Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests

Thomas Dirnböck, Gisela Pröll, Kari Austnes, Jelena Beloica, Burkhard Beudert, Roberto Canullo, Alessandra De Marco, Maria Francesca Fornasier, Martyn Futter, Klaus Goergen, Ulf Grandin, Maria Holmberg, Antti-Jussi Lindroos, Michael Mirtl, Johan Neirynck, Tomasz Pecka, Tiina Maileena Nieminen, Jørn-Frode Nordbakken, Maximilian Posch, Gert-Jan Reinds, Ed Rowe, Maija Salemaa, Thomas Scheuschner, Franz Starlinger, Aldona Katarzyna Uziębło, Salar Valinia, James Weldon, Wieger G.W. Wamelink, Martin Forsius

S1. Sites with EUNIS habitat type and phytosociological syntaxa used to define diagnostic species

S2. Methodological details and model validation

S3. Site-specific diagnostic species according to phytosociological plant community descriptions. The related plant communities can be found in S1 Table 1. Note, that only those species present in the observations were selected for modelling.

S4 Figure 1. Soil chemical changes under the RCP 8.5 scenario

S5 Table 1. Changes in the indicator species groups between 2015 and 2050
S1 Table 1. Sites with EUNIS habitat type and phytosociological syntaxa used to define diagnostic species. Where available, a link to the vegetation observation data is given in the footnotes.

| Site ID | Country   | Site Name                          | Altitude (m asl) | EUNIS | Phytosociological syntaxa                                                                 |
|---------|-----------|------------------------------------|------------------|-------|------------------------------------------------------------------------------------------|
| AT09    | Austria   | Klausen-Leopoldsdorf               | 510              | G1.6  | Hordelymo-Fagetum sylvatici TX. 1937 (Dryopteris-Subass.)                                 |
| IT05    | Italy     | Selvapiana                         | 1500             | G1.6  | Asperulo-Abieti-Fagetum sylvatici (typ. Subass.) Th. Müller 1964                         |
| IT08    | Italy     | Brasimone                          | 975              | G1.6  | Daphno laureolae-Fagetum sylvatici Horánzki 1964                                          |
| PL03    | Poland    | Tatrański National Park            | 1100             | G1.612| Dentario glandulosae-Fagetum W. Mat. 1964 ex Guzikowa & Kornaś 1969                       |
| IT07    | Italy     | Carrega                            | 200              | G1.7  | Castaneo-Quercetum mediterraneum Wraber 1954                                             |
| IT09    | Italy     | Monte Rufeno                       | 690              | G1.7  | Erythronio-Carpinetum betuli Horvat 1938                                                 |
| PL01    | Poland    | Puszcza Borecka                    | 170              | G1.A1 | Tilio cordatae-Carpinetum betuli Tracz. 1962                                             |
| GB54    | United Kingdom | Wytham                       | 138              | G1.A22| Fraxinus excelsior-Acer campestre-Mercurialis perennis woodland (UK National Vegetation Classification) |
| GB55    | United Kingdom | Alice Holt               | 125              | G1.A22| Fraxinus excelsior-Acer campestre-Mercurialis perennis woodland (UK National Vegetation Classification) |
| SE14    | Sweden    | Aneboda                            | 230              | G3.1  | Vaccinio myrtilli-Piceetum TX. 1955                                                      |
| AT16    | Austria   | Murau                              | 1540             | G3.1B | Homogyno alpinae-Piceetum (Rhytidiadelphus loreus-Subass.) Zukrigl 1973                   |
| RS01    | Serbia    | Kopaonik                           | 1700             | G3.1E5| Piceetum excelsae serbicum Rudski 1947 oxalidetosum Mišić et Popović 1960                |
| PL02    | Poland    | Słowiński National Park            | 5                | G3.424| Empetro nigri-Pinetum (Libb. et Siss. 1939 n.n.) Wojt. 1964                             |

1 https://deims.org/dataset/28fe3227-fb9f-4e73-9a2a-30c07e90104d
2 https://deims.org/dataset/a3360bdb-e864-4d3e-ab8d-5c42c0372a95
3 https://deims.org/dataset/e6ada5c2-d386-450c-b1d5-908ed45b0677
4 https://deims.org/dataset/81014905-5615-45d9-8b83-e48bf66f30b2
5 https://deims.org/dataset/af7a051d-3e9e-4cae-a085-b49566ac4ea3
6 https://deims.org/dataset/527a28a3-c229-4d9f-b1ca-2abb97932785
7 https://deims.org/dataset/de2ee7a71-6bc6-45b1-bf65-6377aa996fa0
8 https://deims.org/dataset/933c3f23-f149-440f-885e-1f6f5003e502
| Code | Country | Location | Plot Size | Subtype Code | Subtype Description |
|------|---------|----------|-----------|--------------|---------------------|
| FI01 | Finland | Valkea-Kotinen | 165 | G3.A | Vaccinio myrtilli-Piceetum Tx. 1955 |
| NO01 | Norway | Birkenes | 190 | G3.A | Eu-Piceetum myrtilletosum (Corno-Betuletum myrtilletosum) |
| SE15 | Sweden | Kindla | 345 | G3.A | Vaccinio myrtilli-Piceetum Tx. 1955 |
| SE16 | Sweden | Gammtratten | 425 | G3.A | Vaccinio myrtilli-Piceetum Tx. 1955 |
| FI03 | Finland | Hietajärvi | 170 | G3.B2 | Vaccinio vitis-idaea-Pinetum sylvestris Mayer et Hoffmann 1969 |
| BE01 | Belgium | Brasschaat | 14 | G3.F1 | Quercion robori-petraeae Noirfalise (1984) (MCVM, AFPA, LPOA Subtypes according to (De Keersmaeker et al. 2013)) |
| AT01 | Austria | Zöbelboden IP1 | 895 | G4.6 | Cardamino trifoliae-Fagetum sensu Willner 2002 |
| AT02 | Austria | Zöbelboden IP2 | 879 | G4.6 | Adenostylo glabrae-Fagetum sensu Willner 2002 |
| DE01 | Germany | Forellenbach | 894 | G4.6 | Luzulo-Abietetum (Athyrium-Subass.) Oberdorfer 1957 |
| IT10 | Italy | Val Masino | 1190 | G4.6 | Adenostylo glabrae-Abietetum Mayer 1969 |

This study additionally included one study plot (AT02) from the LTER study site “Zöbelboden”, which was part of a previous modelling study, see Dirnböck et al. (2017). See observation data at https://deims.org/dataset/91fbdffa-0cac-46b6-9311-000aa58c6f33

9 https://deims.org/dataset/c212c5ed-f4a6-4d41-8e02-05a6e56b51f2
10 https://deims.org/dataset/5e7965e8-cd25-4e18-9c44-527c9ca3b6d9
11 https://deims.org/dataset/c619fad8-e00c-4107-bfcc-b8759c762fca
12 https://deims.org/dataset/dad3e1c9-d949-4064-acb3-6e903938261f
13 https://deims.org/dataset/d2bdf0-d272-433b-8fce-ead75e15bd29
14 https://deims.org/dataset/91fbdffa-0cac-46b6-9311-000aa58c6f33
15 https://deims.org/dataset/91fbdffa-0cac-46b6-9311-000aa58c6f33
16 https://deims.org/dataset/c5b1d602-972f-4217-8cde-b33d6e892507
17 https://deims.org/dataset/67727a8a-fe1f-44eb-88b5-bf98bc443104
S2. Methodological details and model validation

Forest understory vegetation

Forest vegetation was recorded on permanent monitoring plots (hereafter called study plots) with different observation intervals (from annual to several years) and sub-sampling unit (hereafter called sampling units) sizes. Whereas study plots were selected subjectively to be representative of the forest monitoring sites, sampling units are arranged by probabilistic sampling designs. Species cover was estimated by visual assessment of the projection surface for each vascular plant and for bryophyte species (as the percentage of the sampling unit surface). Bryophytes were considered for analyses if they covered > 5% per study plot and occurred in > 50% of the sampling units. For the UK sites, species cover was calculated from incidence-frequency (as a proportion: 0.5 * number of sampling units including that given species / number of sampling units without that species). Long-term records of species cover between 1983 and 2017 were used to compare observed versus modelled trends in forest understory vegetation. Scientific nomenclature for plants was standardized using the R package “Taxonstand” version 2.1 (Cayuela et al. 2012).

N, S, and base cation deposition

Site-specific values for the deposition of S and N were obtained both for historic (1880-2005) and future periods. Deposition values for 2010, 2020 and 2030 were based on the EMEP model (Simpson et al. 2012), using the current legislation scenario (CLE), and were scaled with measured deposition data. The CLE scenario includes the pre- and post-2014 regulations implemented in GAINS (http://gains.iiasa.ac.at/gains/EUN/index.login?logout=1, Scenario group “EU Outlook 2017”, “REF_post2014_CLE”). The historic deposition values are based on older EMEP model versions (Schöpp et al. 2003). In addition to the CLE scenario a baseline scenario with no further change in N deposition after the year 2010 was used for comparisons (B10 scenario). The average measured base cation deposition was used. The deposition scenario data was not corrected for future changes in precipitation.

S2 Figure 1. Trends in a) total S deposition in the study sites assuming current legislation scenario (CLE) and b) distribution of S deposition in the two scenarios (CLE, B10: no further reduction after 2010) and in the assessment years 2030 and 2050 in comparison with 1980 and 2015. BDW:
broadleaved deciduous woodland, CW: coniferous woodland, MDCW: mixed deciduous and coniferous woodland.

Climate Scenario data
In EURO-CORDEX, CMIP5 the global climate models GCMs (Taylor et al. 2012) are dynamically downscaled to about 48 km and 12 km resolution for a European model domain. Control simulations, driven by 20th century greenhouse gas concentrations (GHG), cover the time span from 1950 to 2005, from 2006 to 2100 projection simulations based on the Representative Concentration Pathway (RCP) GHG scenarios are available. At the time of the study, overall 69 different combinations of RCP – GCM – RCM (Regional Climate Model) – bias adjustment method and calibration dataset were available from the Earth System Grid Federation (ESGF) data nodes. Out of these, we selected a set of 12 combinations per RCP 4.5 and RCP 8.5, for which model outputs of air temperature, precipitation and radiation for both RCPs were available. Note that only air temperature and precipitation were bias adjusted. Because the actual altitude of a site may not match with the altitude of the closest RCM grid element, the 2 m air temperature was height corrected using a hypsometric lapse rate of 0.65 K per 100 m before temporal averaging was done (see more detail on climate data in Holmberg et al. (2018)).

Model validation
We used all study plots with an observation (see details in S1) interval ≥ 10 years (n=19). For every survey year, the mean observed coverage of each species per study plot was calculated. Temporal change in the indicator groups were characterized by calculating the mean lnRR of species coverage between the first and the last record. Vegetation records of sampling units within study plots were only used for analyses if the vegetation was re-recorded throughout the observation period. The correspondence of observed and modelled lnRR was examined with mean error, RMSE, Pearson correlation coefficient (r), and R².

Metaregression analyses using a random effects model with Sidik-Jonkman estimator were used to test for a significant deviation of lnRR from zero (metafor R package version 2.0-0 (Viechtbauer 2017)). According to this analysis, the change across all sites in the cover of oligophilic species during the last 2-3 decades (first to last survey year) was negative but not significantly (-0.10 lnRR, 0.19 SE, p = 0.62). Modelled changes over the same period, expressed as lnRR, had the highest correspondence among the 6 indicator groups with these observations. Acidophilic species cover decreased in the observations with -0.21 lnRR (0.21 SE), however trends across all sites were non-significant (p = 0.32). Positive trends of cold-tolerant species with 0.33 lnRR (0.37 SE) were also not detectable (p = 0.38). Both, the modelled and observed changes in acidophilic species as well as in the cold-tolerant species group were positively correlated (S2 Table 1).
Table 1. Goodness of fit of modelled versus observed response ratios (lnRR between 1980 and 2015) in species indicator groups.

| Oligophilic (N<5) | Acidophilic (R<5) | Cold-tolerant (T<5) | Nitrophilic (N>5) | Basiphilic (R>5) | Thermophilic (T>5) |
|------------------|------------------|---------------------|------------------|-----------------|------------------|
| n                | 15               | 15                  | 10               | 11              | 9                | 8                |
| Mean Error       | -0.8             | -0.82               | -1.43            | -0.67           | 0.88             | 0.09             |
| RMSE             | 1.58             | 2.02                | 3.09             | 2.8             | 1.85             | 1.83             |
| r                | 0.38             | 0.18                | 0.31             | -0.22           | -0.22            | -0.28            |
| R²               | 0.15             | 0.03                | 0.1              | 0.05            | 0.05             | 0.08             |

The modelled lnRR showed higher magnitudes and on average more negative trends than the observed lnRR (S2 Table 1). Only the modelled mean lnRR of oligophilic, acidophilic and cold-tolerant species indicator groups showed positive correlations with observations (S2 Table 1). The modelled mean lnRR of the other three indicator groups (eutrophilic, basiphilous, and thermophilic species) showed negative correlations with observed lnRR and were therefore not further used in the analyses (S2 Table 1). It is worth mentioning that species in two of these latter indicator groups were not well represented in the study sites. First, thermophilic species were rare in central and northern European forest understory, and, second, there were only few sites with carbonate bedrock which favor basiphilous species.

Since PROPS is modelling the habitat suitability of plant species and not their actual occurrence (Reinds et al. 2014), our results may be biased because regionally extinct species may not be able to recolonize the sites although the model is predicting improved habitat suitability. We avoided this issue by considering only those plant species both ecologically suitable for each site and occurring during the last 2-3 decades. Major species extinctions during this period are also very unlikely as shown in a previous study by Dirnböck et al. (2014) using the same plots. On the other hand, species might immigrate when becoming suitable due to e.g. climate warming. This could also bias our results. However, in most areas in Europe, forest fragmentation will likely prevent rapid immigration until 2030 (Dullinger et al. 2015). We conclude that species selection for modelling the indicator group’s temporal change was robust.

The dynamic soil model in combination with the plant response model did explain 3-15 % of the variation in observed long-term changes in the three indicator species groups finally taken into account in the assessment. Although we consider this a reasonable - though not high - fit for our purpose, we acknowledge that forest understory species occurrence depends on many more factors than we were able to include, thereby increasing the variance between the lnRRs of observations and of model results. Such factors are radiation (De Frenne et al. 2013) and tree species changes (Verheyen et al. 2012) related with forest management (Tonteri et al. 2016), other nutrients than N (Wassen et al. 2005), or herbivory (Bernhardt-Römermann et al. 2015). In addition to these confounding factors, observer errors in both, the long-term observations and the calibration data for PROPS likely were increasing the variance as well (Allegrini et al. 2009).
S3. Site-specific diagnostic species used for modelling with PROPS

AT01 (Zöbelboden IP1)
Abies alba Mill.; Acer pseudoplatanus L.; Aposeris foetida (L.) Cass. ex Less.; Athyrium filix-femina (L.) Roth; Blechnum spicant (L.) Sm.; Cardamine tricholia L.; Carex alba Scop.; Fagus sylvatica L.; Galium odoratum (L.) Scop.; Helleborus niger L.; Huperzia selago (L.) Bernh. ex Schrank & Mart.; Lamium galeobdolon (Pers.) Hayek; Luzula luzulina (Vill.) Racib.; Lycopodium annotinum L.; Oxalis acerosella L.; Picea abies (L.) H.Karst.; Polygonatum verticillatum (L.) All.; Prenanthes purpurea L.; Vaccinium myrtillus L.; Viola reichenbachiana Jord. ex Boreau

AT02 (Zöbelboden IP2)
Abies alba Mill.; Acer pseudoplatanus L.; Adenostyles alpina (L.) Bluff & Fingerh.; Aposeris foetida (L.) Cass. ex Less.; Calamagrostis varia (Schrad.) Host; Campanula rotundifolia L.; Cardamine enneaphyllos (L.) Crantz; Cardamine heptaphylla (Vill.) O.E.Schulz; Carex alba Scop.; Carex digitata L.; Ctenidium molluscum (Hedw.) Mitt.; Cyclamen purpurascens Mill.; Dryopteris filix-mas (L.) Schott; Euphorbia amygdaloides L.; Fagus sylvatica L.; Festuca altissima All.; Galium odoratum (L.) Scop.; Helleborus niger L.; Lonicera alpigena L.; Lonicera nigra L.; Melampyrum sylvaticum Hook.; Mercurialis perennis L.; Oxalis acerosella L.; Picea abies (L.) H.Karst.; Polygala chamaebuxus L.; Polystichum aculeatum (L.) Roth ex Mert.; Prenanthes purpurea L.; Rosa pendulina L.; Rubus idaeus L.; Sesleria albicans Kit.; Solidago virgaurea L.; Valeriana montana L.

AT09 (Klausen-Leopoldsdorf)
Acer pseudoplatanus L.; Dryopteris dilatata (Hoffm.) A. Gray; Euphorbia amygdaloides L.; Fagus sylvatica L.; Festuca altissima All.; Galium odoratum (L.) Scop.; Gymnocarpium dryopteris (L.) Newman; Hordelymus europaeus (L.) Jess. ex Harz; Lactuca muralis (L.) Gaertn.; Lamium galeobdolon (L.) L.; Melica uniflora Retz.; Mercurialis perennis L.; Poa nemoralis L.; AT16 (Murau); Barbilophozia lycopodioides (Wallr.) Loeske; Blechnum spicant (L.) Sm.; Dicranum scoparium Hedw.; Homogyne alpina (L.) Cass.; Hylocomium splendens (Hedw.) Schimp.; Larix decidua Mill.; Leucobryum glaucum (Hedw.) Ångstr.; Linnaea borealis L.; Lonicera caerulea L.; Melica uniflora Retz.; Melica uniflora Retz.; Melampyrum sylvaticum Hook.; Oxalis acerosella L.; Picea abies (L.) H.Karst.; Pinus cembra L.; Pteridium aquilinum (L.) Kuhn; Quercus petraea (Matt.) Liebl.; Quercus robur L.; Vaccinium myrtillus L.; Vaccinium vitis-idaea L.

BE01 (Brasschaat)
Betula pendula Roth; Betula pubescens Ehrh.; Calluna vulgaris (L.) Hull; Carex pilulifera L.; Castanea sativa Mill.; Convallaria majalis L.; Deschampsia flexuosa (L.) Trin.; Frangula alnus Mill.; Ilex aquifolium L.; Maianthemum bifolium (L.) F.W.Schmidt; Molinia caerulea (L.) Moench; Pinus sylvestris L.; Prunus serotina Ehrh.; Pteridium aquilinum (L.) Kuhn; Quercus petraea (Matt.) Liebl.; Quercus robur L.; Quercus rubra L.; Teucrium scorodonia L.; Vaccinium myrtillus L.

DE01 (Forellenbach)
Abies alba Mill.; Athyrium filix-femina (L.) Roth; Blechnum spicant (L.) Sm.; Dicranum scoparium Hedw.; Dryopteris dilatata (Hoffm.) A. Gray; Hylocomium splendens (Hedw.) Schimp.; Leucobryum...
Diagnostic species include UK National Vegetation Classification W8 and ancient species of southern UK according to Glaves et al. (2009).
Euphorbia amygdaloides L.; Festuca gigantea (L.) Vill.; Galium odoratum (L.) Scop.; Holcus mollis L.; Hyacinthoides non-scripta (L.) Chouard ex Rothm.; Ilex aquifolium L.; Iris foetidissima L.; Lamium galeobdolon (L.) L.; Luzula sylvatica (Huds.) Gaudin; Lysimachia nemorum L.; Melica uniflora Retz.; Milium effusum L.; Moehringia trinervia (L.) Clairv.; Narcissus pseudonarcissus L.; Orchis mascula (L.) L.; Oxalis acerosella L.; Platanthera chlorantha (Custer) Rchb.; Poa nemoralis L.; Polygonatum multiflorum (L.) All.; Polyostichum aculeatum (L.) Roth ex Mert.; Polyostichum setiferum (Forssk.) Moore ex Woy.; Populus tremula L.; Potentilla sterilis (L.) Garcke; Primula vulgaris Huds.; Prunus avium (L.) L.; Quercus petraea (Matt.) Liebl.; Ranunculus auricomus L.; Sanicula europaea L.; Sorbus torminalis (L.) Crantz; Tilia cordata Mill.; Ulmus glabra Huds.; Veronica montana L.; Viburnum opulus L.; Vicia sepium L.

**IT05 (Selvapiana)**

Abies alba Mill.; Acer pseudoplatanus L.; Ajuga reptans L.; Bromus ramosus Huds.; Carex sylvatica Huds.; Epilobium montanum L.; Euryynchium striatum (Schreb. ex Hedw.) Schimp.; Fagus sylvatica L.; Festuca altissima All.; Galium odoratum (L.) Scop.; Geranium robertianum L.; Hordelymus europaeus (L.) Jess. ex Harz; Hylocomium splendens (Hedw.) Schimp.; Lactuca muralis (L.) Gaertn.; Lamium galeobdolon (L.) L.; Lathyrus vernus (L.) Bernh.; Lonicera xylosteuem L.; Luzula luzuloides (Lam.) Dandy & Wilmott; Milium effusum L.; Oxalis acerosella L.; Phyteuma spicatum L.; Picea abies (L.) H.Karst.; Plagiochila asplenioides (L.) Dumort.; Polygonatum verticillatum (L.) All.; Prenanthes purpurea L.; Rhytididendus triquetrus (Hedw.) Warnst.; Rubus pedemontanus Pinkw.; Senecio ovatus Willd.; Sorbus aucuparia L.; Thuidium tamariscinum (Hedw.) Schimp.; Viola reichenbachiana Jord. ex Boreau

**IT07 (Carrega)**

Acer campestre L.; Anemone nemorosa L.; Calluna vulgaris (L.) Hull; Carex pilulifera L.; Carpinus betulus L.; Castanea sativa Mill.; Convallaria majalis L.; Cornus sanguinea L.; Corylus avellana L.; Crataegus monogyna Jacq.; Dactylis glomerata L.; Dicranum scoparium Hedw.; Fraxinus ornus L.; Genista tinctoria L.; Hedera helix L.; Hypnum cupressiforme Hedw.; Lathyrus niger (L.) Bernh.; Lathyrus vernus (L.) Bernh.; Luzula forsteri (Sm.) DC.; Melittis melissophyllum L.; Polycladichastrum formosum (Hedw.) G.L. Sm.; Potentilla erecta (L.) Rauesch.; Prunus avium (L.) L.; Pteridium aquilinum (L.) Kuhn; Quercus cerris L.; Quercus petrea (Matt.) Liebl.; Rosa arvensis Huds.; Serratula tinctoria L.; Sesleria autumnalis (Scop.) F.W.Schultz; Viola reichenbachiana Jord. ex Boreau

**IT08 (Brasimone)**

Acer campestre L.; Acer platanoides L.; Asarum europaeum L.; Campanula trachelium L.; Cardamine bulbifera (L.) Crantz; Carex pilosa Scop.; Carpinus betulus L.; Clematis vitalba L.; Daphne laureola L.; Euphorbia amygdaloides L.; Fagus sylvatica L.; Fraxinus excelsior L.; Galium odoratum (L.) Scop.; Geranium robertianum L.; Hedera helix L.; Lactuca muralis (L.) Gaertn.; Lamium galeobdolon (L.) L.; Lathyrus vernus (L.) Bernh.; Melica uniflora Retz.; Mercurialis perennis L.; Tilia platyphyllos Scop.; Viola reichenbachiana Jord. ex Boreau

**IT09 (Monte Rufeno)**

Carpinus betulus L.; Corylus avellana L.; Crocus caeruleus Weston; Cruciata glabra (L.) Opiz; Epilobium alpinum L.; Erythronium dens-canis L.; Euonymus verrucosus Scop.; Fraxinus ornus L.; Lathyrus linifolius (Reichard) Bassler; Lathyrus venetus (Mill.) Wohlf.; Lonicera caprifolium L.; Luzula luzuloides (Lam.) Dandy & Wilmott; Polycladichastrum formosum (Hedw.) G.L. Sm.; Potentilla
micrantha Ramond ex DC.; Prunus avium (L.) L.; Quercus cerris L.; Quercus petraea (Matt.) Liebl.; Quercus robur L.; Ruscus aculeatus L.; Stellaria holostea L.

**IT10 (Val Masino)**
Abies alba Mill.; Acer pseudoplatanus L.; Adenostyles alpina (L.) Bluff & Fingerh.; Athyrium filix-femina (L.) Roth; Calamagrostis varia (Schrad.) Host; Carex flacca Schreb.; Daphne mezereum L.; Dicranum scoparium Hedw.; Fagus sylvatica L.; Homogyne alpina (L.) Cass.; Hylocomium splendens (Hedw.) Schimp.; Luzula sylvatica (Huds.) Gaudin; Melampyrum sylvaticum Hook.; Oxalis acetosella L.; Picea abies (L.) H.Karst.; Polytrichastrum formosum (Hedw.) G.L. Sm.; Prenanthes purpurea L.; Rhytidiadelphus triquetrus (Hedw.) Warnst.; Sorbus aucuparia L.; Vaccinium myrtillus L.; Veronica urticifolia Jacq.; Viola reichenbachiana Jord. ex Boreau

**NO01 (Birkenes)**
Cornus suecica L.; Deschampsia flexuosa (L.) Trin.; Dicranum majus Turner; Hylocomium splendens (Hedw.) Schimp.; Linnaea borealis L.; Picea abies (L.) H.Karst.; Plagiothecium undulatum (Hedw.) Schimp.; Pleurozium schreberi (Willd. ex Brid.) Mitt.; Ptilium crista-castrensis (Hedw.) De Not.; Rhytidiadelphus loreus (Hedw.) Warnst.; Sphagnum quinquefarium (Lindb.) Warnst.; Vaccinium myrtillus L.; Vaccinium vitis-idaea L.

**PL01 (Puszcza Borecka)**
Aegopodium podagraria L.; Ajuga reptans L.; Anemone nemorosa L.; Anemone ranunculoides L.; Asarum europaeum L.; Cardamine bulbifera (L.) Crantz; Carex pilosa Scop.; Carpinus betulus L.; Corydalis cava (L.) Schweigg. & Körte; Corydalis solida (L.) Clairv.; Dryopteris filix-mas (L.) Schott; Equisetum pratense Ehrh.; Euonymous europaeus L.; Festuca gigantea (L.) Vill.; Ficaria verna Huds.; Galium odoratum (L.) Scop.; Gymnocarpium dryopteris (L.) Newman; Hepatica nobilis Mill.; Lamium galeobdolon (L.) L.; Lathyrus vernus (L.) Bernh.; Maianthemum bifolium (L.) F.W.Schmidt; Mercurialis perennis L.; Milium effusum L.; Oxalis acetosella L.; Paris quadrifolia L.; Picea abies (L.) H.Karst.; Polygonatum multiflorum (L.) All.; Polypodium vulgare L.; Quercus robur L.; Ranunculus lanuginosus L.; Stachys sylvatica L.; Stellaria holostea L.; Stellaria nemorum L.; Tilia cordata Mill.; Viola reichenbachiana Jord. ex Boreau

**PL02 (Słowiński National Park)**
Calluna vulgaris (L.) Hull; Carex arenaria L.; Chimaphila umbellata (L.) Nutt.; Deschampsia flexuosa (L.) Trin.; Empetrum nigrum L.; Goodyera repens (L.) R.Br.; Maianthemum bifolium (L.) F.W.Schmidt; Melampyrum pratense L.; Moneses uniflora A.Gray; Neottia cordata (L.) Rich.; Orthilia secunda (L.) House; Oxalis acetosella L.; Polypodium vulgare L.; Quercus robur L.; Solidago virgaurea L.; Vaccinium myrtillus L.; Vaccinium vitis-idaea L.

**PL03 (Tatrański National Park)**
Abies alba Mill.; Actaea spicata L.; Anemone nemorosa L.; Asarum europaeum L.; Athyrium filix-femina (L.) Roth; Cardamine bulbifera (L.) Crantz; Cardamine glanduligera O.Schwarz; Cardamine trifolia L.; Dryopteris filix-mas (L.) Schott; Euphorbia amygdaloides L.; Fagus sylvatica L.; Galium odoratum (L.) Scop.; Gentiana asclepiadea L.; Gymnocarpium dryopteris (L.) Newman; Lamium galeobdolon (L.) L.; Lonicera xylosteum L.; Luzula sylvatica (Huds.) Gaudin; Mercurialis perennis L.; Phytoemia spicatum L.; Polystichum aculeatum (L.) Roth ex Mert.; Prenanthes purpurea L.; Salvia
glutinosa L.; Sambucus racemosa L.; Sanicula europaea L.; Soldanella carpathica Vierh.; Veronica montana L.; Viola reichenbachiana Jord. ex Boreau

RS01 (Kopaonik)
Anemone nemorosa L.; Apometzgeria pubescens (Schrank) Kuwah.; Blechnum spicant (L.) Sm.; Campanula patula L.; Dicranum scoparium Hedw.; Galium rotundifolium L.; Gentiana asclepiadea L.; Hieracium murorum C.B.Clarke; Homogyne alpina (L.) Cass.; Hylocomium splendens (Hedw.) Schimp.; Lonicera alpigena L.; Lonicera nigra L.; Luzula sylvatica (Huds.) Gaudin; Melampyrum sylvaticum Hook.; Moneses uniflora A.Gray; Neottia cordata (L.) Rich.; Oxalis acetosella L.; Picea abies (L.) H.Karst.; Polytrichum juniperinum Hedw.; Prenanthes purpurea L.; Rubus idaeus L.; Senecio nemorensis L.; Solidago virgaurea L.; Sorbus aucuparia L.; Vaccinium myrtillus L.; Valeriana montana L.; Veratrum album L.; Veronica officinalis L.

SE14 (Aneboda)
Betula pendula Roth; Brachythecium rutabulum (Hedw.) Schimp.; Calamagrostis villosa (Chaix) J.F.Gmel.; Calypogeia muelleriana (Schiffner) K. Müller; Deschampsia flexuosa (L.) Trin.; Dicranum scoparium Hedw.; Diphasiastrum complanatum (L.) Holub; Epilobium angustifolium L.; Galium saxatile L.; Picea abies (L.) H.Karst.; Pleurozium schreberi (Willd. ex Brid.) Mitt.; Polytrichastrum formosum (Hedw.) G.L. Sm.; Sorbus aucuparia L.; Vaccinium myrtillus L.

SE15 (Kindla)
Betula pendula Roth; Brachythecium rutabulum (Hedw.) Schimp.; Calamagrostis villosa (Chaix) J.F.Gmel.; Calypogeia muelleriana (Schiffner) K. Müller; Deschampsia flexuosa (L.) Trin.; Dicranum scoparium Hedw.; Diphasiastrum complanatum (L.) Holub; Epilobium angustifolium L.; Galium saxatile L.; Picea abies (L.) H.Karst.; Pleurozium schreberi (Willd. ex Brid.) Mitt.; Polytrichastrum formosum (Hedw.) G.L. Sm.; Sorbus aucuparia L.; Vaccinium myrtillus L.

SE16 (Gammtratten)
Betula pendula Roth; Brachythecium rutabulum (Hedw.) Schimp.; Calamagrostis villosa (Chaix) J.F.Gmel.; Calypogeia muelleriana (Schiffner) K. Müller; Deschampsia flexuosa (L.) Trin.; Dicranum scoparium Hedw.; Diphasiastrum complanatum (L.) Holub; Epilobium angustifolium L.; Galium saxatile L.; Picea abies (L.) H.Karst.; Pleurozium schreberi (Willd. ex Brid.) Mitt.; Polytrichastrum formosum (Hedw.) G.L. Sm.; Sorbus aucuparia L.; Vaccinium myrtillus L.
S4. Soil chemical changes in the RCP 8.5 scenario

S4 Figure 1. Changes in a) soil pH value and b) soil C:N ratio between 2015, 2030 (closed symbol), and 2050 (open symbol) under the current legislation deposition scenario (CLE) and RCP 8.5 climate scenario. The length of the line joining the symbols is a measure of the change from 2030 to 2050 and the vertical distance of the symbols from the 1:1 line shows the change with respect to 2015. BDW: broadleaved deciduous woodland, CW: coniferous woodland, MDCW: mixed deciduous and coniferous woodland.
S5. Changes in the indicator species groups between 2015 and 2050

S5. Table 1. Changes (=response ratios) in the indicator species groups oligophilic (N≤5), acidophilic (R≤5) and cold-tolerant between 2015 and 2050 assuming current legislation deposition (CLE) and RCP 4.5 and RCP 8.5 climate scenarios. Significant changes with p<0.05 are shown in bold. Sites with <2 species per group were not assessed.

|                      | oligophilic (N≤5) | acidophilic (R≤5) | cold tolerant (T≤5) |
|----------------------|------------------|------------------|--------------------|
|                      | RCP 4.5          | RCP 8.5          | RCP 4.5            | RCP 8.5            | RCP 4.5            | RCP 8.5            |
| Broadleaved deciduous woodland |                  |                  |                    |                    |                    |                    |
| AT09                 | -                | -                | -                  | -                  | -                  | -                  |
| GB54                 | -2.14 ± 0.61     | -2.49 ± 0.45     | -0.73 ± 0.42       | -0.88 ± 0.41       | -                  | -                  |
| GB55                 | -0.77 ± 0.36     | -0.77 ± 0.36     | -0.8 ± 0.31        | -0.88 ± 0.29       | -                  | -                  |
| IT05                 | -                | -                | -                  | -                  | -                  | -                  |
| IT07                 | 0.27 ± 0.17      | 0.21 ± 0.18      | 0.42 ± 0.19        | 0.4 ± 0.19         | -                  | -                  |
| IT08                 | -                | -                | -                  | -                  | -                  | -                  |
| TO09                 | 0.46 ± 0.24      | 0.31 ± 0.24      | 0.43 ± 0.37        | 0.27 ± 0.39        | -                  | -                  |
| PL01                 | 0.94 ± 0.44      | 0.41 ± 0.55      | 1.09 ± 0.47        | 0.52 ± 0.58        | -                  | -                  |
| PL03                 | -                | -                | -1.62 ± 0.52       | -4.06 ± 0.69       | -1.92 ± 0.41       | -2.03 ± 0.45       |
| mean ± SD            | -0.25 ± 1.1      | -0.47 ± 1.1      | 0.08 ± 0.73        | -0.24 ± 0.64       |                    |                    |
| Coniferous woodland  |                  |                  |                    |                    |                    |                    |
| AT16                 | -0.75 ± 0.41     | -0.51 ± 0.41     | -2.24 ± 0.43       | -1.51 ± 0.38       | -2.26 ± 0.42       | -1.94 ± 0.41       |
| BE01                 | -1.91 ± 0.13     | -1.87 ± 0.13     | -1.96 ± 0.17       | -1.93 ± 0.17       | -                  | -                  |
| FI01                 | -                | -                | -0.81 ± 0.23       | -0.68 ± 0.2        | -0.3 ± 0.17        | -0.24 ± 0.14       |
| FI03                 | -0.01 ± 0.3      | 0.04 ± 0.3       | 0.1 ± 0.21         | 0.09 ± 0.21        | -0.4 ± 0.34        | -0.35 ± 0.33       |
| NO01                 | -0.48 ± 0.39     | -0.43 ± 0.4      | -0.2 ± 0.15        | -0.2 ± 0.15        | -0.17 ± 0.13       | -0.17 ± 0.13       |
| PL02                 | -1.04 ± 0.19     | -0.96 ± 0.19     | -1.04 ± 0.17       | -0.96 ± 0.17       | -                  | -                  |
| RS01                 | -0.73 ± 0.24     | -0.48 ± 0.25     | -0.72 ± 0.19       | -0.52 ± 0.19       | -0.64 ± 0.15       | -0.45 ± 0.14       |
| SE14                 | -                | -                | -0.64 ± 0.2        | -0.7 ± 0.17        | -0.46 ± 0.26       | -0.51 ± 0.26       |
| SE15                 | -                | -                | -0.22 ± 0.22       | -0.31 ± 0.22       | -0.23 ± 0.22       | -0.4 ± 0.22        |
| SE16                 | -                | -                | -0.2 ± 0           | -0.33 ± 0.18       | -0.03 ± 0.41       | -0.12 ± 0.41       |
| mean ± SD            | -0.82 ± 0.58     | -0.7 ± 0.6       | -0.89 ± 0.71       | -0.71 ± 0.59       | -0.56 ± 0.67       | -0.52 ± 0.55       |
| Mixed woodland       |                  |                  |                    |                    |                    |                    |
| AT01                 | -                | -                | 0.57 ± 0.41        | 0.27 ± 0.42        | -0.06 ± 0.24       | 0.07 ± 0.22        |
| AT02                 | -1.64 ± 0.52     | -0.93 ± 0.3      | -                  | -                  | -0.9 ± 0.33        | -0.54 ± 0.34       |
| DE01                 | -                | -                | -2.85 ± 0.33       | -2.76 ± 0.24       | -3.6 ± 0.23        | -3.64 ± 0.21       |
| IT10                 | -2.26 ± 0.52     | -2.67 ± 0.52     | -2.26 ± 0.52       | -2.67 ± 0.52       | -1.26 ± 0.43       | -1.6 ± 0.44        |
| mean ± SD            | -1.95 ± 0.31     | -1.8 ± 0.87      | -1.51 ± 1.49       | -1.72 ± 1.41       | -1.46 ± 1.31       | -1.43 ± 1.41       |
| mean ± SD            | -0.77 ± 0.98     | -0.78 ± 0.97     | -0.88 ± 1.23       | -1.02 ± 1.19       | -0.94 ± 1.02       | -0.92 ± 1.03       |
**Additional references in Supplementary Materials**

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