two organic soil layers (F and O horizons) are presented in Fig. 4.~~ The outlying points in Fig 3. as well as the high standard deviations of P ~~imply~~ showed rather high variation between and within plots (~~Fig. 3 and Fig. 4,~~ Table B~~A~~1, Fig. B2). ~~Other soil elements showed similar variation.~~ Birch-dominated plots had the highest P and N contents and lowest C:N ratio compared with coniferous plots in all soil layers where the elements were measured (Figs. 3 and 4), and these differences were mostly statistically significant (Table B2). We found no statistical evidence for differences in soil N:P ratio or total C content based on the dominant tree species of the plots. There was only one spruce-dominated plot and thus only four soil samples from each soil horizon from the spruce plot, which may have affected these results. ~~The significant differences between plots are presented in Tables A2, A3 and A4.~~ In general, topsoil had the highest P content, but ~~at~~ in many plots~~, also~~ deeper soil layers also had high P content. Certain plots (A1, A3, B1, D2) had clearly different ~~distinct~~ P and N contents~~,~~ and C:N ratio~~s than~~ than most other plots. The N contents and C:N ratios were in most cases higher in F than O horizon. The ~~Soil N:P ratios were similar across the plots. M~~majority of the plots had higher N:P ratio in the F horizon than O horizon.

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3.2 Needle and leaf element contents

~~The average contents of elements are presented in Table 2.~~ Needle P contents were highest in the C needles~~,~~ and significantly different from other age classes in both pine and spruce (Table ~~B1~~C1). ~~Unlike~~ Against our~~the~~ expectations, the needle P contents of both conifer species were rather similar across plots (Table ~~B2~~C2). On the other hand, N and C contents, as well as the C:N ~~-~~ratio of the conifers showed some between-plot variation ($p < 0.05$), but no significant variation was found in the foliar~~.~~ ~~Foliar~~ N:P ratio ~~did not show any differences~~ in either species. ~~between plots.~~ Spruce had slightly higher needle P contents~~s~~ than pine in all age classes, whereas N contents ~~seemed to go vice versa~~were higher in pine than in spruce ~~between the species~~ needles (Table 3). Birch had ~~highest~~ higher P contents of green leaves ~~compared to other species~~than the conifers. Also leaf litter of birch had quite high P contents, and in general litter leaves showed more variation in element contents than the green ~~leaves~~ones. Nitrogen contents were lower in birch leaf litter than in green leaves, but the contents of C increased slightly from green leaves to litter. ~~Green leaves had significantly higher contents of elements than leaf litter, but~~However, no differences between the plots were ~~discovered~~detected in either of the elements. According to the correlation matrix between the elements in the soil O horizon, tree leaves and needles, and number of species in the understory (Fig. 5) ~~Figure 5 presents a correlation table including soil elements in the O horizon together with leaf element contents and number of species in the understory. B~~birch K (green leaves) correlated with soil K and pH, birch litter N with soil N:P and birch litter K with soil N~~,~~. O~~but o~~therwise no significant correlations between foliar element contents and soil element contents were found. The ~~N~~number of ~~species in the understory~~mosses and lichen correlated negatively with soil total C ($p < 0.01$) and C:N ($p < 0.05$)~~elements,~~ the number of sedges and grasses positively with soil total P ($p < 0.001$) and pH ($p < 0.01$) and negatively with soil C:N ($p < 0.01$) and N:P ($p < 0.001$) and the number of dwarf shrubs and trees positively with soil total K ($p < 0.05$). No significant correlations were found between number of species and foliar element contents. The cover (% of surface) of grass and sedge species correlated positively with soil P ($p < 0.001$) and number of sedges and grasses ($p < 0.05$), while the cover of dwarf shrubs and trees correlated positively with the P content of green birch leaves ($p < 0.05$). ~~but not with foliar elements.~~

3.3 Mixed-effect model results

We used linear mixed-effect models for determining which environmental factors can best explain soil total P and N contents and the C:N ratio. The dominant tree species and soil horizon explained 45 % of the total P of soil, and the soil horizon explained 20 % of the total N of soil as well as the C:N ratio of soil (Table 5). The other tested fixed effects had p-values > 0.05 and were for that reason excluded from the models. The highest estimates of P were produced with birch as the dominant tree species and F as the soil layer, and the highest estimates of N with F as the soil layer in the final models.

3.~~3~~ 4 Ordination analysis of understor~~e~~y vegetation

~~Figure 6a-d depicts how the plots were related to each other and how the weighted averages of the plant species were located in the ordination space (dimensions 1 vs. 2 and 1 vs. 3).~~ The closer the plots were to each other in the ordination space, the more similar their vegetation was (Fig. 6a,b). Plots ~~located~~ positioned more on the left-hand side in the figure had a higher number of forbs and grasses growing on them than the plots positioned on the right-hand side in the figure (Fig. 6a,b). Species such as *Calamagrostis epigejos*, *Carex* spp., *Rubus arcticus* and *Luzula pilosa* had relatively high coverage ~~on~~ in the plots ~~on~~ on the left. The plots further on the right in the figure had more species~~,~~ which tolerate poor and dry growing conditions, such

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as *Cladonia* and *Cladina* lichens. ~~The~~ Also the tree species ~~(Table 3) also~~ changed from right to left, as the plots on the right were dominated by pine, whereas furthest on the left in plot D2 birch was the only tree species present. In general, the fertility trend in the vegetation followed the first dimension, while the moisture gradient followed the second dimension. Moisture demanding species, such as *Equisetum sylvaticum* and *Rhododendron tomentosum* ~~were~~ are located in the upper part of Fig. 6b~~.~~, and those tolerating drier conditions, such as *Peltigera rufescens* and *Stereocaulon tomentosum*, ~~were~~ are located in the lower part of the ordination space in Fig. 6b. Another moisture gradient, expressing specific paludified conditions, seemed to follow the third dimension. Peatland species like *Sphagnum angustifolium* and *Aulacomnium palustre* ~~were~~ are located ~~on~~ in the upper part, and species preferring dry conditions, such as *Cetraria islandica*, ~~were~~ are in the lower part of Fig 6d. Considering all three dimensions of ordination space, the generalist species, such as *Polytrichum commune*, *Pleurozium s~~h~~chreberi* and *Vaccinium myrtillus* a~~we~~re located in the middle.

T~~T~~he vector arrows fitted to the ordination space (Fig. 7c,d) depict the maximum correlations between environmental variables and ~~sample~~ plot ordination.~~ (Fig. 7c-d).~~ The length of an arrow indicates the magnitude and ~~the~~ direction of the polarity (plus~~–~~minus) of the correlation. ~~The correlation values between the ordination pattern and different explanatory vectors are given in Table 4.~~ The highest correlations occurred between the plot-wise average P content of the soil O horizon and the ordination pattern of the plots. The isocline gradient of soil P in relation to the ordination pattern was almost linear (Fig. 7a). Vectors of soil pH, N and P content all increased towards the more fertile plots, but the vectors of soil C:N and N:P went to the opposite directions (Fig. 7b) indicating poor soil conditions. The average total number of grass, forb and sedge species as well as their coverage in the study plots also increased towards the more fertile plots (Fig. 7~~-~~d).

4 Discussion

All the plant species growing in the study plots were common forest species in Finland (e.g., Reinikainen et al. 2000, Finnish Biodiversity Information Facility https://laji.fi/en) (Appendix A). However, in some plots the structure and abundance of species in the understorey clearly differed from the surrounding, more typical northern boreal forests. We found evidence that the number of species in the group of grasses and sedges as well as the cover (% of surface) of the same plant group had a higher positive correlation with humus P content than N content (Fig. 5). However, both of these nutrients were important factors explaining the vegetation composition in the ordination configuration (Fig. 7), which supports our first hypothesis. We also found that the humus C:N ratio correlated negatively with the abundance and species composition in the understorey. Also, Salemaa et al. (2008) have observed that total N and the C:N ratio of the humus layer explained most large-scale vegetation variation, across several forest sites in Finland. They also measured extractable soil P, which seemed to have more power in explaining vegetation patterns in northern than southern Finland. Soil P availability was one of the key factors in plant community variation in alpine habitats in Troms, northern Norway (Arnesen et al. 2007), where a higher variety of lichen species and the frequency of occurrence of *Salix herbacea* and certain sedge and grass species were explained by higher availability of P in soil. We conclude that the possible aerial deposition of phosphate from the mine in Sokli could lead to changes in plant species composition and abundance if high amounts of P are deposited into the ecosystem surrounding the mining region.

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Our second hypothesis stated that the N and P contents of the topmost soil layers correlate with the N and P contents of foliar biomass, but our results (Table B2) did not support this hypothesis. The reason could be that we measured total contents of N and P in soil instead of the plant available contents of these nutrients. The plant available contents of these nutrients might have given different results. Perhaps plant species composition in ground vegetation is sensitive to even small additions of available N and P in the upper soil layers where the roots occur, whereas higher contents of these elements are required to have any effect on the needles. The P and N levels of our needle samples were similar to those previously measured in Finland (Helmisaari 1990, Merilä and Derome 2008, Moilanen et al. 2013). The higher P contents of C needles compared with older needles is common for conifers and occurs because the dry weight in recently matured needles increases faster than the transportation of P to the needles (Helmisaari 1990). The N contents of both green birch leaves and leaf litter agreed with those reported by Ferm and Markkola (1985). The P contents of the green leaves were higher than they measured (approximately 2.0 g kg^{-1}). Although the foliar N and P contents were not reflected in the uppermost soil layers, our results support the third hypothesis, and the occurrence of birch correlates positively with the N and P content of the top layers of soil (Table B2). The plots dominated by birch had significantly higher total P content in all but the B layer compared with plots dominated by the conifers (Figs. 3 and 4). Birch leaves were a major source of litter in the plots where soil P was high. These findings are supported by the study of Lukina et al. (2019), which found that the extractable P content of organic soil layers was significantly higher in birch- and spruce-dominated forest sites than in sites dominated by pine in North-Western Russia. Viro (1955) found that the leaf litter of birch had remarkably high P content compared with other Finnish tree species. Our litter P contents were near the approximate 1.50 g kg^{-1} that Ferm and Markkola (1985) measured from a 40-year-old forest but much less than those reported from younger forests. In a litter experiment in Abisko (northern Sweden), the addition of birch litter increased both the total P (Sorensen and Michelsen 2011) and the available P (Rinnan et al. 2008) contents in the organic soil layer in those subarctic heaths, where *Hylocomium splendens* dominated the moss layer. These results imply that birch is an important factor in recycling and providing P to the soil in certain types of northern forest sites.

~~The~~ In general, the spatial variation in soil element contents between ~~clusters was very high at some~~ plots was high, emphasizing the heterogeneity of soil fertility level (Figs. A1 and A2). As our results showed, this heterogeneity can partially be explained by the dominant tree species of the research plot, which especially affects the topmost soil layers. According to the nutrient-uplifting hypothesis (Jobbágy and Jackson 2004), trees and other vegetation can transport minerals such as P and K from the deep soil layers to the surface of soils. The P contents of soil samples (Table B1) in our study (1.80–2.60~~0~~ ~~m~~g kg^{-1} in the O horizon) fell mostly in the category we could expect based on the literature. The P content of the humus layer in southern Finnish forest soil has been observed to vary ~~Mäkipää (1999) reported values~~ between 0.80~~0~~ and –2.10~~0~~ ~~m~~g kg^{-1}

(Mäkipää 1999), whereas different studies in northern Finland have found the P contents of 0.39–3.00 g kg^{-1} in the organic topsoil (Mikkola and Sepponen 1986, Reimann et al. 1997). ~~for P content in humus layer of forest soil in southern Finland. The P contents from the top 5 cm of soil in northern Finland varied widely in both Naruska (385–1970 mg kg^{-1}) and Pallas (599–3030 mg kg^{-1}) in a study by Reimann et al. (1997). Mikkola and Sepponen (1986) found high variation in P content from organic soil in Kilpisjärvi, northwestern Finland, with highest values at around 800 mg kg^{-1}.~~ Most of our plots had highest P content in the ~~at~~ organic soil layers, implying that decaying plant parts ~~were a major source of~~ were a major source of P added to the soil. Low ~~arctic~~ Arctic soils tend to have organic P as the primary form of P (Weintraub 2011). The content of organic P usually gets smaller in the deeper soil (Achat et al. 2009). Thus, if P content is high in deep soil layers, as it was in some of our plots, the source of P in these plots is most likely to be ~~in~~ the underlying bedrock. The plot-~~-~~wise average pH of our soil samples agreed ~~to~~ with that measured by Köster et al. (2014), who conducted their study at the same site, albeit not in the same plots. The pH of the soil humus layer correlated positively with the number of grass, herb and sedge species, which is reasonable, since higher pH usually implies a more fertile site. The soil N contents from our plots agreed with the reported values from Finnish forest sites (Merilä and Derome 2008, Salemaa et al. 2008), ranging between 9.8 and ~~–~~12.8 g kg^{-1}. Salemaa et al. (2008) reported a soil C:N~~-~~ ratio of 40 from a northern Finnish forest site, which is higher than ~~what~~ we measured.

Our study area does not represent typical northern boreal forest, as it was located near the phosphate massif, the effect of which needs to be considered. Talvitie (1979), who used remote sensing for a geobotanical survey of the Sokli massif, found that the density of occurrence of birch, juniper and grass species increased when carbonatite was the underlying rock material. The surveys related to Natura 2000 (Standard Data Forms FI1301512 and FI1301513) stated that the Törmäoja and Yli-Nuortti areas, where plots B1-B3 and A1-A2 were, have a high occurrence of grass species and a sparse birch-dominated tree cover due to carbonatite in the soil. According to the geological map, only small parts in the western ends of both the Törmäoja and Yli-Nuortti Natura areas are located on top of carbonatite rock. Similarly, the map shows that those of our plots where the vegetation community was reminiscent of Sokli have something other than carbonatite as the rock parent material. However, all of our plots have metamorphic (tonalitic migmatite and amphibolite) or igneous (mafic volcanic and ultramafic) rock as the parent material, and phosphate mineral apatite can occur in such rocks (Walker and Syers 1976). It is likely that these types of rock materials leach more phosphate than other types of bedrock (Arnesen et al. 2007). Thus, the rocks outside of the carbonatite massif may also have locally high P content, which affects the P content of the soil. The mixed-effect model factor 'geology' did not consider this, which could be the reason why it was not important in explaining soil P content.

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~~The P and N levels of our needle samples were similar than previously measured in Finland (Helmisaari 1990, Merilä and Derome 2008, Moilanen et al. 2013). The mean P contents of our pine C needles were within the deficiency range of 1200–1500 mg kg^{-1}, which Brække (1994) reported for Norway spruce and Scots pine. The mean spruce needle P contents were within the pre-optimum range of 1500–1800 mg kg^{-1}. Both pine and spruce needles had N contents falling in the deficiency range. The N contents of both green birch leaves and leaf litter agreed with those reported by Ferm and Markkola (1985). The~~

~~P contents of green leaves were higher than the approximately 2000 mg kg^{-1} they measured, which is also considered as the deficiency limit (Miller 1983). Our litter P contents were near the approximately 1500 mg kg^{-1} that Ferm and Markkola (1985) measured from a 40-year-old forest, but much less than those reported from younger forests. Birch leaves were a major source of litter at the plots where soil P was high. Viro (1955) found that the leaf litter of birch had remarkably high P content compared to other Finnish tree species. In a litter experiment in Abisko (northern Sweden), the addition of birch litter increased both the total P (Sorensen and Michelsen 2011) and the available P (Rinnan et al. 2008) contents in the organic soil layer at those subarctic heaths, where *H. splendens* dominated the moss layer.~~

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~~All the plant species, which grew on our plots, were common Finnish forest species (e.g., Reinikainen et al. 2010, Finnish Biodiversity Info Facility 2018), and most plots resembled each other in their plant species composition. We found evidence that the richness of understory vegetation was more related to soil P content than to soil N content. Both soil P and N contents correlated with the abundance and species composition of understory vegetation, which supports our first hypothesis. We also found soil C:N ratio correlating negatively with the abundance and species composition in the understory. Soil C:N ratio was an important variable explaining aboveground species richness also in a deciduous forest in north-western Germany (Schuster & Diekmann 2005). Salemaa et al. (2008) studied connections between understory vegetation and the nutrient concentrations of soil organic layer at several sites in Finland. They found soil N concentration and C:N ratio the most important nutrient variables explaining site vegetation patterns. They also measured extractable soil P, which showed highest concentrations on the plots located in northern Finland, and seemed to have more power in explaining vegetation patterns in northern Finland compared to southern Finland. Soil P availability was one of the key factors in plant community variation in alpine habitats in Troms, northern Norway (Arnesen et al. 2007).~~

~~Our second hypothesis stated that the N and P contents of foliar biomass reflect N and P contents of soil, but our results did not support this hypothesis. The reason could be that we measured total contents of N and P in soil instead of plant available contents of these nutrients. What should also be noted is that needles were sampled at different time of year than soil, and both needle (e.g. Helmisaari 1990) and soil nutrient contents vary along the seasons. For instance, snowmelt can cause release of P in the spring (Weintraub 2011). Our soil samples were taken a couple of weeks after the snowmelt. On the other hand in the early summer soil contained less litter than in the autumn. However, as all soil sampling was conducted at the same time of the season and all needle sampling at the same time of the season, the comparison between the plots is not hindered.~~

The baseline status and the current vegetation composition of our research site was worth studying for several reasons. We conducted our study in a region which has for decades been under more or less heated discussion related to whether mining activities will begin or not. The site is very remote and the plan is to move the material from the mine to the locations of further production by trucks (Pöyry Environment 2009). In addition to the aerial deposition from the mine, this could increase the dust and pollution caused by transportation, the amount of which is currently minimal. The effects of mining on the surrounding ecosystem and its vegetation composition can be unpredictable when combined with the changes caused by climate change. High latitude regions are considered more vulnerable to climate change than more southern regions (Hartmann et al. 2013). ~~As s~~Soil microbial activity may change due to a warmer climate, and so N may become more available from organic sources ~~at high latitudes in the future~~ (Rustad et al. 2001). This, together with high soil P may induce growth and affect vegetation dynamics. Climate change has already caused variation in the vegetation at high latitudes, as deciduous shrub coverage has expanded ~~at~~ in the Arctic region (Sturm et al. 2001, Park et al. 2016). Greater deciduous shrub cover causes increased leaf litter input, which in turn may bring more nutrients that are recyclable to the ecosystem.

5 Conclusions

We found that ~~that~~ the total P content of the soil humus layer ~~is~~ was an important factor ~~-~~explaining the community composition of forest understorey vegetation ~~dynamics at our research plots~~ near the Sokli phosphate ore in Finnish Lapland. The plots with high soil total P in the humus layer ~~(max. 2600 mg kg^{-1})~~ had birch as the dominating tree species. As also green birch leaves and leaf litter high high contents of P, ~~Downy birch leaf litter has been discovered to contain large contents of P, so it is possible~~ we suggest that the leaf litter from birch caused the high total P contents in the humus layer, but the rock parent material ~~. The mean P content of our birch litter samples was 1280 mg kg^{-1}, which is higher than the P contents of C+1 and C+2 needles of pine (1150 and 1160 mg kg^{-1}, respectively). Most of the plots with high total P in the humus layer had high total P contents also in the B layer, where the maximum content was as high as 5500 mg kg^{-1}. It is interesting that in our study the soil total P explained the understory vegetation dynamics better than soil total N did, as usually N is considered more important for understory vegetation in boreal forests.~~ As climate change and the possible mining activities may affect the nutrient and vegetation dynamics in the studied region, the research that we carried out has an important ~~part~~ role in both clarifying the current situation and forming a baseline for evaluating the magnitude of changes in the future.

Data availability

We have made all data used in the analyses publicly available. All can be downloaded at: https://doi.org/10.23728/b2share.615b46018cef40fe8c9d9245c56f0547.

Author contributions

LM and JB planned the study set-up; LM conducted all fieldwork, laboratory analyses and statistical analyses and led the writing process; MS had a substantial role in guiding the ordination analyses and the writing process; all authors contributed to the writing.

Competing interests

The authors declare that they have no conflict of interest.

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References

Achat D. L., Bakker M. R., Augusto L., Saur E., Dousseron L., and Morel C.: Evaluation of the phosphorus status of P-deficient podzols in temperate pine stands: combining isotopic dilution and extraction methods, Biogeochemistry, 92, 183–200, doi:10.1007/s10533-008-9283-7, 2009.

~~Akujärvi A., Hallikainen V., Hyppönen M., Mattila E., Mikkola K., and Rautio P.: Effects of reindeer grazing and forestry on ground lichens in Finnish Lapland, Silva Fenn., 48, 1–18 , doi:10.14214/sf.1153, 2014.~~

Arnesen G., Beck P. S. A., and Engelskjøn T.: Soil Acidity, Content of Carbonates, and Available Phosphorus Are the Soil Factors Best Correlated with Alpine Vegetation: Evidence from Troms, North Norway, Arct. Antarct. Alp. Res., 39, 189–199, doi:10.1657/1523-0430(2007)39[189:SACOCA]2.0.CO;2, 2007.

Augusto L., Achat D. L., Jonard M., Vidal D., and Ringeval B.: Soil parent material—A major driver of plant nutrient limitations in terrestrial ecosystems, Glob. Change Biol., 23, 3808–3824, doi:10.1111/gcb.13691, 2017.

~~-~~Bates D., Maechler M., Bolker B., Walker S: Fitting Linear Mixed-Effects Models Using lme4, J. Stat. Soft., 67, 1 – 48, doi:10.18637/jss.v067.i01, 2015.

~~Brække F. H.: Diagnostic levels of nutrient elements in Norway spruce and Scots pine needles (in Norwegian), Aktuelt Skogforsk, 15, 1–11, 1994.~~

Brække F. H. and Salih N.: Reliability of Foliar Analyses of Norway Spruce Stands in a Nordic Gradient, Silva Fenn., 36, 489–504, http://dx.doi.org/10.14214/sf.540, 2002.

Cajander A.K.: Über Waldtypen, Acta For. Fenn., 1,1–175, 1909.

Cajander A.K.: Forest types and their significance, Acta For. Fenn., 56, 1–71, 1949.

~~Deiss L., de Moraes A., and Maire V.: Environmental drivers of soil phosphorus composition in natural ecosystems, Biogeosciences, 15, 4575–4592, doi:10.5194/bg-15-4575-2018, 2018.~~

Dirnböck~~,~~ T., Grandin~~,~~ U., Bernhardt-Römermann~~n,~~ M., Beudert~~,~~ B., Canullo~~,~~ R., Forsius~~,~~ M., Grabner~~,~~ M.-T., Holmberg~~,~~ M., Kleemola~~,~~ S., Lundin~~,~~ L., Mirtl~~,~~ M., Neumann~~,~~ M., Pompei~~,~~ E., Salemaa~~,~~ M., Starlinger~~,~~ F., Staszewski~~,~~ T., and Uzieblo~~,~~ A.K.: Forest floor vegetation response to nitrogen deposition in Europe, Glob. Change Biol., 20, 429–440, doi:10.1111/gcb.12440, 2014.

Dupré C., Wessberg C., and Diekmann M.: Species richness in deciduous forests: Effects of species pools and environmental variables, J. Veg. Sci., 13, 505–516, doi:10.1111/j.1654-1103.2002.tb02077.x, 2002.

FAO: FAO/Unesco Soil map of the world, revised legend, World Soil Resources Report 60, FAO, Rome, 140 pp., 1988.

Ferm A. and Markkola A.: Hieskoivun lehtien, oksien ja silmujen ravinnepitoisuuksien kasvukautinen vaihtelu. Abstract: Nutritional variation of leaves, twigs and buds in Betula pubescens stands during the growing season, Folia For., 613, 1–28, 1985.

Finnish Biodiversity Information Facility: https://laji.fi/en, last access March 20th 2019.

Hakku service: https://hakku.gtk.fi/en/locations/search, last access February 28th 2019.

Hari~~,~~ P., Kulmala~~,~~ M., Pohja~~,~~ T., Lahti~~,~~ T., Siivola~~,~~ E., Palva~~,~~ L., Aalto~~,~~ P., Hämeri~~,~~ K., Vesala~~,~~ T., Luoma~~,~~ S., and Pulliainen~~n,~~ E.: Air pollution in Eastern Lapland: Challenge for an environmental measurement station, Silva Fenn., 28, 29–39, doi: 10.14214/sf.a9160, 1994.

Hartmann D.L., Klein Tank A.M.G., Rusticucci M., Alexander L.V., Brönnimann S., Charabi Y., Dentener F.J., Dlugokencky E.J., Easterling D.R., Kaplan A., Soden B.J., Thorne P.W., Wild M. and Zhai P.M.: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, editeb by: Stocker, T.F., Qin D., Plattner G.-K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V. and Midgley P.M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Hedwall P-O., Bergh J., and Brunet J.: Phosphorus and nitrogen co-limitation of forest ground vegetation under elevated anthropogenic nitrogen deposition, Oecologia, 185, 317–326, doi:10.1007/s00442-017-3945-x, 2017.

Helmisaari H-S.: Temporal Variation in Nutrient Concentrations of Pinus sylvestris Needles, Scand. J. of Forest Res., 5, 177–193, doi:10.1080/02827589009382604, 1990.

~~Hinsinger P.: Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review, Plant Soil, 237, 173–195, doi:10.1023/A:1013351617532, 2001.~~

Hobbie S. E., Nadelhoffer K. J., and Högberg P.: A synthesis: The role of nutrients as constraints on carbon balances in boreal and arctic regions, Plant Soil, 242, 163–170, doi:10.1023/A:1019670731128, 2002.

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Hofmeister J., Hošek J., Modrý M., and Roleček J.: The influence of light and nutrient availability on herb layer species richness in oak-dominated forests in central Bohemia, Plant Ecol., 205, 57–75, doi:10.1007/s11258-009-9598-z, 2009.

Hämet-Ahti L.: The boreal zone and its biotic subdivision, Fennia, 159, 69–75, 1981.

~~Jackman, R. H. and Black, C. A.: Hydrolysis of phytate phosphorus in soils, Soil Sci., 73, 167–171, 1952.~~Jaeger B.: r2glmm: Computes R Squared for Mixed (Multilevel) Models. R package version 0.1.2. available at: https://CRAN.R-project.org/package=r2glmm, 2017.

Jaeger B., Edwards L. J., Das K., and Sen P. K.: An R^2 statistic for fixed effects in the generalized linear mixed model, J. Appl. Stat., 44, 1086 – 1105, doi: 10.1080/02664763.2016.1193725, 2016.

Jobbágy E. G. and Jackson R.B.: The uplift of soil nutrients by plants: biogeochemical consequences across scales. Ecology, 85, 2380 – 2389, doi: 10.1890/03-0245, 2004.

Johnson P. C. D.: Extension of Nakagawa & Schielzeth's R^2GLMM to random slopes models, Methods Ecol. Evol., 5, 944 – 946, doi: 10.1111/2041-210X.12225, 2014.

Koerselman W. and Meuleman A. F. M.: The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation, J. Appl. Ecol., 33, 1441–1450, doi:10.2307/2404783, 1996.

~~Kreutz A., Aakala T., Grenfell R., and Kuuluvainen T.: Spatial tree community structure in three stands across a forest succession gradient in northern boreal Fennoscandia, Silva Fenn., 49, id 1279, doi:10.14214/sf.1279, 2015.~~

Kuusipalo J.: An ecological study of upland forest site classification in southern Finland, Acta For. Fenn., 192, 77 pp., doi:10.14214/aff.7638, 1985.

Köster K., Berninger F., Lindén A., Köster E., and Pumpanen J.: Recovery in fungal biomass is related to decrease in soil organic matter turnover time in a boreal fire chronosequence, Geoderma, 235–236, 74–82, doi:10.1016/j.geoderma.2014.07.001, 2014.

~~Köster K., Berninger F., Köster E., and Pumpanen J.: Influences of Reindeer Grazing on Above- and Belowground Biomass and Soil Carbon Dynamics, Arct. Antarct. Alp. Res., 47, 495–503, doi: 10.1657/AAAR0014-062, 2018.~~

Laasasenaho~~,~~ J.: Taper curve and volume functions for pine, spruce and birch, Commun. Inst. For. Fenn., 108, 1–74, available at: http://jukuri.luke.fi/handle/10024/522516, 1982.

Liski J.: Variation in soil organic carbon and thickness of soil horizons within a boreal forest stand – effect of trees and implications for sampling, Silva Fenn., 29, 255–266, doi:10.14214/sf.a9212, 1995.

~~Liptzin D., Sanford Jr. R. L., and Seastedt T. R.: Spatial patterns of total and available N and P at alpine treeline, Plant Soil, 365, 127–140, doi:10.1007/s11104-012-1379-0, 2013.~~Lukina N., Tikhonova E., Danilova M., Bakhmet O., Kryshen A., Tebenkova D., Kuznetsova A., Smirnov A., Braslavskaya T., Gornov A., Shashkov M., Knyazeva S., Kataev A., Isaeva L., and Zukert N.: Associations between forest vegetation and the fertility of soil organic horizons in northwestern Russia, Forest Ecosyst., 6, 34, doi: 10.1186/s40663-019-0190-2, 2019.

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Marschner H.: Mineral Nutrition of Higher Plants, Academic Press Limited, Cambridge, Great Britain, 1995.

Merilä P. and Derome J.: Relationships between needle nutrient composition in Scots pine and Norway spruce stands and the respective concentrations in the organic layer and in percolation water, Boreal Env. Res., 13 (suppl. B), 35–47, 2008.

Mikkola K. and Sepponen P.: Kasvupaikkatekijöiden ja kasvillisuuden suhteet Luoteis-Enontekiön tunturikoivikossa – Relatioships between site factors and vegetation in mountain birch stands in northwestern Enontekiö, Folia For., 674, 1–30, 1986.

Minchin P. R.: An evaluation of the relative robustness of techniques for ecological ordination, Vegetatio, 69, 89–107, 1987.

Moilanen ~~n~~ M., Saarinen~~,~~ M., and Silfverberg~~,~~ K.: Foliar nitrogen, phosphorus and potassium concentrations of Scots pine in drained mires in Finland, Silva Fenn., 44, 583–601, doi:10.14214/sf.129, 2010.

Moilanen M., Saarsalmi A., Kukkola M., and Issakainen J.: Effects of stabilized wood ash on nutrient status and growth of Scots pine – Comparison between uplands and peatlands, Forest Ecol. Manag., 295, 136–144, doi:10.1016/j.foreco.2013.01.021, 2013.

Mäkipää R.: Response Patterns of Vaccinium myrtillus and V. vitis-idaea along Nutrient Gradients in Boreal Forest, J. Veg. Sci., 10, 17–26, doi:10.2307/3237156, 1999.

Nakagawa S. and Schielzeth H.: A general and simple method for obtaining R^2 from generalized linear mixed-effects models, Methods. Ecol. Evol., 4, 133 – 142, doi: 10.1111/j.2041-210x.2012.00261.x, 2013.

NASA: https://worldview.earthdata.nasa.gov/ ~~http://gibs.earthdata.nasa.gov/image-download?TIME=2015229&extent=3.3508300781250107,53.666015625,32.178955078125014,72.615234375&epsg=4326&layers=MODIS_Terra_CorrectedReflectance_TrueColor,Coastlines,Reference_Features&opacities=1,1,1&worldfile=false&format=image/jpeg&width=6561&height=4313~~, last access ~~February~~December ~~28th~~ 17th 2019.

NATURA 2000 - Standard Data Form FI1301512: http://natura2000.eea.europa.eu/Natura2000/SDF.aspx?site=FI1301512, last access February 28th 2019.

NATURA 2000 - Standard Data Form FI1301513: http://natura2000.eea.europa.eu/Natura2000/SDF.aspx?site=FI1301513, last access February 28th 2019.

Näsholm T., Kielland K., and Ganeteg U.: Uptake of organic nitrogen by plants, New Phytol., 182, 31–48, doi: 10.1111/j.1469-8137.2008.02751.x, 2008.

Økland R. H. and Eilertsen O.: Dynamics of understory vegetation in an old-growth boreal coniferous forest, 1988 -1993, J. Veg. Sci., 7, 747–762, doi:10.2307/3236386, 1996.

Oksanen J., Blanchet F. G., Friendly M., Kindt, R., Legendre P., McGlinn D., Minchin P. R., O'Hara R. B., Simpson G. L., Solymos P., Stevens M. H. H., Szoecs E., and Wagner H.: vegan: Community Ecology Package, R package version 2.4-6, available at: https://CRAN.R-project.org/package=vegan, 2018.

Park T., Sangram G., Tømmervik H., Euskirchen E. S., Høgda K-A., Karlsen S. R., Brovkin V., Nemani R. R., and Myneni R. B.: Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data, Environ. Res. Lett., 11, 1–11 , doi:10.1088/1748-9326/11/8/084001, 2016.

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Pirinen P., Simola H., Aalto J., Kaukoranta J-P., Karlsson P., and Ruuhela R.: Tilastoja Suomen ilmastosta 1981-2010. Ilmatieteen laitos, Raportteja 2012:1, Finnish Meteorological Institute. 94 pp, available at: https://helda.helsinki.fi/handle/10138/35880, 2012.

Pöyry Environment: Soklin kaivoshankkeen YVA-selostus, 332 pp., 2009.

R Development Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, available at: http://www.R-project.org/, 2017.

Rautio P., Fürst A., Stefan K., Raitio H., and Bartels U.: Sampling and Analysis of Needles and Leaves, Manual Part XII, in: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, edited by: UNECE, ICP Forest Programme Co-ordinating Centre, Hamburg, 19 pp., available at: http://icp-forests.net/page/icp-forests-manual, 2010.

Reimann C., Boyd R., de Caritat P., Halleraker J. H., Kashulina G., Niskavaara H., and Bogatyrev I.: Topsoil (0-5 Cm) Composition In Eight Arctic Catchments In Northern Europe (Finland, Norway And Russia), Environ. Pollut., 1, 45–56, doi: 10.1016/S0269-7491(96)00102-9, 1997.

Reinikainen~~,~~ A., Mäkipää~~,~~ R., Vanha-Majamaa~~,~~ I., and Hotanen~~,~~ J.-P.: Kasvit muuttuvassa metsäluonnossa (Changes in the frequency and abundances of forest and mire plants in Finland since 1950), Kustannusyhtiö Tammi, Helsinki, 2000.

Reta G., Dong X., Li Z., Su B., Hu X., Bo H., Yu D., Wan H., Liu J., Li Y., Xu G., Wang K., and Xu S.: Environmental impact of phosphate mining and beneficiation: review, Int. J. Hydro., 2, 424–431, doi: 10.15406/ijh.2018.02.00106, 2018.

Rinnan R., Michelsen A., and Jonasson S.: Effects of litter addition and warming on soil carbon, nutrient pools and microbial communities in a subarctic heath ecosystem, Appl. Soil Ecol., 39, 271–281, doi:10.1016/j.apsoil.2007.12.014, 2008.

Rustad L.E., Campbell J.L., Marion G.M., Norby R.J., Mitchell M.J., Hartley A.E., Cornelissen J.H.C., Gurevitch J., and GCTE-NEWS: A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming, Oecologia, 126, 543–562, doi:10.1007/s004420000544, 2001.

Ruuskanen T. M., Reissel A., Keronen P., Aalto P. P., Laakso L., Grönholm T., Hari P., and Kulmala M.: Atmospheric trace gas and aerosol particle concentration measurements in Eastern Lapland, Finland 1992-2001, Boreal Env. Res., 8, 335–349, 2003.

Saarsalmi A. and Mälkönen E.: Forest Fertilization Research in Finland: A Literature Review, Scand. J. Forest Res., 16, 514–535 doi:10.1080/02827580152699358, 2001.

Salemaa~~,~~ M., Monni~~,~~ S., Royo Peris~~,~~ F., and Uhlig~~,~~ C.: Sampling strategy for the assessment of temporal change in ground vegetation in boreal forests, in: Forest condition monitoring in Finland, edited by: Raitio, H. and Kilponen, T., National report 1998, The Finnish Forest Research Institute, Research Papers, 743,117–127, 1999.

Salemaa M., Derome J., and Nöjd P.: Response of boreal forest vegetation to the fertility status of the organic layer along a climatic gradient, Boreal Env. Res., 13 (suppl. B), 48–66, 2008.

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Salemaa, M., Lindroos, A.-J., Merilä, P., Mäkipää, R., and Smolander, A: N_2 fixation associated with the bryophyte layer is suppressed by low levels of nitrogen deposition in boreal forests, Sci. Total Environ., 653, 995–1004, doi: 10.1016/j.scitotenv.2018.10.364, 2019.

~~Schuster B. and Diekmann M.: Species richness and environmental correlates in deciduous forests of Northwest Germany, Forest Ecol. Manag., 206, 197–205, doi:10.1016/j.foreco.2004.10.063, 2005.~~

Sorensen P. L. and Michelsen A.: Long-term warming and litter addition affects nitrogen fixation in a subarctic heath, Glob. Change Biol., 17, 528–537, doi: 10.1111/j.1365-2486.2010.02234.x, 2011.

Sturm M., Racine C., and Tape K.: Increasing shrub abundance in the Arctic, Nature, 411, 546–547, doi:10.1038/35079180, 2001.

~~Susiluoto S., Rasilo T., Pumpanen J., and Berninger F.: Effects of grazing on the vegetation structure and carbon dioxide exchange of a Fennoscandian fell ecosystem, Arct. Antarct. Alp. Res., 40, 422–431, doi:10.1657/1523-0430(07-035)[SUSILUOTO]2.0.CO;2, 2008.~~

Talvitie J.: Remote sensing and geobotanical prospecting in Finland, Bull. Geol. Soc. Finland, 51, 63–73, 1979.

Tamm C. O.: Nitrogen in terrestrial ecosystems: Questions of productivity, vegetational changes, and ecosystem stability, Ecological Studies 81, Spriger-Verlag, Berlin, Heidelberg, 116 pp., 1991.

Tonteri~~,~~ T., Salemaa~~,~~ M., Rautio~~,~~ P., Hallikainen~~,~~ V., Korpela~~,~~ L., and Merilä~~,~~ P.: Forest management regulates temporal change in the cover of boreal plant species, Forest Ecol. Manag., 381, 115–124, doi:10.1016/j.foreco.2016.09.015, 2016.

Tuovinen H., Vesterbacka D., Lempinen J., Pohjolainen. E., Read D., Solatie D., and Lehto J.: Radionuclide and heavy metal redistribution at the former pilot-scale apatite plant in Sokli, northern Finland, Boreal Env. Res., 20, 350–362, available at: https://helda.helsinki.fi/handle/10138/228212, 2015.

Ukonmaanaho L., Merilä P., Nöjd P. and Nieminen T. M.: Litterfall production and nutrient return to the forest floor in Scots pine and Norway spruce stands in Finland, Boreal Env. Res., 13 (suppl. B), 67–91, 2008.

Vartiainen H., and Paarma H.: Geological Characteristics of the Sokli Carbonatite Complex, Finland, Econ. Geol., 74, 1296–1306, doi:0.2113/gsecongeo.74.5.1296, 1979.

Verheyen ~~,~~K., Baeten~~,~~ L., De Frenne ~~,~~P., Bernhardt-Romermann ~~,~~M., Brunet ~~,~~J., Cornelis ~~,~~J., Decocq ~~,~~G., Dierschke~~,~~ H., Eriksson~~,~~ O., Hedl~~,~~ R., Heinken~~,~~ T., Hermy~~,~~ M., Hommel~~,~~ P., Kirby~~,~~ K., Naaf~~,~~ T., Peterken~~,~~ G., Petrik~~,~~ P., Pfadenhauer~~,~~ J., Van Calster~~,~~ H., Walther~~,~~ G.R., Wulf~~,~~ M., and Verstraeten~~,~~ ~~-~~G.: Driving factors behind the eutrophication signal in understorey plant communities of deciduous temperate forests, J. Ecol., 100, 352–365, doi: 10.1111/j.1365-2745.2011.01928.x, 2012.

Vinton M. A. and Burke I.C.: Interactions between individual plant species and soil nutrient status in shortgrass steppe, Ecology, 76, 1116-1133, doi:10.2307/1940920, 1995.

Viro P. J.: Investigations on forest litter, Commun. Inst. For. Fenn., 45, 60 pp., 1955.

~~Vitousek P. M., Porder S., Houlton B. Z., and Chadwick O. A.: Terrestrial phosphorus limitation: mechanisms, implications,~~

~~and nitrogen–phosphorus interactions, Ecol. Appl., 20, 5–15, doi:10.1890/08-0127.1, 2010.~~

~~Väre, H., Ohtonen, R., and Oksanen, J.: Effects of reindeer grazing on understorey vegetation in dry Pinus sylvestris forests, J. Veg. Sci., 6, 523–530, doi:10.2307/3236351, 1995.~~

Walker T. W. and Syers J. K.: The fate of phosphorus during pedogenesis, Geoderma, 15, 1–19, doi:10.1016/0016-7061(76)90066-5, 1976.

Weintraub M. N.: Biological Phosphorus Cycling in Arctic and Alpine Soils, in: Phosphorus in action , edited by: Bünemann E. K., Oberson A., and Frossard E., Soil Biol., 26, 295–316, Springer, Berlin, Heidelberg, doi:10.1007/978-3-642-15271-9_12, 2011.

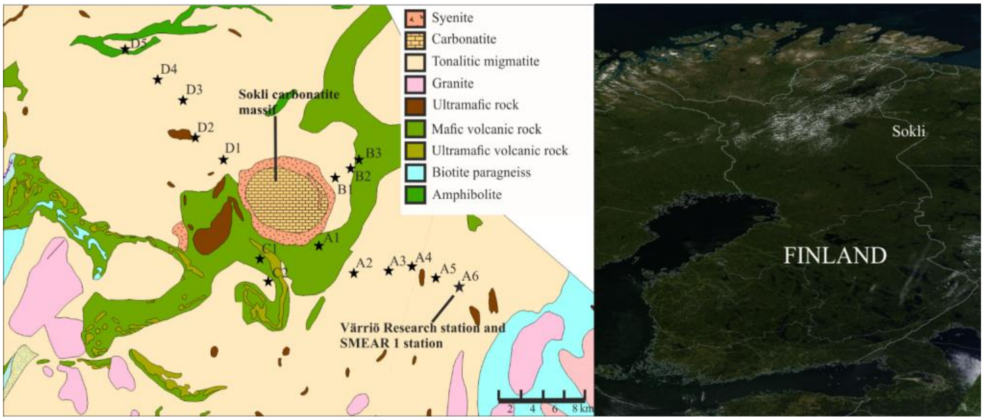
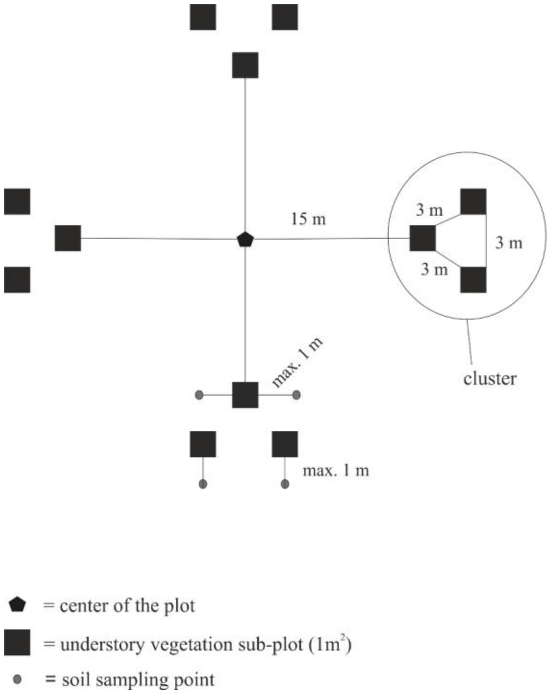


Figure 1: L~~On the l~~eft: G~~a g~~eological map of the research area.~~, where p~~Plots are marked with black stars. The easternmost plot is located at the SMEAR~~-~~1 station. (Source:~~Geologigal map from~~ Hakku Service, https://hakku.gtk.fi/en/locations/search.), Right: Satellite image showing the study location (source: NASA).~~satellite image from NASA).~~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⬟ = center of the plot
■ = understory vegetation sub-plot (1m²)
● = soil sampling point

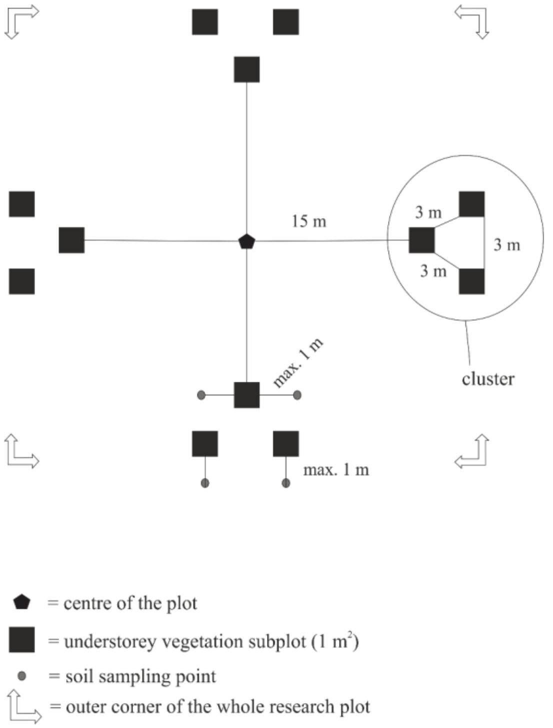
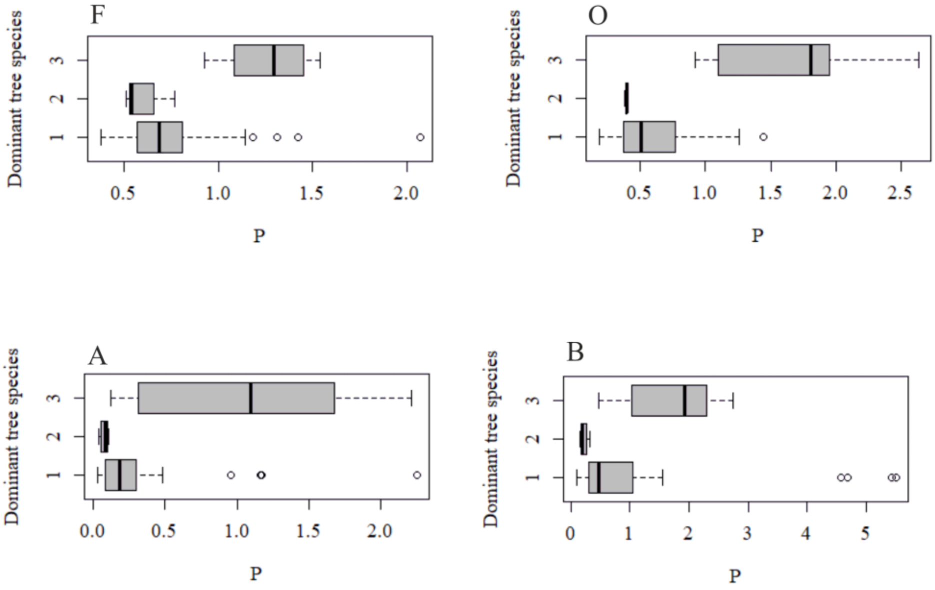


Figure 2: S~~The s~~et-up of each research plots with clusters and sub~~-~~plots within clusters. Trees were measured from the whole 30 × 30 m area.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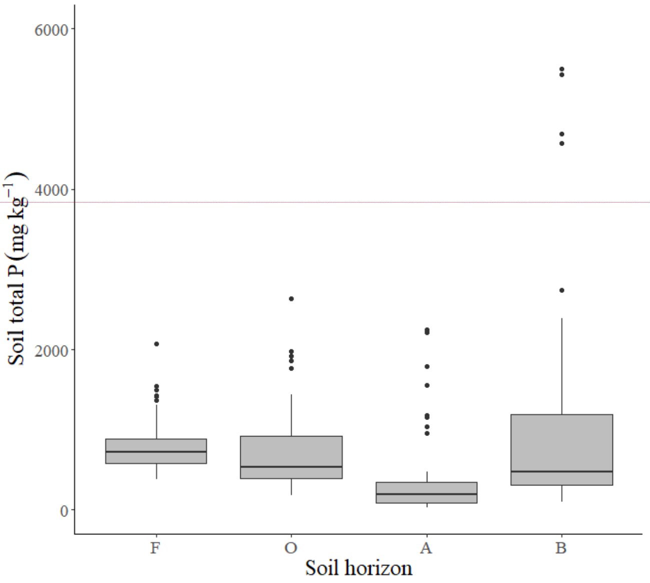

Figure 3. Soil total phosphorus (P) contents of the research plots (based on dominant tree species) in different soil horizons. Species 1 = pine, 2 = spruce and 3 = birch.~~. The lines inside boxes denote medians, lower and upper hinges are the first and third quantiles, the whiskers cover values ranging 1.5 x the inter-quartile range (IQR, the distance between the first and third quartiles) from the hinge and the points outside are outliers not fitting inside the previously mentioned range.~~

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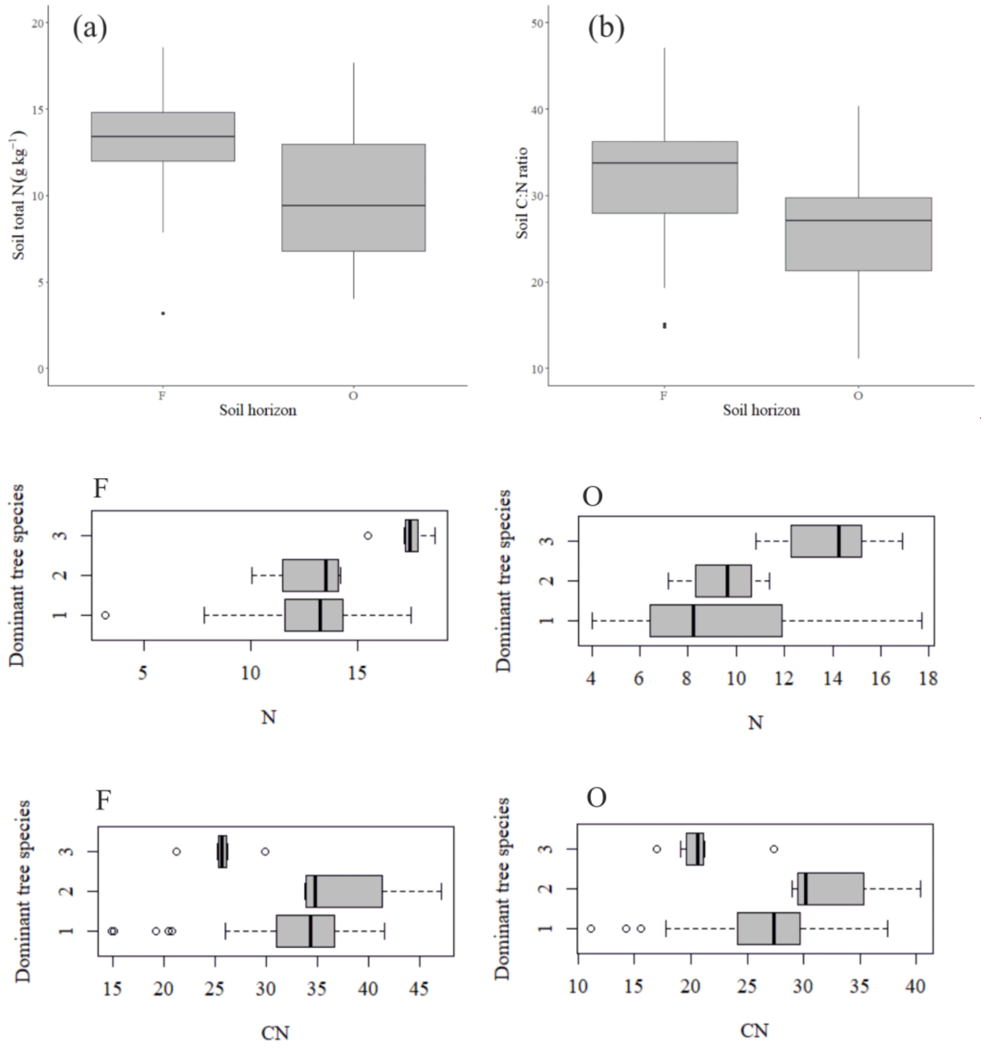

Figure 4. Soil total N content (~~a~~upper panel) and soil C:N ratio (~~b~~lower panel) of the research plots (based on dominant tree species) in soil horizons F and O. Species 1 = pine, 2 = spruce and 3 = birch.~~The lines inside boxes denote medians, lower and upper hinges~~

~~are the first and third quantiles, the whiskers cover values ranging 1.5 x the inter-quartile range (IQR, the distance between the first and third quartiles) from the hinge and the points outside are outliers not fitting inside the previously mentioned range.~~

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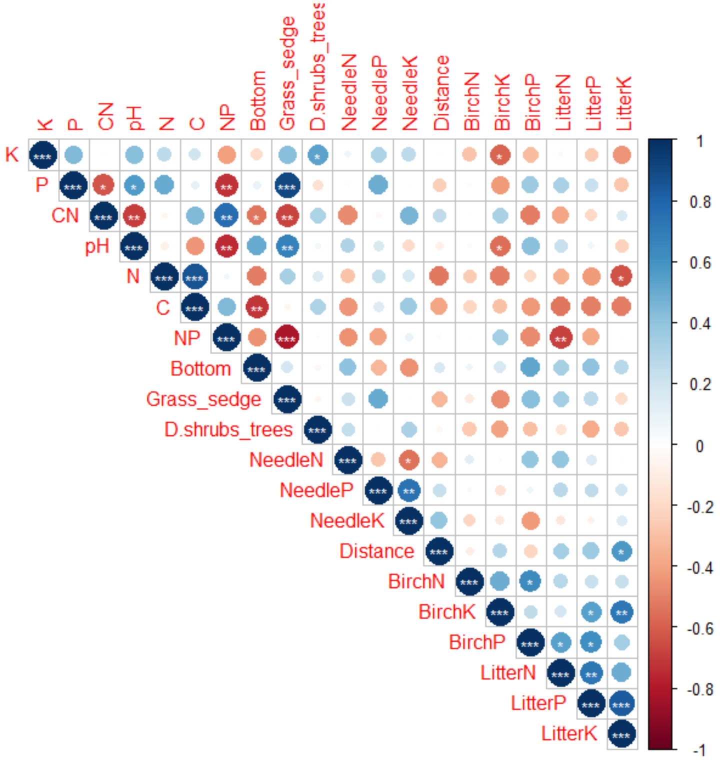
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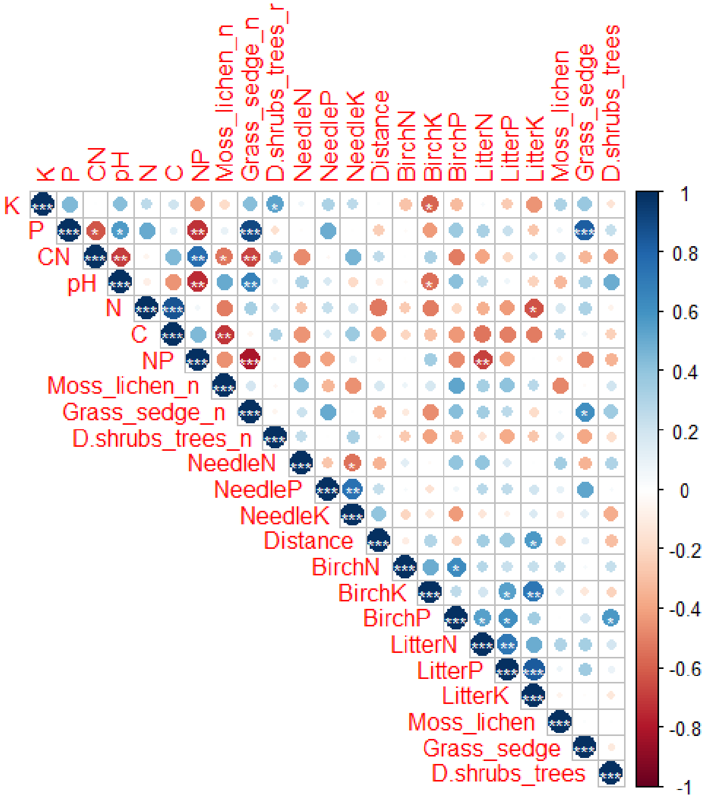


Figure 5. C~~The c~~orrelation (Pearson) ~~figure~~ including soil elements (K, P, C:N, pH, C, N:P), ~~the~~ number of species (with _n in the end of the name) and total % cover of plant species in different layers (~~the bottom layer~~moss and lichen, grasses, herbs and sedges, dwarf shrubs and trees), needle elements (N, P, K), plot distance from Sokli, green birch elements (N, P, K) and birch litter elements (N, P, K). Levels of significance * = 0.05, ** = 0.01, * = 0.001. Positive correlations are displayed in blue and negative correlations in red. Colour intensity and size of the circle are proportional to the correlation coefficients.**

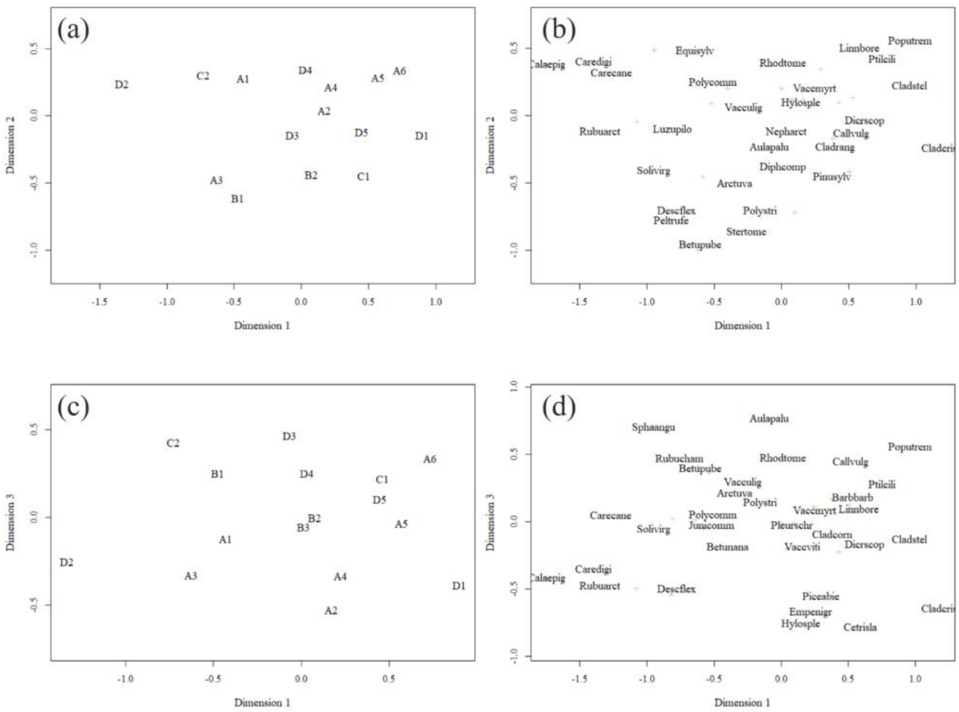
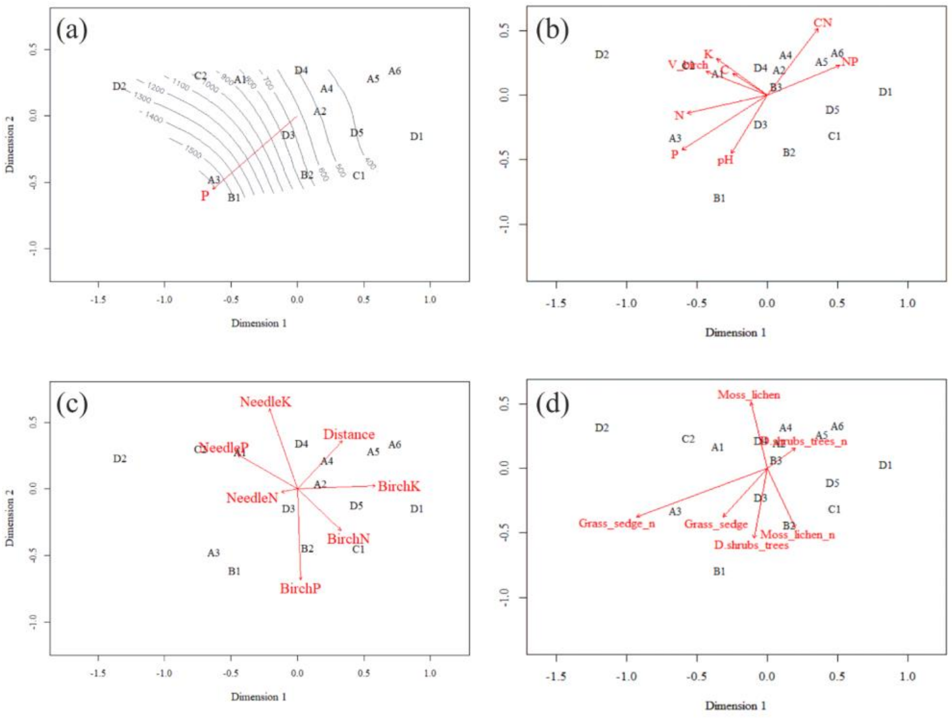


Figure 6: ~~The upper panel (a and b) presents the o~~Ordination pattern of the research plots in dimensions 1 ~~&~~ and 2 (a and b), and ~~the lower panel (c and d) in~~ dimensions 1 ~~&~~ and 3 (c and d). Figures (a) and (c) give plot ordinations and b and d weighted averages of the most abundant species (highest cover % of surface). Less abundant species are marked with light-coloured crosses. The names of species are combinations of the first four letters of genera~~ic~~ and species names (e.g. Solivirg = *Solidago virgaurea*). The tree species mentioned in the figure are at seedling stage. In (a) and (c) ~~P~~plots D4 and B3 were located on top of each other and only D4 is shown.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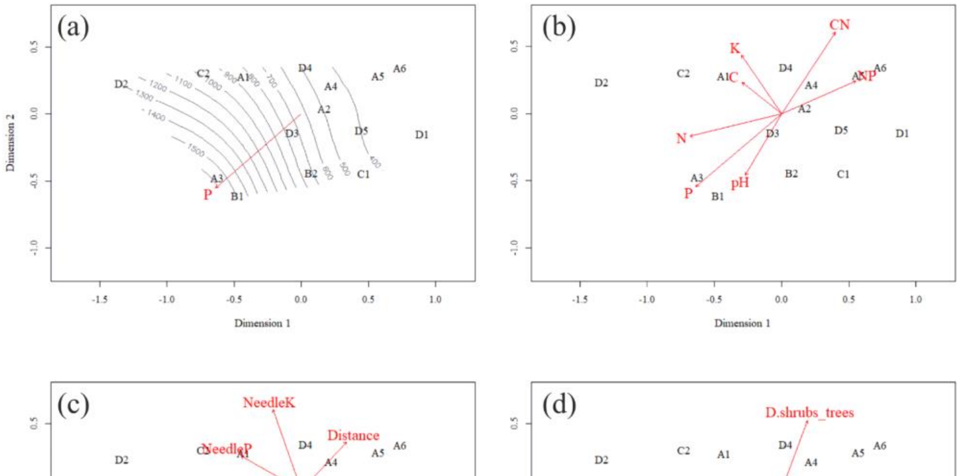
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Figure 7: Ordination pattern with smooth surface fit and linear vector fit of soil phosphorus (P) in the O layer (a), linear vector fits of soil element contents in the O layer (b), linear vector fits of foliar data as well as plot distance from Sokli phosphate ore (c), and linear vector fits of number of species in different layers of understorey (d). ~~Bottom layer~~Moss_lichen includes moss and lichen species, Grass_sedge includes forb, grass, and sedge species and D.shrubs_trees includes dwarf shrubs and tree seedlings. In (a) and (c) ~~Plots~~ plots D4 and B3 were located on top of each other and only D4 is shown.

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Table 1. Meteorological parameters from Värriö. SWE=snow water equivalent, *= data from SMEAR 1 station, **= data from SMEAR station (only 2009–2015), otherwise data are collected from Värriö Subarctic Reseach Station by the Finnish Meteorological Institute. Values for the climatological normal period are from Pirinen et al. 2012. Growing degree day sum was calculated as the average daily temperature (average of daily maximum and minimum temperatures) above 5 °C base temperature, accumulated on a daily basis over the year. Negative values are treated as zeros and ignored.

-	2014	2015	Climatological normal period (1981-2010)
Average annual temperature (°C)	0.84	0.95	−0.5
Average min. temperature (°C)	−2.09	−1.7	−3.5
Average max. temperature (°C)	3.9	3.8	2.6
Growing degree day sum	860	640	680
Total precipitation (mm)	610	660	601
· Snowfall (mm, SWE)*	390	420	400 **
· Rainfall (mm)	220	240	190 **

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~~**Table 1. Meteorological parameters from Värriö. SWE=snow water equivalent, *= data from SMEAR 1 station, **= data from SMEAR station, only 2009-2015, otherwise data is collected from Värriö Reseach Station by Finnish Meteorological Institute. The values for climatological normal period are from Pirinen et al. 2012.**~~

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~~-~~	~~2014~~	~~2015~~	~~Climatological normal period (1981-2010)~~
~~Mean annual temperature (°C)~~	~~0.84~~	~~0.95~~	~~-0.5~~
~~Degree days~~	~~860~~	~~640~~	~~680~~
~~Total precipitation (mm)~~	~~610~~	~~660~~	~~601~~
~~· Snowfall (mm, SWE)*~~	~~390~~	~~420~~	~~400 **~~
~~· Rainfall (mm)~~	~~220~~	~~240~~	~~190 **~~

~~**Table 2. Mean foliar element contents of the three major nutrients and C, and the relationships of C:N and N:P with standard deviations. Units for elements are mg kg^{-1} for K and P, and g kg^{-1} for N and C.**~~

~~**Table 2. Mean foliar element contents of the three major nutrients and C, and the relationships of C:N and N:P with standard deviations. Units for elements are mg kg^{-1} for K and P, and g kg^{-1} for N and C.**~~

	~~**K**~~	~~**P**~~	~~**N**~~	~~**C**~~	~~**C:N**~~	~~**N:P**~~
~~Pine C~~	~~4480 (910.0)~~	~~1420 (140.0)~~	~~14.10 (0.80)~~	~~510.0 (3.70)~~	~~36.0 (1.90)~~	~~10.0 (1.10)~~
~~Pine C+1~~	~~3650 (370.0)~~	~~1150 (76.20)~~	~~13.80 (0.90)~~	~~510.0 (7.30)~~	~~38.0 (2.40)~~	~~11.80 (1.10)~~
~~Pine C+2~~	~~3520 (330.0)~~	~~1160 (89.0)~~	~~12.10 (3.70)~~	~~480.0 (140.0)~~	~~36.6 (11.20)~~	~~10.60 (3.30)~~
~~Spruce C~~	~~6430 (870.0)~~	~~1700 (190)~~	~~12.0 (1.00)~~	~~500 (3.80)~~	~~42.0 (3.50)~~	~~7.10 (0.70)~~
~~Spruce C+1~~	~~4240 (850.0)~~	~~1470 (210.0)~~	~~10.70 (4.20)~~	~~440.0 (170.0)~~	~~37.0 (14.50)~~	~~7.30 (2.90)~~
~~Spruce C+2~~	~~3650 (750.0)~~	~~1360 (230.0)~~	~~10.10 (3.90)~~	~~440.0 (165.0)~~	~~39.2 (14.90)~~	~~7.50 (3.00)~~
~~Birch, green~~	~~8170.0 (1450.0)~~	~~2580 (340.0)~~	~~25.0 (1.20)~~	~~470.0 (3.40)~~	~~19.0 (1.0)~~	~~9.80 (1.0)~~
~~Birch, litter~~	~~2380.0 (1010.0)~~	~~1280.0 (450.0)~~	~~10.10 (1.40)~~	~~490.0 (6.0)~~	~~50.0 (7.40)~~	~~8.50 (2.10)~~

~~**Table 3. Tree species composition of the research plots**~~

~~Plot~~	~~Trees/ha~~	~~Total volume of trees (m3/ha)~~	~~Tree species composition (% of volume)~~
~~A1~~	~~1300~~	~~75~~	~~Pinus sylvestris 58.9, Picea abies 0.1, Betula pubescens 41~~
~~A2~~	~~1200~~	~~78~~	~~Pinus sylvestris 88, Picea abies 3, Betula pubescens 9~~
~~A3~~	~~900~~	~~46~~	~~Picea abies 1, Betula pubescens 99~~
~~A4~~	~~600~~	~~130~~	~~Pinus sylvestris 66, Picea abies 25, Betula pubescens 9~~
~~A5~~	~~1200~~	~~125~~	~~Pinus sylvestris 77, Picea abies 15, Betula pubescens 8~~
~~A6~~	~~500~~	~~54~~	~~Pinus sylvestris 99, Betula pubescens 1~~
~~B1~~	~~300~~	~~3~~	~~Pinus sylvestris 93, Picea abies 1, Betula pubescens 6~~
~~B2~~	~~300~~	~~33~~	~~Pinus sylvestris 100~~

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~~B3~~	~~500~~	~~128~~	~~Pinus sylvestris 99.5, Picea abies 0.2, Betula pubescens 0.3~~
~~C1~~	~~800~~	~~14~~	~~Pinus sylvestris 100~~
~~C2~~	~~1100~~	~~105~~	~~Pinus sylvestris 48, Picea abies 34, Betula pubescens 18~~
~~D1~~	~~700~~	~~99~~	~~Pinus sylvestris 99.9, Betula pubescens 0.1~~
~~D2~~	~~1100~~	~~48~~	~~Betula pubescens 100~~
~~D3~~	~~500~~	~~18~~	~~Pinus sylvestris 86, Betula pubescens 14~~
~~D4~~	~~300~~	~~43~~	~~Pinus sylvestris 34, Picea abies 37 , Betula pubescens 29~~
~~D5~~	~~700~~	~~98~~	~~Pinus sylvestris 100~~

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Table ~~3~~2. Tree species composition of the research plots. dbh = diameter at breast height.

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Plot	Trees/ha	Basal area of trees (m^2/ha)	Total volume of trees (m3/ha)	Volume of pine (m^3/ha)	Volume of spruce (m^3/ha)	Volume of birch (m^3/ha)	Average dbh of pine (cm)	Average dbh of spruce (cm)	Average dbh of birch (cm)
A1	1300	10	75	44	0.02	30.7	10	1.8	7
A2	1200	12	78	69.2	2.3	6.9	9.1	6.5	5.7
A3	900	8	46	-	0.5	45.5	-	6.4	9.1
A4	600	16	130	83.7	35.5	11.2	21.5	11.3	9
A5	1200	17	125	94.5	20.9	10.0	18.7	8.4	6.2
A6	500	10	54	53.7	-	0.7	16.7	-	3.9
B1	300	1	3	2.8	0.07	-	13.4	5.6	-
B2	300	5	33	32.6	-	-	18.2	-	-
B3	500	17	128	127.9	0.2	0.4	19.2	6.8	5.7
C1	800	3	14	14.3	-	-	6.1	-	-
C2	1100	14	105	47.1	41.1	17.7	21.6	12.1	7
D1	700	14	99	99.3	-	0.03	11.9	-	3.3
D2	1100	9	48	-	-	48	-	-	9.8
D3	500	4	18	15.3	-	2.5	8.5	-	9.2
D4	300	7	43	13.6	17.2	12.3	21.5	22	9.9
D5	700	11	98	98.3	-	-	11.4	-	-

	C	N	P	K	C:N	N:P
Pine C	510.0 (3.70)	14.10 (0.80)	1.40 (1.40)	4.50 (9.10)	36.0 (1.90)	10.0 (1.10)
Pine C+1	510.0 (7.30)	13.80 (0.90)	1.20 (0.80)	3.70 (3.70)	38.0 (2.40)	11.80 (1.10)
Pine C+2	480.0 (140.0)	12.10 (3.70)	1.2 (0.90)	3.50 (3.30)	36.6 (11.20)	10.60 (3.30)
Spruce C	500 (3.80)	12.0 (1.00)	1.70 (0.20)	6.40 (0.90)	42.0 (3.50)	7.10 (0.70)
Spruce C+1	440.0 (170.0)	10.70 (4.20)	1.50 (0.20)	4.20 (0.90)	37.0 (14.50)	7.30 (2.90)
Spruce C+2	440.0 (165.0)	10.10 (3.90)	1.40 (0.20)	3.70 (0.80)	39.2 (14.90)	7.50 (3.00)
Birch, green	470.0 (3.40)	25.0 (1.20)	2.60 (0.30)	8.20 (1.50)	19.0 (1.0)	9.80 (1.0)
Birch, litter	490.0 (6.0)	10.10 (1.40)	1.30 (0.50)	2.40 (1.00)	50.0 (7.40)	8.50 (2.10)

Table 3. Average foliar element contents (g kg^{-1}) of the three major nutrients and C, and the relationships of C:N and N:P with standard deviations. Needle age classes: C = current year, C+1 = one-year-old needles, C+2 = two-year-old needles.

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Table 4. Linear correlations of element contents of soil, needles and leaves, number of species in different vegetation layers and plot distance from Sokli with the ~~NMDS~~ non-metric multidimensional scaling ordination pattern. The group of ‘g~~Bottom layer includes moss and lichen species, g~~rasses and sedges’ includes forb, grass and sedge species and ‘d. shrubs and trees’ includes dwarf shrubs and tree seedlings. Levels of significance: ^{o} = 0.1, * = 0.05, ** = 0.01~~, * = 0.001~~. The first seven rows are soil values.**

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Variable	R^2	p <
K	0.~~199~~225	0.~~287~~220
P	0.~~726~~717	0.~~001~~002***
N	0.~~414~~368	0.0~~50*~~87^{o}
C	0.~~171~~137	0.~~347~~461
C:N	0.~~606~~576	0.~~005~~012**
N:P	0.~~380~~431	0.~~064^{o}~~045*
pH	0.~~316~~386	0.~~126~~075^{o}
Needle P	0.~~235~~440	0.~~243~~033*
Needle N	0.~~013~~010	0.~~932~~927
Needle K	0.~~361~~465	0.~~085^{o}~~029*
Birch P	0.~~410~~247	0.~~062^{o}~~213
Birch N	0.~~179~~104	0.~~324~~569
Birch K	0.~~303~~346	0.~~121~~099^{o}
~~Bottom layer~~Moss and lichen, species number	0.~~148~~249	0.~~408~~223
Grasses and sedges, species number	0.~~721~~738	0.~~002~~003**
D. shrubs and trees, species number	0.~~375~~181	0.~~070^{o}~~341
Moss and lichen, % cover of surface	0.180	0.325
Grasses and sedges, % cover of surface	0.248	0.196
D.shrubs and trees, % cover of surface	0.250	0.198
Plot distance from Sokli	0.~~214~~183	0.~~269~~344

Table 5. Results from the mixed-effect models, testing the effects of environmental variables on soil total P and N content and C:N ratio. The tested variables were dominant tree species of the research plot, estimated tree age, rock parent material (geology) and soil layer. Random effect was related to plot number. Pseudo-R^2 was calculated based on Nakagawa and Schielzeth (2013), Johnson (2014) and Jaeger et al. (2016).

	Soil total P content		
Fixed effects	Chisq value	p-value	Pseudo-R^2
factor (dominant tree species)	7.9009	0.01925	0.45
factor (tree age)	4.0408	0.1326	
factor (geology)	4.8171	0.08995	
factor (soil layer)	155.97	2.20×10^{-16}	

	Soil total N content		
Fixed effects	Chisq value	p-value	Pseudo-R^2
factor (dominant tree species)	4.9146	0.08567	0.2
factor (tree age)	2.1769	0.3367	
factor (geology)	2.2291	0.3281	
factor (soil layer)	53.408	2.71×10^{-13}	

	Soil total C:N ratio		
Fixed effects	Chisq value	p-value	Pseudo-R^2
factor (dominant tree species)	4.2076	0.122	0.2
factor (tree age)	1.3484	0.5096	
factor (geology)	0.3339	0.8462	
factor (soil layer)	60.036	9.31×10^{-15}	

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~~Appendix A. Soil element contents across plots~~

~~Table A1. Mean total contents of elements in soil layers and their standard deviations in parenthesis. All plots are included. Units for K and P are mg kg^{-1}, and for N and C g kg^{-1}.~~

~~-~~	**~~K~~**	**~~P~~**	**~~N~~**	**~~C~~**	**~~C:N~~**	**~~N:P~~**	**~~pH~~**
~~F layer~~	~~830 (300)~~	~~810 (320)~~	~~13.3 (2.9)~~	~~420 (98)~~	~~32 (6.8)~~	~~17.8 (5.5)~~	~~-~~
~~O layer~~	~~490 (220)~~	~~720 (500)~~	~~9.9 (3.7)~~	~~260 (106)~~	~~26 (5.7)~~	~~17.2 (7.3)~~	~~3.7 (0.2)~~
~~A layer~~	~~320 (220)~~	~~380 (510)~~	~~–~~	~~–~~	~~-~~	~~-~~	~~-~~
~~B layer~~	~~590 (230)~~	~~1030 (1300)~~	~~–~~	~~–~~	~~-~~	~~-~~	~~-~~

~~Table A2. Plots differing from other plots in soil total P, p< 0.05. Letters F, O, A and B denote soil horizons.~~

~~All plots~~	~~A1~~	~~A3~~	~~A4~~	~~B1~~	~~D2~~
~~A1~~	~~-~~	~~O, A, B~~	~~-~~	~~A, B~~	~~-~~
~~A2~~	~~-~~	~~All layers~~	~~-~~	~~All layers~~	~~O~~
~~A3~~	~~O, A, B~~	~~-~~	~~All layers~~	~~O, B~~	~~O, A, B~~
~~A4~~	~~O~~	~~All layers~~	~~-~~	~~All layers~~	~~O~~
~~A5~~	~~B~~	~~All layers~~	~~-~~	~~All layers~~	~~O~~
~~A6~~	~~B~~	~~All layers~~	~~B~~	~~All layers~~	~~O~~
~~B1~~	~~A, B~~	~~O, B~~	~~All layers~~	~~-~~	~~A, B~~
~~B2~~	~~-~~	~~All layers~~	~~-~~	~~F, A, B~~	~~-~~
~~B3~~	~~-~~	~~All layers~~	~~-~~	~~All layers~~	~~O~~
~~C1~~	~~F~~	~~All layers~~	~~-~~	~~All layers~~	~~F, O~~
~~C2~~	~~B~~	~~All layers~~	~~B~~	~~F, A, B~~	~~-~~
~~D1~~	~~B~~	~~All layers~~	~~-~~	~~All layers~~	~~O~~
~~D2~~	~~-~~	~~O, A, B~~	~~F, O~~	~~A, B~~	~~-~~
~~D3~~	~~F, B~~	~~All layers~~	~~B~~	~~F, A, B~~	~~F~~
~~D4~~	~~B~~	~~All layers~~	~~B~~	~~All layers~~	~~F, O~~
~~D5~~	~~F, B~~	~~All layers~~	~~B~~	~~All layers~~	~~F, O~~

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~~**Table A3. Plots differing from other plots in soil total N, $p<0.05$. Letters F and O denote soil horizons.**~~

~~All plots~~	~~A3~~	~~A6~~	~~C2~~	~~D2~~	~~D3~~
~~A1~~	-	~~F~~	-	-	-
~~A2~~	~~F~~	~~F~~	-	-	-
~~A3~~	-	~~F, O~~	-	-	-
~~A4~~	~~F, O~~	~~F~~	~~O~~	~~F,O~~	~~O~~
~~A5~~	~~F, O~~	~~F~~	~~O~~	~~O~~	~~O~~
~~A6~~	~~F, O~~	~~F~~	~~F, O~~	~~F,O~~	~~F~~
~~B1~~	~~F~~	-	-	~~F, O~~	~~O~~
~~B2~~	-	~~F~~	-	-	-
~~B3~~	-	~~F~~	-	~~O~~	~~O~~
~~C1~~	~~F~~	-	-	~~F~~	~~O~~
~~C2~~	-	~~F, O~~	-	-	~~O~~
~~D1~~	~~F~~	~~F~~	-	~~F~~	~~O~~
~~D2~~	-	~~F, O~~	-	-	-
~~D3~~	-	~~F~~	~~O~~	-	~~O~~
~~D4~~	~~F~~	~~F~~	-	~~F~~	~~O~~
~~D5~~	~~F, O~~	~~F~~	~~O~~	~~F,O~~	~~O~~

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~~**Table A4. Plots differing from other plots in soil C:N ratio, p<0.05. Letters F and O denote soil horizons.**~~

~~All plots~~	~~A6~~	~~B1~~	~~B2~~	~~C2~~	~~D3~~
~~A1~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~A2~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~A3~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~A4~~	~~F~~	~~F~~	~~F~~	~~O~~	~~-~~
~~A5~~	~~F~~	~~F~~	~~F~~	~~O~~	~~O~~
~~A6~~	~~-~~	~~-~~	~~-~~	~~F, O~~	~~F, O~~
~~B1~~	~~-~~	~~-~~	~~-~~	~~F, O~~	~~F, O~~
~~B2~~	~~-~~	~~-~~	~~-~~	~~F, O~~	~~F, O~~
~~B3~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~C1~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~C2~~	~~F, O~~	~~F, O~~	~~F, O~~	~~-~~	~~-~~
~~D1~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~D2~~	~~F~~	~~F~~	~~F~~	~~-~~	~~-~~
~~D3~~	~~F, O~~	~~F~~	~~F, O~~	~~-~~	~~-~~
~~D4~~	~~F~~	~~F~~	~~F~~	~~-~~	~~F~~
~~D5~~	~~F~~	~~-~~	~~F~~	~~-~~	~~O~~

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~~Appendix B: Needle and leaf nutrient contents per plot~~

~~**Table B1. Statistically significant differences between different needle and leaf age groups (C = youngest needles , C+1 = one-year-old needles, C+2 = two-year-old needles),** ***p*****<0.05**~~

~~-~~	~~P~~	~~N~~	~~C~~	~~C:N~~	~~N:P~~
~~Pine~~	~~C & C+1, C & C+2~~	~~C & C+2~~	~~C & C+1, C & C+2~~	~~C & C+2~~	~~C & C+1, C & C+2~~
~~Spruce~~	~~C & C+1, C & C+2~~	~~No differences between age classes~~	~~No differences between age classes~~	~~No differences between age classes~~	~~C & C+1, C & C+2~~

~~-~~	~~P~~	~~N~~	~~C~~	~~C:N~~	~~N:P~~
~~Pine~~	~~C & C+1, C & C+2~~	~~C & C+2~~	~~C & C+1, C & C+2~~	~~C & C+2~~	~~C & C+1, C & C+2~~
~~Spruce~~	~~C & C+1, C & C+2~~	~~No differences between age classes~~	~~No differences between age classes~~	~~No differences between age classes~~	~~C & C+1, C & C+2~~

~~**Table B2. Statistically significant differences of needle nutrient contents between plots,** ***p*****<0.05.**~~

~~-~~	~~P~~	~~N~~	~~C~~	~~C:N~~	~~N:P~~

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~~Pine~~	~~No differences between plots~~	~~Plots: 1&6, 2&11, 5&11, 6&11, 7&11, 6&14, 7&14~~	~~No differences between plots~~	~~Plots: 11&5, 11&6, 11&7~~	~~No differences between plots~~
~~Spruce~~	~~Plots: 10&4~~	~~Plots: 3&1, 4&1, 8&1, 8&2, 8&6, 10&8, 12&8, 15&8~~	~~Plots: 2&1, 3&1, 6&1, 15&1, 4&2, 12&2, 12&3, 6&4, 15&4, 12&6~~	~~Plots: 3&1, 4&1, 8&1, 8&2, 8&6, 12&8, 15&8~~	~~No differences between plots~~

Appendix ~~C~~A: Average coverage (% of surface area) of understorey plant species per plot

Species	A1	A1	A3	A4	A5	A6	B1	B2	B3	C1	C2	D1	D2	D3	D4	D5
Pleurozium schreberi	43.3	51.3	39.6	59.3	44.4	57.1	25.0	24.7	64.7	9.0	38.8	0.3	1.2	53.5	14.5	38.7
Hylocomium splendens	38.7	8.3	22.8	9.6	3.3	1.7	–	3.8	1.3	–	28.9	–	44.6	–	14.5	–
Dicranum scoparium	–	12.6	–	4.2	5.9	10.7	1.6	2.8	–	8.3	–	72.9	–	1.0	9.7	4.1
Dicranum polysetum	–	–	–	–	0.2	0.1	–	0.9	0.8	–	–	–	–	–	0.6	0.4
Dicranum majus	–	–	–	1.1	–	–	–	–	–	–	–	–	–	–	–	1.3
Barbilophozia barbata	–	–	–	0.1	0.7	0.6	–	–	–	–	–	–	–	0.2	0.2	5.8
Polytrichum strictum	–	–	2.8	–	–	–	5.0	5.3	–	0.8	–	–	–	2.1	–	–
Polytrichum commune	3.4	0.4	0.7	0.1	–	–	0.4	–	–	–	1.4	–	23.4	4.0	4.9	0.1
Aulacomnium palustre	–	–	–	–	–	–	–	–	–	–	–	–	–	3.7	–	–
Sphagnum angustifolium	–	–	–	–	–	–	–	–	–	–	1.0	–	–	–	–	–
Sphagnum girgensohnii	–	–	–	–	–	–	–	–	–	–	0.3	–	–	–	–	–
Sphagnum capillifolium	–	–	–	–	–	–	–	–	–	–	–	–	–	0.2	–	–
Ptilidium ciliare	–	–	–	–	–	1.1	–	–	–	–	–	–	–	–	–	–
Peltigera aphthosa	1.1	–	–	–	1.0	–	0.6	0.7	0.4	–	–	–	–	–	0.1	–
Peltigera rufescens	–	–	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–
Peltigera neopolydactyla	–	–	–	–	–	–	10.9	0.1	–	–	–	–	–	–	–	–
Nephroma arcticum	–	2.3	1.0	3.9	–	–	6.1	1.5	0.5	–	–	–	–	0.5	0.1	1.3
Umbilicaria deusta	–	–	–	–	–	–	–	0.1	–	–	–	–	–	–	–	–
Cladonia rangiferina	0.3	1.0	0.3	1.6	1.5	2.0	6.2	2.8	1.6	31.0	–	3.8	–	5.2	0.3	5.3
Cladonia cornuta	–	–	0.1	–	0.2	–	0.1	0.2	–	0.1	–	0.2	–	–	–	0.3
Cladonia stellaris	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cladonia deformis	–	–	–	–	–	–	–	0.1	–	0.6	–	–	–	–	–	0.1
Cladonia crispata var. crispata	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cetraria islandica	–	0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stereocaulon tomentosum	–	–	–	–	–	–	4.7	2.2	–	–	–	–	–	–	–	–
Linnaea borealis	–	–	–	–	0.3	0.2	–	–	0.1	–	–	–	–	–	–	–
Vaccinium myrtillus	1.2	4.3	–	10.7	14.7	27.7	–	5.2	2.3	1.4	8.4	1.3	2.7	18.8	6.0	6.9
Vaccinium vitis~~-~~–idaea	15.3	26.8	5.6	22.2	11.9	5.2	1.3	5.5	21.6	5.7	3.4	28.2	25.8	4.0	7.4	4.4

Vaccinium uliginosum	7.1	0.8	–	–	–	0.5	15.5	5.3	2.3	2.9	34.3	–	11.6	41.7	6.3	1.5
Empetrum nigrum	2.7	9.8	0.8	8.4	14.1	12.4	–	9.6	32.8	9.3	14.5	15.0	4.1	40.4	7.0	6.9
Arctostaphylos uva–ursi	–	–	–	–	–	–	10.7	0.2	0.4	–	–	–	–	–	–	–
Arctostaphylos alpina	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Betula nana	23.9	6.3	1.3	–	–	–	–	–	–	–	2.2	–	–	2.7	–	–
Calluna vulgaris	–	–	–	–	–	0.5	–	–	–	0.2	–	–	–	0.6	–	0.4
Rhododendron tomentosum	–	–	–	–	–	–	–	–	–	–	–	–	–	0.8	3.6	–
Juniperus communis	0.9	–	0.8	0.6	–	–	5.7	0.3	2.2	–	2.5	–	3.7	–	–	–
Picea abies	–	–	–	0.5	–	–	–	–	–	–	–	–	–	–	–	–
Pinus sylvestris	–	–	–	–	–	–	1.6	0.8	–	2.1	0.1	0.9	–	0.8	–	0.7
Betula pubescens	1.1	0.2	1.4	–	–	0.4	2.5	0.7	–	–	–	–	–	0.2	0.1	–
Populus tremula	–	–	–	–	–	0.4	–	–	–	–	–	–	–	–	–	–
Diphasiastrum complanatum	–	–	–	–	–	0.1	0.7	–	–	–	–	–	–	–	–	–
Trientalis europaea	–	0.1	0.7	–	–	–	–	–	–	–	–	–	3.4	–	–	–
Melampyrum sylvaticum	–	–	0.3	–	–	–	0.1	–	–	–	–	–	–	0.1	–	–
Solidago virgaurea	–	–	1.1	–	–	–	1.2	–	–	–	0.2	–	0.7	–	–	–
Rubus arcticus	–	–	0.6	–	–	–	–	–	–	–	–	–	3.2	–	–	–
Rubus chamaemorus	–	–	–	–	–	–	–	–	–	–	0.4	–	–	–	–	–
Antennaria dioica	–	–	–	–	–	–	1.2	–	–	–	–	–	–	–	–	–
Orthilia secunda	–	–	–	–	–	–	–	–	–	–	0.1	–	–	–	–	–
Epilobium angustifolium	–	–	–	–	–	–	–	–	–	–	–	–	0.7	–	–	–
Galium uliginosum	–	–	–	–	–	–	–	–	–	–	–	–	0.1	–	–	–
Geranium sylvaticum	–	–	–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
Chelidonium majus	–	–	–	–	–	–	–	–	–	–	–	–	0.1	–	–	–
Comarum palustre	–	–	–	–	–	–	–	–	–	–	–	–	0.3	–	–	–
Equisetum sylvaticum	0.1	–	–	–	–	–	–	–	–	–	–	–	0.8	–	0.2	–
Luzula pilosa	0.6	–	0.4	–	–	–	1.8	–	–	–	0.2	–	2.4	0.3	–	–
Elymus repens	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Deschampsia flexuosa	3.5	0.6	10.3	0.6	–	0.2	2.1	0.3	0.4	–	2.8	–	15.9	7.1	2.2	0.2
Festuca rubra	–	–	–	–	–	–	–	–	–	–	–	–	1.9	–	–	–
Calamagrostis epigejos	–	–	–	–	–	–	–	–	–	–	–	–	5.4	–	–	–
Carex digitata	–	–	–	–	–	–	–	–	–	–	–	–	0.6	–	–	–

Carex nigra	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	0.2	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–
Carex canescens	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	0.5	~~-~~–	3.4	~~-~~–	~~-~~–	~~-~~–
Carex globularis	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	~~-~~–	1.7	~~-~~–	~~-~~–

Appendix B1. Soil element contents within and across plots

Table B1. Average total contents of elements (g kg^{-1}) in soil layers and their standard deviations in parenthesis. All plots are included.

	K	P	N	C	C:N	N:P	pH
F layer	0.83 (0.30)	0.81 (0.32)	13.3 (2.9)	420 (98)	32 (6.8)	17.8 (5.5)	-
O layer	0.49 (0.22)	0.72 (0.50)	9.9 (3.7)	260 (106)	26 (5.7)	17.2 (7.3)	3.7 (0.2)
A layer	0.32 (0.22)	0.38 (0.51)	-	-	-	-	-
B layer	0.59 (0.23)	0.10 (0.13)	-	-	-	-	-

Table B2. Statistical differences of soil elements in each soil layer of different plots, grouped by their dominant tree species. Levels of significance: * = 0.05, ** = 0.01, * = 0.001.**

	P	N	C:N
F layer	birch & pine*** birch & spruce**	birch & pine*** birch & spruce**	birch & pine** birch & spruce**
O layer	birch & pine*** birch & spruce***	birch & pine**	birch & pine* birch & spruce**
A layer	birch & pine*** birch & spruce*	–	–
B layer	–	–	–

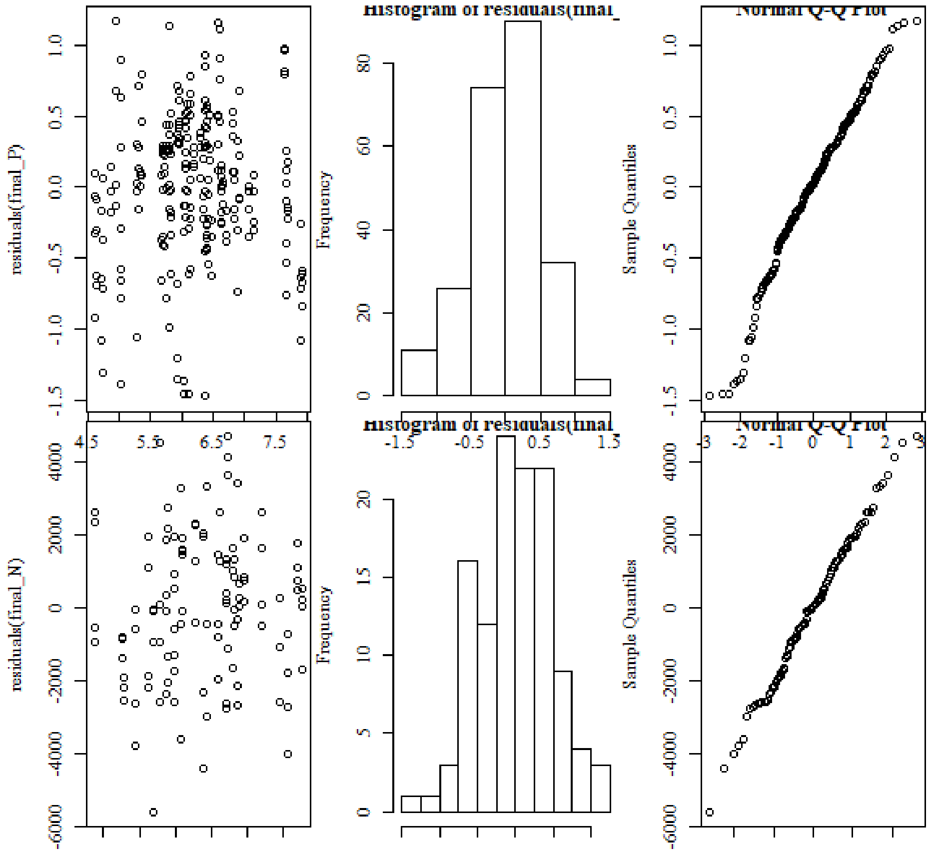

Figure B1. The fitted vs. residuals, q-q plots and histograms of residuals from the mixed effect models (upper = phosphorus (P), lower = nitrogen (N).

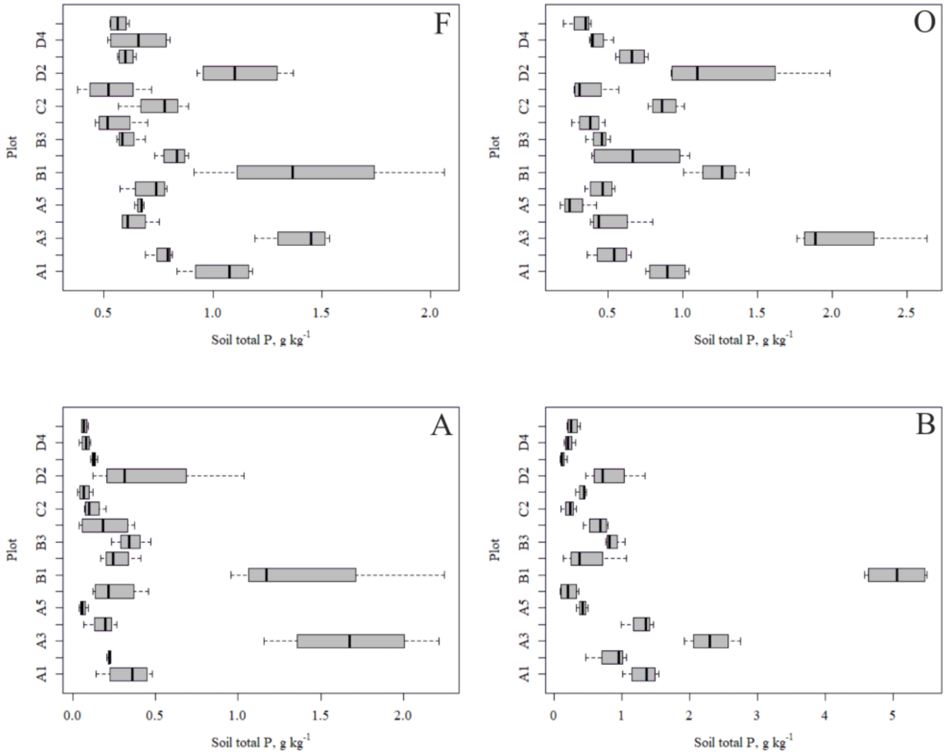

Figure B2. Soil total P content within plots in different soil layers.

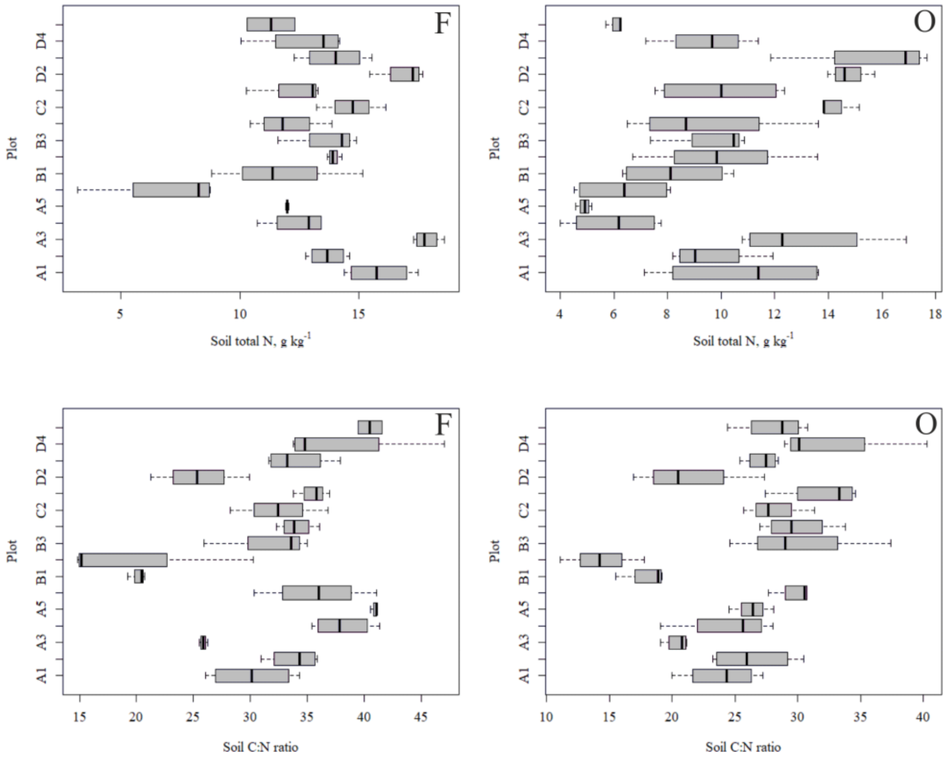

Figure B3. Soil total N content and C:N ratio within plots in the F and O layers.

Appendix C: Needle and leaf nutrient contents per plot

Table C1. Statistically significant differences between needle age group by species (C = youngest needles , C+1 = one-year-old needles, C+2 = two-year-old needles), *p* < 0.05 one-way analysis of variance, with Tukey's honestly significant difference post hoc test.

	P	N	C	C:N	N:P
Pine	C & C+1, C & C+2	C & C+2	C & C+1, C & C+2	C & C+2	C & C+1, C & C+2
Spruce	C & C+1, C & C+2	No differences between age classes	No differences between age classes	No differences between age classes	C & C+1, C & C+2

Table C2. Statistically significant differences of needle nutrient contents between plots, $p < 0.05$.

	P	N	C	C:N	N:P
Pine	No differences between plots	Plots: A5&B1, A4&D3, A1&D3, B1&D3, B2&D3, B1&D1, B2&D1	No differences between plots	Plots: D3&A1, D3&B1, D3&B2	No differences between plots
Spruce	Plots: C2&A2	Plots: A3&A5, A2&A5, B3&A5, B3&A4, B3&B1, C2&B3, D5&B3, D4&B3	Plots: A4&A5, A3&A5, B1&A5, D4&A5, A2&A4, D5&A4, D5&A3, B1&A2, D4&A2, D5&B1	Plots: A3&A5, A2&A5, B3&A5, B3&A4, B3&B1, D5&B3, D4&B3	No differences between plots