Ecography

**E7922**
le Roux, P. C., Virtanen, R. and Luoto, M. 2012. Geomorphological disturbance is necessary for predicting fine-scale species distributions. – Ecography 35: xxx–xxx.

## Supplementary material

## Appendix 1: Boosted regression tree analyses

### Methods

We used R (R Development Core Team 2011) with functions from the gbm and dismo packages (Elith et al. 2008, Ridgeway 2006) to fit BRTs, setting interaction depth (i.e. tree complexity) to six, learning rate to 0.001 (reduced for species where inadequate trees were calculated) and bagging fraction to 0.75. The explanatory power of BRT models was assessed by comparing the predictive deviance (unlike $R^2$, smaller predictive deviance values indicate better model fit) for all relationships. The relative importance of predictor variables was assessed using Friedman's (2001) method, with variables' contributions scaled to sum to 100, with higher numbers indicating stronger influence on the response.

### Results

BRT models including the two geomorphological disturbance variables had better explanatory power than equivalent models lacking the variables, with significantly lower mean predictive deviance (mean improvement = -1 %, max. = -17 %; Table A1). As for GAM models, temperature of the warmest month was an average the most important predictor of species occurrence in both simple and full models (Fig. A1a). After including terrestrial and fluvial disturbance, the importance of $Temp_{July}$ declined strongly and $Disturb_{terr}$ became the third most important variable. Similar to results from GAMs, the importance of the two geomorphological disturbance variables differed strongly between species, with a combined importance of 10 - 40 % for the majority of species (Fig. A1b).

BRT models' predictive performance improved with the inclusion of the two disturbance variables, with small but significant improvement in AUC values for full models (mean

increase = 0.02, max. = 0.13; Appendix 2: Table A1). Mean TSS values were also significantly higher for models incorporating the two disturbance variables (mean increase = 0.03, max. = 0.31; Table A1). Overall, 72 - 79 % of BRT models had higher AUC and TSS values for full models than simple topography-soil-climate models. Analysing species subsets based on taxon or biogeographic distribution gave similar results to the initial analysis of all species (Appendix 2: Table A3). As for GAM models, the BRT response curves for the disturbance variables varied strongly between species (data in Appendix 2: Table A2 with additional analysis presented in Table A4).

Species distribution patterns were also strongly affected by the inclusion of the two geomorphological disturbance variables (for example *Saussurea alpina*; Fig. A2), although the impacts of fluvial disturbance on species richness were weaker in the BRT models than in the GAM models (Appendix 2: Fig. A4).

**Supplementary references**

Elith, J. et al. 2008. A working guide to boosted regression trees - J. Anim. Ecol. 77: 802-813.

Friedman, J.H. 2001. Greedy function approximation: A gradient boosting machine - Ann. Stat. 29: 1189-1232.

R Development Core Team. 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing - Vienna, Austria.

Ridgeway, G. 2006. gbm: Generalized boosted regression models - retrievable from http://cran.r-project.org/web/packages/gbm/.

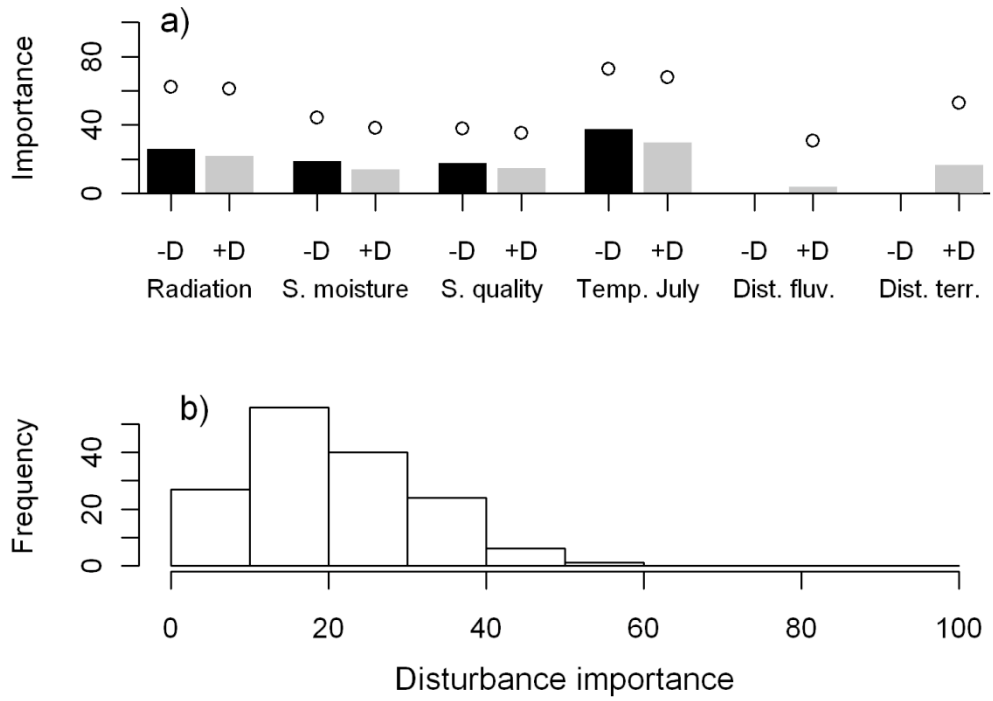


**Figure A1.** The relative importance of disturbance variables as calculated from boosted regression tree models: a) variable importance for the simple ("-D": topography-soil-climate variables) and full ("+D": topography-soil-climate-disturbance) models, and b) the distribution of the combined importance of terrestrial and fluvial disturbances for all species. In a), empty circles indicate the maximum importance for each variable across all 154 species modeled and standard error bars are omitted as they are too small to display clearly (all SE < 2). Abbreviations as in Fig. 1.

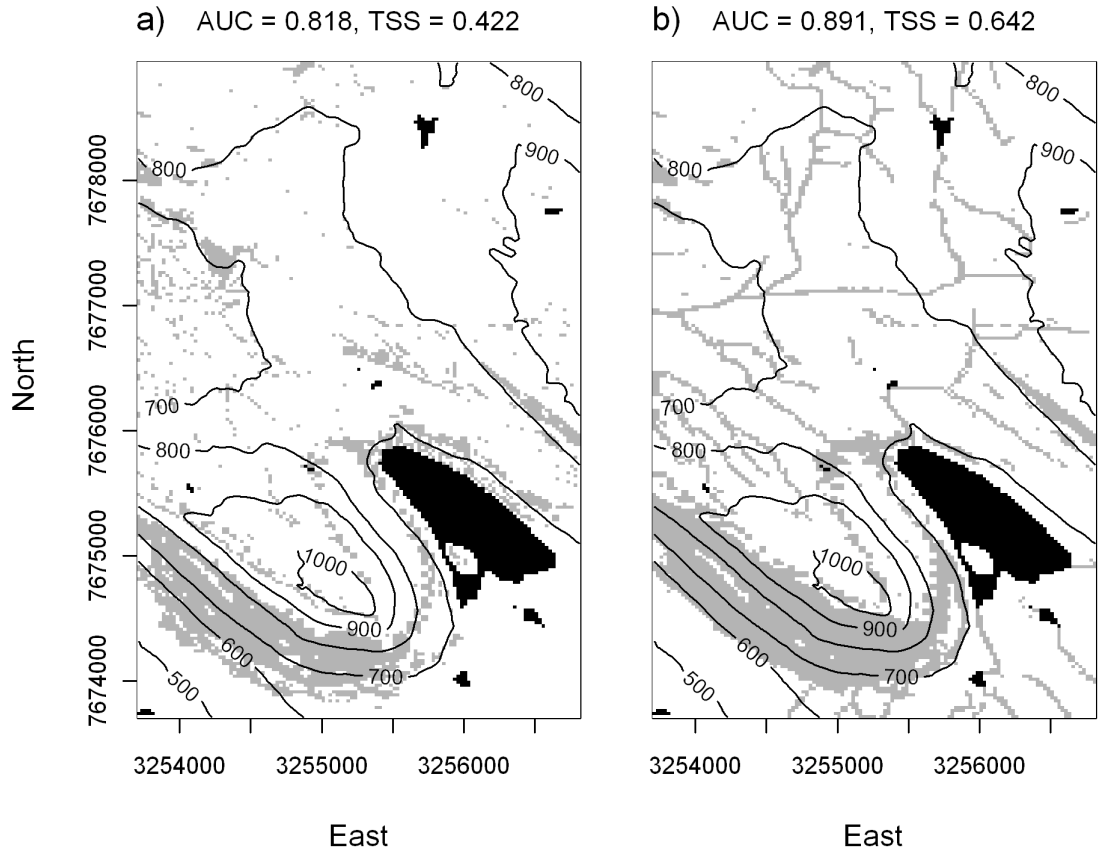


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**Figure A2.** Modeled distribution of *Saussurea alpina* in a 3.1 x 5.2 km area in the centre of
60 our study region, based on the predictions of a) simple and b) full boosted regression tree models. Grey indicates predicted areas of occurrence, and black indicates lakes and ponds.
62 Latitude and longitude are indicated in the Finnish coordinate system.

**Table A1.** Results from Wilcoxon's matched pairs tests, testing if the explanatory accuracy and predictive power of full boosted regression tree models (including geomorphological variables) differs from that of simple models (containing topography, soil and climate variables). Explanatory accuracy is measured as predictive deviance, and predictive power as the area under the curve of a receiver operating characteristic plot (AUC) and the true skill statistic (TSS). N = 154.

| Metric | Simple model (mean ± SE) | Full model (mean ± SE) | Wilcoxon V | p |
|---|---|---|---|---|
| Predictive deviance | 46.1 ± 1.3 | 45.0 ± 1.2 | 7961 | < 0.001 |
| AUC | 85.4 ± 0.6 | 86.8 ± 0.6 | 1640 | 0.001 |
| TSS | 48.6 ± 1.5 | 52.0 ± 1.5 | 2975 | 0.001 |

## Appendix 2: Supplementary results

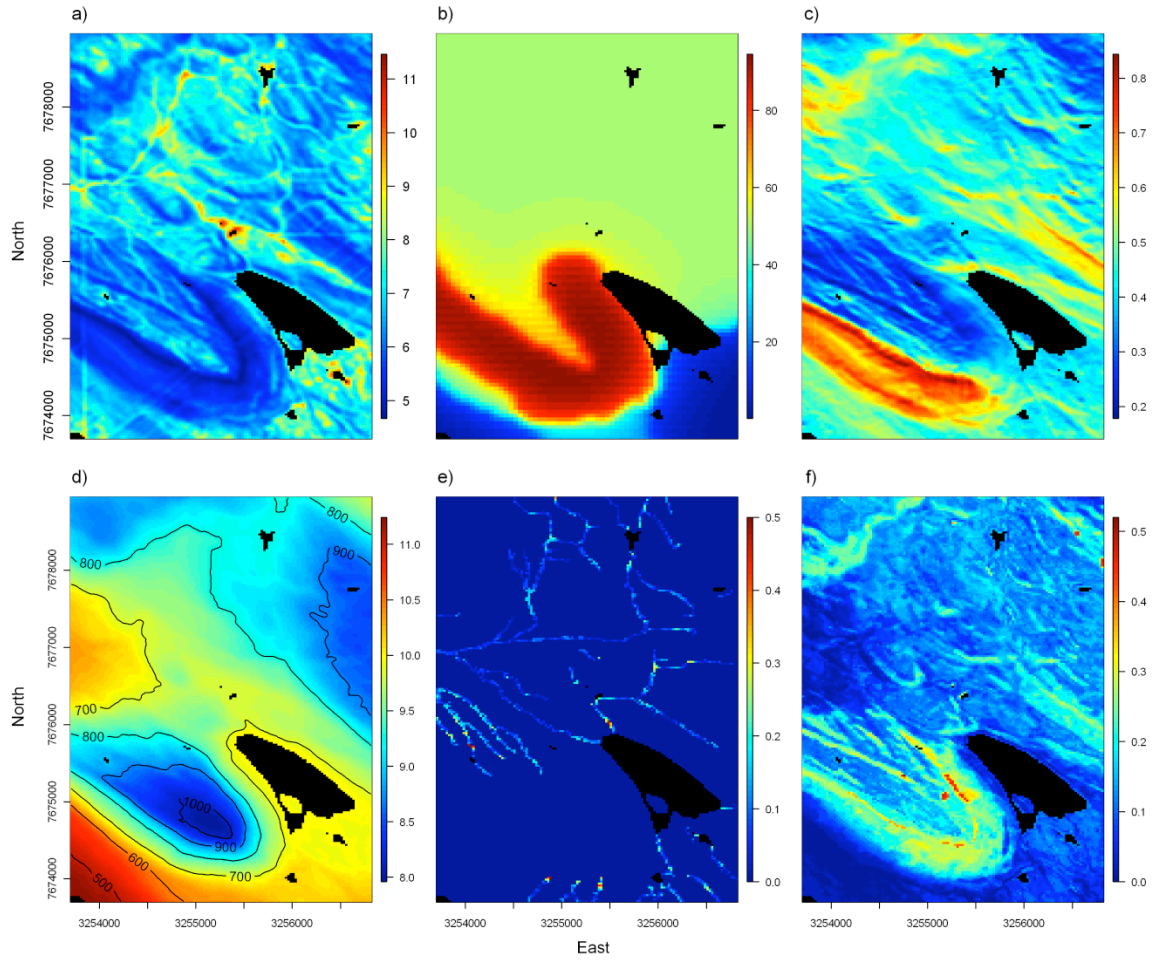


**Figure A3.** Spatial variation in environmental parameters used for species distribution predictions: a) soil moisture (topographic wetness index), b) soil quality (% calcareous), c) solar radiation (Mj/cm$^2$/a), d) mean temperature of the hottest month (°C), e) fluvial disturbance (proportion of area with active fluvial disturbance) and f) terrestrial disturbance (proportion of area with active terrestrial disturbance; see text for details). Latitude and longitude are indicated in the Finnish coordinate system. Black areas are lakes and ponds, and were masked during projections.

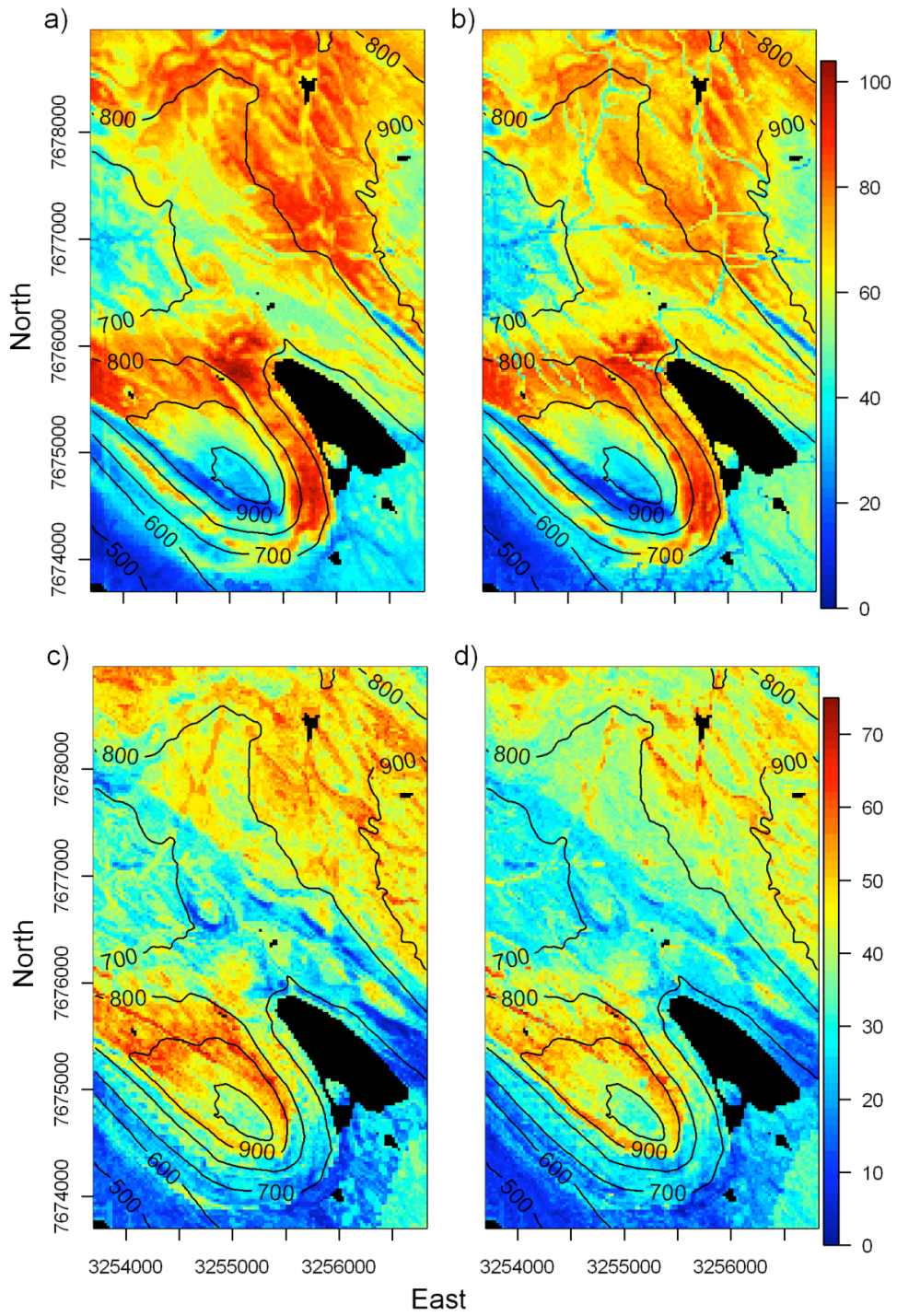


**Figure A4.** Total richness of the modeled species of vascular plants, bryophytes and lichens across a 3.1 x 5.2 km area in the centre of our study region, as calculated from the predictions for 154 individual species, using a) GAM simple models, b) GAM full models, c) BRT simple models, and d) BRT full models. Latitude and longitude are indicated in the Finnish coordinate system. Black areas are lakes and ponds.

**Table A2.** ANOVA test results comparing the performance of the simple (Presence/Absence = Soil moisture + Radiation + Soil quality + $Temp_{July}$) and full (Presence/Absence = Soil moisture + Radiation + Soil quality + $Temp_{July}$ + $Disturb_{terr}$ + $Disturb_{fluv}$) generalized additive (GAM) models for each modeled species. P values marked as "n.a." indicate where the best-fit full model used the same number (or fewer) degrees of freedom than the best-fit simple model and thus cannot be calculated (for both species with this result, the full model is considered superior to the simple model). Species or genera which could not confidently be assigned to an arctic-alpine or boreal distribution are reported as "n/a" and were excluded when splitting species by biogeographic distribution. Also reported is the form of each species GAM and BRT response curve for fluvial and terrestrial geomorphological disturbances.

| | | | | | | | GAM response curve | | BRT response curve | |
|---|---|---|---|---|---|---|---|---|---|---|
| Species | Presence records | Taxon | Biogeographic distribution | $Chi^2$ statistic | D.f. | p value | Fluvial disturbance | Terrestrial disturbance | Fluvial disturbance | Terrestrial disturbance |
| *Antennaria alpina* | 34 | vascular | arctic-alpine | 27.2 | 2.1 | < 0.001 | positive | positive | positive | positive |
| *Antennaria dioica* | 23 | vascular | boreal | 17.7 | 5.2 | 0.004 | negative | other | positive | positive |
| *Anthoxanthum odoratum* ssp. *alpinum* | 53 | vascular | arctic-alpine | 71.8 | 5.3 | < 0.001 | humped | positive | humped | positive |
| *Arctostaphylos alpina* | 24 | vascular | arctic-alpine | 9.3 | 4.0 | 0.054 | other | other | other | humped |
| *Astragalus alpinus* | 30 | vascular | arctic-alpine | 15.0 | 1.6 | < 0.001 | positive | positive | positive | positive |
| *Bartsia alpina* | 19 | vascular | arctic-alpine | 6.9 | 2.0 | 0.032 | positive | humped | positive | negative |

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|---|---|---|---|---|---|---|---|---|---|---|
| *Betula pubescens ssp.* | | | | | | | | | | |
| *czerepanovii* | 46 | vascular | boreal | 12.5 | 4.9 | 0.027 | positive | negative | other | other |
| *Betula nana* | 228 | vascular | boreal | 83.7 | 3.8 | < 0.001 | negative | negative | negative | negative |
| *Bistorta vivipara* | 106 | vascular | boreal | 25.8 | 0.0 | na | positive | positive | positive | positive |
| *Calamagrostis* | | | | | | | | | | |
| *lapponica* | 166 | vascular | boreal | 12.8 | 3.0 | 0.005 | negative | negative | other | negative |
| *Campanula* | | | | | | | | | | |
| *rotundifolia* | 37 | vascular | boreal | 6.4 | 3.7 | 0.144 | negative | other | other | other |
| *Cardamine bellidifolia* | 33 | vascular | arctic-alpine | 27.6 | 4.0 | < 0.001 | positive | positive | positive | positive |
| *Carex bigelowii* | 115 | vascular | arctic-alpine | 24.1 | 5.0 | < 0.001 | positive | other | positive | other |
| *Carex lachenalii* | 22 | vascular | arctic-alpine | 48.2 | 5.3 | < 0.001 | humped | other | other | other |
| *Carex vaginata* | 99 | vascular | boreal | 60.7 | 4.6 | < 0.001 | humped | other | positive | other |
| *Cassiope hypnoides* | 50 | vascular | arctic-alpine | 32.3 | 3.4 | < 0.001 | positive | positive | positive | positive |
| *Cassiope tetragona* | 138 | vascular | arctic-alpine | 34.9 | 4.9 | < 0.001 | other | humped | other | humped |
| *Cornus suecica* | 54 | vascular | boreal | 46.9 | 5.2 | < 0.001 | positive | negative | other | negative |
| *Deschampsia flexuosa* | 248 | vascular | boreal | 16.4 | 2.8 | 0.001 | humped | other | other | other |
| *Diapensia lapponica* | 35 | vascular | arctic-alpine | 23.6 | 4.3 | < 0.001 | other | humped | other | humped |

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| *Diphasiastrum alpinum* | 19 | vascular | arctic-alpine | 8.5 | 3.5 | 0.053 | negative | other | other | other |
| *Dryas octopetala* | 32 | vascular | arctic-alpine | 36.0 | 3.6 | < 0.001 | other | humped | positive | humped |
| *Empetrum nigrum ssp. hermaphroditum* | 478 | vascular | boreal | 104.8 | 5.4 | < 0.001 | other | negative | negative | negative |
| *Equisetum pratense* | 20 | vascular | boreal | 34.2 | 2.3 | < 0.001 | other | other | humped | other |
| *Equisetum scirpoides* | 21 | vascular | arctic-alpine | 28.5 | 3.8 | < 0.001 | other | other | other | other |
| *Festuca ovina* | 204 | vascular | boreal | 11.0 | 3.1 | 0.013 | negative | positive | other | positive |
| *Festuca vivipara* | 29 | vascular | arctic-alpine | 7.2 | 2.2 | 0.032 | positive | positive | positive | other |
| *Geranium sylvaticum* | 48 | vascular | boreal | 73.4 | 4.9 | < 0.001 | other | negative | positive | other |
| *Gnaphalium supinum* | 31 | vascular | arctic-alpine | 62.3 | 2.8 | < 0.001 | positive | positive | positive | positive |
| *Hieracium spp.* | 94 | vascular | n/a | 15.5 | 2.8 | 0.001 | humped | other | positive | positive |
| *Huperzia selago* | 70 | vascular | boreal | 25.8 | 5.9 | < 0.001 | positive | humped | positive | humped |
| *Juniperus communis* | 106 | vascular | boreal | 11.9 | 4.3 | 0.022 | positive | negative | other | negative |
| *Juncus triglumis* | 94 | vascular | arctic-alpine | 6.7 | 2.8 | 0.071 | negative | other | other | humped |
| *Linnaea borealis* | 237 | vascular | boreal | 40.5 | 4.4 | < 0.001 | other | negative | other | negative |
| *Loiseleuria* | 22 | vascular | arctic-alpine | 19.6 | 4.6 | 0.001 | negative | other | other | humped |

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| *procumbens* | | | | | | | | | | |
| *Luzula confusa* | 65 | vascular | arctic-alpine | 7.7 | 2.8 | 0.046 | other | other | other | positive |
| *Luzula pilosa* | 20 | vascular | boreal | 12.3 | 3.2 | 0.008 | other | other | other | other |
| *Luzula spicata* | 26 | vascular | arctic-alpine | 8.9 | 3.8 | 0.055 | other | positive | positive | positive |
| *Lycopodium* | | | | | | | | | | |
| *annotinum* | 60 | vascular | boreal | 18.8 | 3.3 | < 0.001 | negative | negative | other | negative |
| *Melampyrum pratense* | 42 | vascular | boreal | 4.9 | 2.7 | 0.153 | other | other | positive | other |
| *Melampyrum* | | | | | | | | | | |
| *sylvaticum* | 19 | vascular | boreal | 26.6 | 3.8 | < 0.001 | other | other | other | other |
| *Oxyria digyna* | 20 | vascular | arctic-alpine | 22.3 | 0.6 | < 0.001 | positive | positive | positive | positive |
| *Pedicularis lapponica* | 98 | vascular | boreal | 5.9 | 1.5 | 0.032 | other | negative | other | negative |
| *Phyllodoce caerulea* | 115 | vascular | arctic-alpine | 7.5 | 2.7 | 0.047 | positive | positive | positive | positive |
| *Poa alpina* | 17 | vascular | arctic-alpine | 25.5 | 2.9 | < 0.001 | positive | positive | positive | positive |
| *Pyrola minor* | 19 | vascular | boreal | 24.3 | 1.6 | < 0.001 | positive | positive | positive | other |
| *Ranunculus glacialis* | 15 | vascular | arctic-alpine | 30.6 | 3.7 | < 0.001 | other | positive | positive | positive |
| *Salix glauca* | 51 | vascular | boreal | 19.1 | 4.3 | 0.001 | positive | negative | positive | other |
| *Salix hastata* | 27 | vascular | boreal | 52.7 | 7.4 | < 0.001 | positive | negative | positive | other |

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| *Salix herbacea* | 127 | vascular | arctic-alpine | 21.6 | 3.2 | < 0.001 | other | positive | other | positive |
| *Salix polaris* | 72 | vascular | arctic-alpine | 37.8 | 3.9 | < 0.001 | positive | positive | positive | positive |
| *Saussurea alpina* | 54 | vascular | arctic-alpine | 60.1 | -1.1 | na | positive | positive | positive | positive |
| *Saxifraga oppositifolia* | 16 | vascular | arctic-alpine | 5.9 | 0.4 | 0.005 | positive | humped | positive | other |
| *Selaginella selaginoides* | 31 | vascular | boreal | 49.9 | 4.4 | < 0.001 | positive | positive | positive | positive |
| *Silene acaulis* | 24 | vascular | arctic-alpine | 15.2 | 2.8 | 0.001 | other | positive | positive | other |
| *Solidago virgaurea* | 161 | vascular | boreal | 25.4 | 4.4 | < 0.001 | humped | other | other | positive |
| *Taraxacum* spp. | 26 | vascular | n/a | 73.6 | 3.6 | < 0.001 | positive | positive | positive | positive |
| *Thalictrum alpinum* | 32 | vascular | arctic-alpine | 58.9 | 3.5 | < 0.001 | positive | positive | positive | positive |
| *Trientalis europaea* | 108 | vascular | boreal | 23.4 | 2.2 | < 0.001 | humped | negative | other | negative |
| *Trollius europaeus* | 37 | vascular | boreal | 40.5 | 1.6 | < 0.001 | positive | positive | humped | positive |
| *Vaccinium myrtillus* | 258 | vascular | boreal | 2.3 | 2.1 | 0.344 | other | other | other | negative |
| *Vaccinium uliginosum* | 219 | vascular | boreal | 32.0 | 4.1 | < 0.001 | other | other | positive | humped |
| *Vaccinium vitis-idaea* | 500 | vascular | boreal | 61.1 | 3.7 | < 0.001 | negative | negative | negative | negative |
| *Viola biflora* | 78 | vascular | arctic-alpine | 84.9 | 5.1 | < 0.001 | positive | positive | positive | positive |
| *Anastrophyllum* | 86 | bryophyte | arctic-alpine | 5.5 | 2.7 | 0.116 | negative | other | negative | other |

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| *minutum* | | | | | | | | | | |
| *Andreaea rupestris* | 110 | bryophyte | boreal | 24.3 | 2.3 | < 0.001 | other | humped | other | negative |
| *Anthelia juratzkana* | 79 | bryophyte | arctic-alpine | 37.7 | 5.5 | < 0.001 | positive | positive | positive | positive |
| *Arctoa fulvella* | 25 | bryophyte | arctic-alpine | 16.8 | 5.4 | 0.007 | negative | humped | other | other |
| *Barbilophozia* | | | | | | | | | | |
| *attenuata* | 22 | bryophyte | boreal | 7.0 | 2.8 | 0.062 | other | negative | other | negative |
| *Barbilophozia* spp. | 27 | bryophyte | n/a | 4.5 | 2.9 | 0.194 | negative | negative | other | negative |
| *Barbilophozia hatcheri* | 58 | bryophyte | boreal | 16.9 | 3.6 | 0.001 | other | positive | positive | positive |
| *Barbilophozia* | | | | | | | | | | |
| *lycopodioides* | 220 | bryophyte | boreal | 39.0 | 5.5 | < 0.001 | humped | negative | other | negative |
| *Blepharostoma* | | | | | | | | | | |
| *trichophyllum* | 20 | bryophyte | boreal | 13.6 | 3.1 | 0.004 | positive | positive | positive | other |
| *Bryum* spp. | 28 | bryophyte | n/a | 17.5 | 2.9 | < 0.001 | negative | positive | other | positive |
| *Conostomum* | | | | | | | | | | |
| *tetragonum* | 29 | bryophyte | arctic-alpine | 6.2 | 3.0 | 0.101 | humped | other | other | other |
| *Dicranoweisia crispula* | 25 | bryophyte | arctic-alpine | 10.7 | 3.6 | 0.022 | humped | other | other | other |
| *Dicranum elongatum* | 29 | bryophyte | arctic-alpine | 4.4 | 2.0 | 0.108 | negative | other | other | other |

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|---|---|---|---|---|---|---|---|---|---|---|
| *Dicranum fuscescens* | 394 | bryophyte | boreal | 52.9 | 2.7 | < 0.001 | negative | negative | negative | negative |
| *Dicranum scoparium* | 182 | bryophyte | boreal | 5.2 | 2.3 | 0.097 | negative | other | other | negative |
| *Dicranum spadiceum* | 37 | bryophyte | arctic-alpine | 14.0 | 3.7 | 0.006 | other | humped | other | other |
| *Diplophyllum taxifolium* | 42 | bryophyte | boreal | 7.5 | 3.2 | 0.065 | positive | humped | positive | humped |
| *Gymnomitrion concinnatum* | 109 | bryophyte | arctic-alpine | 6.0 | 2.5 | 0.077 | other | positive | other | other |
| *Gymnomitrion corallioides* | 78 | bryophyte | arctic-alpine | 23.5 | 2.9 | < 0.001 | negative | humped | negative | humped |
| *Hepaticae* spp. | 97 | bryophyte | n/a | 2.5 | 2.8 | 0.429 | other | other | positive | other |
| *Hylocomium splendens* | 206 | bryophyte | boreal | 28.0 | 0.4 | < 0.001 | positive | other | positive | negative |
| *Kiaeria starkei* | 15 | bryophyte | arctic-alpine | 15.1 | 2.7 | 0.001 | negative | positive | positive | other |
| *Lophozia sudetica* | 63 | bryophyte | boreal | 31.4 | 4.7 | < 0.001 | humped | positive | positive | positive |
| *Lophozia ventricosa* | 25 | bryophyte | boreal | 6.0 | 4.2 | 0.221 | negative | positive | other | positive |
| *Oligotrichum hercynicum* | 19 | bryophyte | arctic-alpine | 12.8 | 4.1 | 0.013 | other | positive | positive | positive |

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|---|---|---|---|---|---|---|---|---|---|---|
| *Pleurocladula albescens* | 19 | bryophyte | arctic-alpine | 23.5 | 4.5 | < 0.001 | positive | positive | positive | positive |
| *Pleurozium schreberi* | 238 | bryophyte | boreal | 15.0 | 2.3 | 0.001 | negative | negative | negative | negative |
| *Pogonatum dentatum* | 65 | bryophyte | arctic-alpine | 14.4 | 3.6 | 0.004 | positive | positive | positive | other |
| *Pohlia cruda* | 23 | bryophyte | boreal | 8.3 | 2.0 | 0.015 | other | positive | positive | other |
| *Pohlia spp.* | 42 | bryophyte | n/a | 20.4 | 2.4 | < 0.001 | positive | positive | positive | positive |
| *Pohlia nutans* | 97 | bryophyte | boreal | 2.0 | 2.3 | 0.440 | positive | positive | other | humped |
| *Polytrichastrum alpinum* | 68 | bryophyte | arctic-alpine | 27.8 | 3.9 | < 0.001 | other | positive | positive | positive |
| *Polytrichum commune* | 150 | bryophyte | boreal | 14.9 | 2.1 | 0.001 | other | other | other | negative |
| *Polytrichum hyperboreum* | 96 | bryophyte | arctic-alpine | 17.9 | 3.0 | < 0.001 | negative | humped | other | humped |
| *Polytrichum juniperinum* | 171 | bryophyte | boreal | 22.1 | 3.9 | < 0.001 | negative | negative | negative | negative |
| *Polytrichum piliferum* | 76 | bryophyte | boreal | 4.8 | 2.4 | 0.122 | negative | positive | other | other |
| *Polytrichastrum sexangulare* | 17 | bryophyte | arctic-alpine | 17.2 | 2.8 | 0.001 | positive | other | other | positive |

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|---|---|---|---|---|---|---|---|---|---|---|
| *Polytrichum strictum* | 26 | bryophyte | boreal | 4.4 | 2.7 | 0.191 | negative | negative | other | other |
| *Ptilidium ciliare* | 202 | bryophyte | boreal | 64.9 | 4.4 | < 0.001 | negative | humped | negative | humped |
| *Racomitrium lanuginosum* | 93 | bryophyte | boreal | 44.4 | 4.0 | < 0.001 | negative | humped | negative | humped |
| *Sanionia uncinata* | 69 | bryophyte | boreal | 26.8 | 3.3 | < 0.001 | positive | positive | positive | positive |
| *Sciuro-hypnum reflexum* | 52 | bryophyte | boreal | 16.1 | 2.2 | < 0.001 | humped | other | humped | other |
| *Tetralophozia setiformis* | 72 | bryophyte | arctic-alpine | 40.7 | 2.7 | < 0.001 | negative | humped | negative | humped |
| *Tritomaria quinquedentata* | 38 | bryophyte | boreal | -0.1 | 1.3 | 0.950 | positive | positive | positive | other |
| *Alectoria ochroleuca* | 74 | lichen | arctic-alpine | 26.7 | 3.6 | < 0.001 | other | humped | negative | humped |
| *Bryocaulon divergens* | 55 | lichen | arctic-alpine | 22.4 | 3.7 | < 0.001 | negative | other | other | humped |
| *Cetraria crispiformis* | 170 | lichen | boreal | 1.7 | 2.0 | 0.416 | negative | positive | other | other |
| *Cetrariella delisei* | 39 | lichen | boreal | 18.3 | 6.2 | 0.006 | other | positive | other | positive |
| *Cetraria ericetorum* | 91 | lichen | boreal | 13.4 | 1.0 | < 0.001 | negative | other | negative | humped |
| *Cetraria islandica* | 84 | lichen | boreal | 5.0 | 2.6 | 0.135 | negative | other | negative | other |

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|---|---|---|---|---|---|---|---|---|---|---|
| *Cetraria nigricans* | 27 | lichen | arctic-alpine | 18.3 | 2.0 | < 0.001 | negative | other | other | humped |
| *Cladonia bellidiflora* | 53 | lichen | boreal | 12.5 | 1.8 | 0.002 | negative | other | negative | other |
| *Cladonia borealis* | 89 | lichen | boreal | 26.4 | 4.4 | < 0.001 | other | humped | negative | humped |
| *Cladonia chlorophaea* | 77 | lichen | boreal | 18.0 | 4.2 | 0.002 | other | other | other | other |
| *Cladonia cornuta* | 47 | lichen | boreal | 3.6 | 2.8 | 0.281 | negative | positive | other | other |
| *Cladonia crispata* | 64 | lichen | boreal | 28.0 | 4.3 | < 0.001 | negative | other | other | humped |
| *Cladonia deformis* | 68 | lichen | boreal | 1.7 | 2.1 | 0.434 | negative | positive | other | positive |
| *Cladonia digitata* | 94 | lichen | boreal | 8.2 | 2.7 | 0.032 | negative | negative | other | negative |
| *Cladonia ecmocyna* | 34 | lichen | boreal | 19.5 | 3.1 | < 0.001 | other | other | positive | negative |
| *Cladonia gracilis* | 366 | lichen | boreal | 48.7 | 2.9 | < 0.001 | negative | other | negative | humped |
| *Cladonia maxima* | 30 | lichen | boreal | 10.9 | 1.3 | 0.002 | negative | negative | other | negative |
| *Cladonia merochlorophaea* | 85 | lichen | boreal | 11.5 | 3.3 | 0.012 | negative | other | negative | humped |
| *Cladonia mitis* | 382 | lichen | boreal | 50.6 | 1.8 | < 0.001 | other | other | negative | humped |
| *Cladonia pleurota* | 143 | lichen | boreal | 15.8 | 2.0 | < 0.001 | negative | other | negative | other |
| *Cladonia pyxidata* | 139 | lichen | boreal | 11.7 | 3.9 | 0.019 | negative | other | negative | positive |
| *Cladonia rangiferina* | 311 | lichen | boreal | 31.8 | 1.9 | < 0.001 | negative | negative | negative | humped |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Cladonia squamosa* | 21 | lichen | boreal | 3.0 | 1.6 | 0.168 | positive | positive | positive | positive |
| *Cladonia stellaris* | 25 | lichen | boreal | 12.2 | 3.4 | 0.010 | negative | other | other | other |
| *Cladonia subfurcata* | 23 | lichen | arctic-alpine | 8.3 | 3.8 | 0.073 | other | positive | other | humped |
| *Cladonia sulphurina* | 131 | lichen | boreal | 20.8 | 3.5 | < 0.001 | other | negative | negative | negative |
| *Cladonia uncialis* | 244 | lichen | boreal | 30.3 | 2.3 | < 0.001 | negative | negative | negative | humped |
| *Crustose lichen* | 62 | lichen | n/a | 24.0 | 3.7 | < 0.001 | negative | other | other | other |
| *Flavocetraria cucullata* | 195 | lichen | arctic-alpine | 56.6 | 2.6 | < 0.001 | negative | humped | negative | humped |
| *Flavocetraria nivalis* | 175 | lichen | arctic-alpine | 92.0 | 4.6 | < 0.001 | negative | humped | negative | humped |
| *Gowardia nigricans* | 80 | lichen | arctic-alpine | 24.1 | 3.0 | < 0.001 | negative | humped | negative | humped |
| *Nephroma arcticum* | 89 | lichen | boreal | 5.1 | 2.8 | 0.139 | negative | negative | other | negative |
| *Ochrolechia frigida* | 154 | lichen | boreal | 36.8 | 4.8 | < 0.001 | other | humped | negative | humped |
| *Peltigera apthosa* | 63 | lichen | boreal | 4.1 | 2.7 | 0.216 | negative | other | other | other |
| *Peltigera leucophlebia* | 24 | lichen | boreal | 27.6 | 2.2 | < 0.001 | positive | positive | positive | positive |
| *Peltigera malacea* | 37 | lichen | boreal | 8.0 | 3.0 | 0.045 | negative | humped | other | humped |
| *Peltigera rufescens* | 16 | lichen | boreal | 7.8 | 2.1 | 0.022 | negative | other | other | other |
| *Peltigera scabrosa* | 23 | lichen | boreal | 12.3 | 3.2 | 0.008 | negative | negative | other | negative |
| *Pertusaria dactylina* | 117 | lichen | arctic-alpine | 28.4 | 1.5 | < 0.001 | negative | humped | negative | humped |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Pseudephebe pubescens* | 25 | lichen | arctic-alpine | 9.8 | 4.8 | 0.072 | negative | humped | other | other |
| *Psoroma hypnorum* | 22 | lichen | boreal | 5.5 | 2.0 | 0.060 | negative | positive | negative | positive |
| *Solorina crocea* | 60 | lichen | arctic-alpine | 35.8 | 4.7 | < 0.001 | negative | positive | other | positive |
| *Sphaerophorus globosus* | 108 | lichen | arctic-alpine | 35.8 | 2.6 | < 0.001 | negative | humped | negative | humped |
| *Stereocaulon* spp. | 196 | lichen | n/a | 17.1 | 3.7 | 0.001 | other | positive | other | humped |
| *Thamnolia vermicularis* | 87 | lichen | arctic-alpine | 29.2 | 3.8 | < 0.001 | negative | negative | negative | negative |
| *Umbilicaria* spp. | 43 | lichen | n/a | 34.2 | 1.9 | < 0.001 | other | other | positive | other |

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**Table A3.** Results from Wilcoxon's matched pairs test, testing if the explanatory accuracy and predictive power of full models (see Table A2) differs from that of simple models (containing only topography, soil and climate variables), repeating the analysis for subsets of species based on taxon (vascular species, bryophytes or lichens) or biogeographic distribution (arctic-alpine or boreal), using both generalized additive models (GAM) and boosted regression trees (BRT). Explanatory accuracy is assessed with adjusted $R^2$ (GAM) and predictive deviance ("Pred. dev."; BRT), and predictive power with AUC and TSS. Differences that remain significant after Bonferroni correction are indicated with an asterisk (adjusted alpha level = 0.05 / 10).

| Species group | Metric | n | Simple model | Full model | Wilcoxon V | p | % of species where full model superior |
|---|---|---|---|---|---|---|---|
| Generalized additive models | | | | | | | |
| Vascular | Adjusted $R^2$ | 64 | 22.6 ± 1.7 | 32.2 ± 1.7 | 0 | < 0.001* | 100 % |
| | AUC | 64 | 85.3 ± 0.9 | 88.2 ± 0.8 | 253 | < 0.001* | 78 % |
| | TSS | 64 | 56.4 ± 2.0 | 60.1 ± 1.9 | 670 | < 0.001* | 61 % |
| Bryophyte | Adjusted $R^2$ | 44 | 17.1 ± 1.8 | 21.3 ± 1.9 | 2 | < 0.001* | 98 % |
| | AUC | 44 | 81.0 ± 1.2 | 82.2 ± 1.2 | 268 | < 0.001* | 70 % |
| | TSS | 44 | 50.1 ± 2.3 | 51.3 ± 2.5 | 361 | < 0.001* | 59 % |
| Lichen | Adjusted $R^2$ | 46 | 17.5 ± 1.7 | 20.8 ± 1.9 | 11 | < 0.001* | 93 % |
| | AUC | 46 | 79.9 ± 1.2 | 81.6 ± 1.1 | 135 | < 0.001* | 83 % |
| | TSS | 46 | 44.4 ± 2.5 | 48.6 ± 2.3 | 183 | < 0.001* | 76 % |
| Arctic-alpine | Adjusted $R^2$ | 60 | 19.3 ± 1.3 | 27.0 ± 1.4 | 0 | < 0.001* | 100 % |
| | AUC | 60 | 84.7 ± 0.9 | 87.1 ± 0.8 | 240 | < 0.001* | 83 % |
| | TSS | 60 | 55.4 ± 2.0 | 58.5 ± 1.9 | 539 | < 0.001* | 63 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Boreal | Adjusted $R^2$ | 84 | 20.6 ± 1.6 | 25.6 ± 1.7 | 20 | < 0.001* | 95 % |
| | AUC | 84 | 81.4 ± 0.9 | 83.1 ± 0.9 | 676 | < 0.001* | 71 % |
| | TSS | 84 | 48.7 ± 1.9 | 51.5 ± 1.8 | 987 | < 0.001* | 67 % |
| Boosted regression trees | | | | | | | |
| Vascular | Pred. dev. | 64 | 36.3 ± 1.7 | 35.9 ± 1.7 | 1258 | 0.146 | 61 % |
| | AUC | 64 | 88.4 ± 0.9 | 90.2 ± 0.8 | 276 | 0.369 | 78 % |
| | TSS | 64 | 53.0 ± 2.4 | 59.2 ± 2.2 | 334 | 0.303 | 70 % |
| Bryophyte | Pred. dev. | 44 | 51.2 ± 1.9 | 50.4 ± 1.9 | 566 | 0.414 | 52 % |
| | AUC | 44 | 83.8 ± 1.1 | 84.9 ± 1.1 | 212 | 0.263 | 73 % |
| | TSS | 44 | 46.3 ± 2.6 | 47.3 ± 2.8 | 266 | 0.117 | 66 % |
| Lichen | Pred. dev. | 46 | 55.0 ± 1.9 | 52.5 ± 2.1 | 907 | < 0.001* | 83 % |
| | AUC | 46 | 82.7 ± 1.2 | 83.9 ± 1.2 | 61 | < 0.001* | 85 % |
| | TSS | 46 | 44.7 ± 2.7 | 46.4 ± 2.7 | 411 | 0.006 | 67 % |
| Arctic-alpine | Pred. dev. | 60 | 42.9 ± 1.5 | 41.1 ± 1.4 | 1256 | 0.012 | 62 % |
| | AUC | 60 | 87.1 ± 0.9 | 89.1 ± 0.7 | 219 | 0.013 | 85 % |
| | TSS | 60 | 49.8 ± 2.4 | 55.5 ± 2.3 | 371 | 0.023 | 73 % |
| Boreal | Pred. dev. | 84 | 47.8 ± 1.9 | 46.9 ± 1.9 | 2438 | 0.004 | 69 % |
| | AUC | 84 | 84.7 ± 0.9 | 85.7 ± 0.9 | 475 | 0.040 | 75 % |
| | TSS | 84 | 49.0 ± 2.1 | 50.8 ± 2.1 | 1017 | 0.052 | 67 % |

**Table A4.** Percentage of species (split by taxon or biogeographic distribution) exhibiting positive, negative or humped-shape response curves to increasing fluvial and terrestrial geomorphological disturbances (see Table S1 for raw data). For boosted regression trees (BRT) stepped response curves were classified as positive or negative if they changed monotonically, but for generalized additive models (GAM) response curves had to be approximately linear to be classed in either of those categories. Pairwise $Chi^2$ tests were used to assess the significance of differences in the numbers of species per response curve category, after accounting for unequal numbers of species per species group. Where the humped-shape category contained cells with less than five observations (i.e. GAM and BRT analyses of fluvial disturbance), this category was combined with the "Other" class prior to analysis.

| | | | | | Pairwise $Chi^2$ tests | | | |
|---|---|---|---|---|---|---|---|---|
| Species | Positive (%) | Negative (%) | Hump-shape (%) | Other (%) | Comparison | $Chi^2$ | d.f. | p |
| GAM: Fluvial disturbance response curves | | | | | | | | |
| All | 26 | 40 | 8 | 27 | | | | |
| Vascular spp | 42 | 16 | 11 | 31 | Vasc. vs Bryo. | 31.7 | 2 | < 0.001 |
| Bryophytes | 25 | 41 | 11 | 23 | Vasc. vs. Lich. | 155.8 | 2 | < 0.001 |
| Lichens | 4 | 72 | 0 | 24 | Bryo. vs. Lich. | 53.2 | 2 | < 0.001 |
| Arctic-alpine | 33 | 33 | 7 | 27 | Arc. vs. Bor. | 7.8 | 2 | 0.020 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Boreal | 21 | 44 | 8 | 26 | | | | |
| GAM: Terrestrial disturbance response curves | | | | | | | | |
| All | 34 | 19 | 16 | 31 | | | | |
| Vascular spp | 38 | 22 | 9 | 31 | Vasc. vs Bryo. | 11.1 | 3 | 0.011 |
| Bryophytes | 41 | 16 | 20 | 23 | Vasc. vs. Lich. | 16.5 | 3 | 0.001 |
| Lichens | 22 | 17 | 22 | 39 | Bryo. vs. Lich. | 11.0 | 3 | 0.012 |
| Arctic-alpine | 45 | 2 | 28 | 25 | Arc. vs. Bor. | 73.5 | 3 | < 0.001 |
| Boreal | 24 | 32 | 10 | 35 | | | | |
| BRT: Fluvial disturbance response curves | | | | | | | | |
| All | 34 | 21 | 3 | 42 | | | | |
| Vascular spp | 52 | 5 | 5 | 39 | Vasc. vs Bryo. | 27.8 | 2 | < 0.001 |
| Bryophytes | 36 | 18 | 2 | 43 | Vasc. vs. Lich. | 252.0 | 2 | < 0.001 |
| Lichens | 9 | 46 | 0 | 46 | Bryo. vs. Lich. | 48.1 | 2 | < 0.001 |
| Arctic-alpine | 43 | 17 | 2 | 38 | Arc. vs. Bor. | 13.4 | 2 | 0.001 |
| Boreal | 26 | 26 | 4 | 44 | | | | |
| BRT: Terrestrial disturbance response curves | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| All | 28 | 19 | 23 | 31 | | | | |
| Vascular spp | 39 | 19 | 13 | 30 | Vasc. vs Bryo. | 5.3 | 3 | 0.149 |
| Bryophytes | 25 | 23 | 16 | 36 | Vasc. vs. Lich. | 59.2 | 3 | < 0.001 |
| Lichens | 15 | 15 | 43 | 26 | Bryo. vs. Lich. | 14.5 | 3 | 0.002 |
| Arctic-alpine | 38 | 3 | 30 | 28 | Arc. vs. Bor. | 46.1 | 3 | < 0.001 |
| Boreal | 18 | 31 | 19 | 32 | | | | |