High aquatic macrophyte diversity in Norwegian lakes north of the arctic circle

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**Supplementary material**

**Supplementary Tables**

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**Figure S8.** GDM results for compositional dissimilarity (Sorensen beta-diversity).

**Table S1.** Aquatic macrophytes in Norway (see Mjelde et al. 2022). Species marked with \* are included in the analyses in this article.

|  |  |
| --- | --- |
|  | **ISOETIDS** |
| \* | *Baldellia repens* (Lam.) Ooststr. Ex Lawalrèe |
|  | *Calamistrum globuliferum* (L.) Kuntze |
| \* | *Crassula aquatica* (L.) Schönl. |
|  | *Crassula helmsii* (T. Kirk) Cockayne |
| \* | *Elatine hexandra* (Lapierre) DC. |
| \* | *Elatine hydropiper* L. |
| \* | *Elatine orthosperma* Düben |
| \* | *Elatine triandra* Schkuhr |
| \* | *Eleocharis acicularis* (L.) Roem. & Schult. |
|  | *Eleocharis parvula* (Roem. & Schult.) Link ex Bluff, Nees & Schauer |
| \* | *Isoëtes echinospora* Durieu |
| \* | *Isoëtes lacustris* L. |
| \* | *Limosella aquatica* L. |
| \* | *Littorella uniflora* (L.) Asch. |
| \* | *Lobelia dortmanna* L. |
| \* | *Lythrum portula* (L.) D.A.Webb |
|  | *Persicaria foliosa* (H. Lindb.) Kitag. |
| \* | *Ranunculus reptans* L. |
| \* | *Subularia aquatica* L. |
|  | *Ranunculus x levensis* Druce ex Gornall(*R. flammula* x *R. reptans*) |
| \* | **ELODEIDS** |
|  | *Callitriche brutia* Petagna |
| \* | *Callitriche cophocarpa* Sendtn. ex Hegelm. |
| \* | *Callitriche hamulata* Kütz. ex W.D.J.Koch |
| \* | *Callitriche hermaphroditica* L. |
| \* | *Callitriche palustris* L. |
|  | *Callitriche platycarpa* Kütz. |
| \* | *Callitriche stagnalis* Scop. |
|  | *Callitriche* x *vigens* K.Martinson (*C. cophocarpa* x *C. platycarpa*) |
| \* | *Ceratophyllum demersum* L. |
|  | *Elatine alsinastrum* L. |
| \* | *Elodea canadensis* Michx. |
| \* | *Elodea nuttallii* (Planch.) H. St. John |
|  | *Groenlandia densa* (L.) Fourr. |
|  | *Hippuris lanceolata* Retz. |
|  | *Hippuris tetraphylla* L. f. |
| \* | *Hippuris vulgaris* L. |
| \* | *Juncus bulbosus* L. |
| \* | *Myriophyllum alterniflorum* DC. |
| \* | *Myriophyllum sibiricum* Kom. |
| \* | *Myriophyllum spicatum* L. |
| \* | *Myriophyllum verticillatum* L. |
| \* | *Najas flexilis* (Willd.) Rostk. & W.L.E.Schmidt |
|  | *Najas marina* L. |
| \* | *Potamogeton alpinus* Balb*.* |
| \* | *Potamogeton berchtoldii* Fieber |
| \* | *Potamogeton compressus* L. |
| \* | *Potamogeton crispus* L. |
| \* | *Potamogeton friesii* Rupr*.* |
| \* | *Potamogeton gramineus* L. |
| \* | *Potamogeton lucens* L. |
| \* | *Potamogeton obtusifolius* Mert. & W.D.J.Koch |
| \* | *Potamogeton perfoliatus* L. |
| \* | *Potamogeton praelongus* Wulfen |
| \* | *Potamogeton pusillus* L. |
| \* | *Potamogeton rutilus* Wolfg*.* |
| \* | *Potamogeton trichoides* Cham. & Schltdl. |
| \* | *Potamogeton x cognatus* Asch. & Graebn. (*P.perfoliatus x P. praelongus*) |
|  | *Potamogeton x cooperi* (Fryer)Fryer (*P. crispus x P. perfoliatus*) |
|  | *Potamogeton x dualis* Hagstr. (*P. berchtoldii x P. pusillus*) |
| \* | *Potamogeton x nericius* Hagstr. (*P.* *alpinus* x *P. gramineus*) |
| \* | *Potamogeton x nitens* Weber *(P. gramineus x P. perfoliatus)* |
| \* | *Potamogeton x prussicus* Hagstr. (*P. alpinus* x *P. perfoliatus*) |
|  | *Potamogeton x saxonicus* Hagstr.(*P. berchtoldii x P. obtusifolius*) |
| \* | *Potamogeton x semifructus* A. Benn. exAsch. & Graebn. (*P. friesii x P. obtusifolius*) |
| \* | *Potamogeton x sparganifolius* Læst. ex Fr. (*P. gramineus x P. natans*) |
|  | *Potamogeton x torssandri (*Tiselius)G.Fisch. (*P. gramineus x P. lucens x P. perfoliatus*) |
| \* | *Potamogeton x zizii* W.D.J.Koch. ex Roth (*P. gramineus x P. lucens*) |
| \* | *Ranunculus aquatilis* L. |
|  | *Ranunculus aquatilis x R. peltatus* |
|  | *Ranunculus circinatus* Sibth. |
| \* | *Ranunculus confervoides* (Fr.) Fr. |
|  | *Ranunculus confervoides x R. peltatus* |
| \* | *Ranunculus peltatus* Schrank |
|  | *Ranunculus peltatus x R. trichophyllus* |
| \* | *Ranunculus trichophyllus* Chaix |
|  | *Ruppia cirrhosa* (Petagna) Grande |
|  | *Ruppia maritima* L. |
| \* | *Stuckenia filiformis* (Pers.) Börner |
| \* | *Stuckenia pectinata* (L.) Börner |
| \* | *Stuckenia vaginata* (Turcz.) Holub |
|  | *Stuckenia x fennica* (Hagstr.) Holub (*S. filiformis x S. vaginata*) |
| \* | *Stuckenia x suecica* (K.Richt.) Holub(*S. filiformis x S. pectinata*) |
| \* | *Utricularia australis* R.Br. |
| \* | *Utricularia intermedia* Hayne |
| \* | *Utricularia minor L.* |
| \* | *Utricularia ochroleuca* R.W.Hartm. |
|  | *Utricularia stygia* G.Thor |
| \* | *Utricularia vulgaris* L. |
|  | *Zannichellia major* Boenn. ex Rchb. |
| \* | *Zannichellia palustris* L. |
|  | *Zannichellia palustris* var. *pedicullata* (Wahlenb. & Rosén) |
|  | *Zostera angustifolia* (Hornem.) Rchb. |
|  | *Zostera marina L.* |
|  | *Zostera noltei* Hornem*.* |
|  | **NYMPHAEIDS** |
|  | *Eleogiton fluitans* (L.) Link |
| \* | *Luronium natans* (L.) Raf. |
| \* | *Nuphar lutea* (L.) Sm. |
| \* | *Nuphar pumila* (Timm) DC. |
| \* | *Nuphar x spenneriana* Gaudin (*N. lutea x N. pumila*) |
| \* | *Nymphaea alba* L. coll. |
|  | *Nymphoides peltata* (S.S.Gmel) Kuntze |
| \* | *Persicaria amphibia* (L.) Delarbre |
| \* | *Potamogeton natans* L. |
| \* | *Potamogeton polygonifolius* Pourret |
| \* | *Sagittaria sagittifolia L.* |
| \* | *Sagittaria x lunata* (C.D.Preston & Uotila) (*S. sagittifolia x S. natans*) |
| \* | *Sparganium angustifolium* Michx. |
| \* | *Sparganium emersum* Rehmann |
|  | *Sparganium glomeratum* (Laest. Ex Beurl.) Beurl. |
| \* | *Sparganium gramineum* Georgi |
| \* | *Sparganium hyperboreum* Læst. ex Beurl. |
| \* | *Sparganium natans* L. |
|  | *Sparganium x longifolium* Turcz. ex Ledeb.(*S. emersum x S. gramineum*) |
|  | *Sparganium x oligocarpon* Ångstr. (*S. emersum x S. natans*) |
| \* | *Sparganium x speirocephalum* Neum. (*S. angustifolium x S. gramineum*) |
| \* | *Sparganium x splendis* Meinsh (*S. angustifolium x S. emersum*) |
|  | **LEMNIDS** |
|  | *Azolla filiculoides* Lam. |
|  | *Hydrocharis morsus-ranae* L. |
|  | *Lemna gibba* L. |
|  | *Lemna japonica* Landolt |
| \* | *Lemna minor* L. |
|  | *Lemna minuta* Kunth |
| \* | *Lemna trisulca* L. |
|  | *Lemna turionifera* Landolt |
|  | *Pistia stratiotes* L. |
| \* | *Ricciocarpos natans* (L.) Corda |
| \* | *Spirodela polyrhiza* (L.) Schleid. |
|  | *Stratiotes aloides* L. |
|  | **CHAROPHYTES** |
| \* | *Chara aculeolata* Kützing, 1832 |
| \* | *Chara aspera* Willdenow |
|  | *Chara baltica* Bruzelius |
| \* | *Chara braunii* C.C. Gmelin |
|  | *Chara canescens* Desvaux & Loiseleur |
| \* | *Chara contraria* A. Braun ex Kützing |
|  | *Chara curta* Nolte ex Kützing |
| \* | *Chara globularis* Thuiller |
| \* | *Chara hispida* Linnaeus |
| \* | *Chara papillosa* Kützing, 1834 |
| \* | *Chara strigosa* A. Braun |
| \* | *Chara subspinosa* Ruprecht, 1846 |
| \* | *Chara tomentosa* Linnaeus |
| \* | *Chara virgata* Kützing |
|  | *Chara vulgaris* Linnaeus |
|  | *Lamprothamnium papulosum* (Wallroth) J.Groves |
| \* | *Nitella confervacea* (Brébisson) A. Braun ex Leonhardi |
| \* | *Nitella flexilis* (Linnaeus) C. Agardh |
|  | *Nitella gracilis* (Smith) Agardh |
| \* | *Nitella mucronata* (A. Braun) Miquel |
| \* | *Nitella opaca* (C. Agardh ex Bruzelius) C. Agardh |
| \* | *Nitella translucens* (Persoon) C. Agardh |
|  | *Nitella wahlbergiana* Wallman |
| \* | *Tolypella canadensis*Sawa |
|  | *Tolypella nidifica*(O. F. Müller) Leonhardi |
|  | *Tolypella normaniana* Nordstedt (Nordstedt) |

**Table S2. Correlations between pairs of explanatory variables after log transformation**

**Pearson correlations:**

**lat long elev area Ca TN TP T.av**

**long 0.8182**

**elev -0.2052 -0.0386**

**area -0.0546 -0.0526 -0.0377**

**Ca 0.1662 0.3358 -0.1009 -0.3723**

**TN -0.5284 -0.2995 -0.1411 -0.1651 0.4034**

**TP -0.2898 -0.1003 -0.2090 -0.2952 0.4210 0.6792**

**T.av -0.6818 -0.3532 -0.1423 -0.0329 0.2024 0.6143 0.4425**

**colour -0.2789 -0.2554 -0.2966 -0.0244 -0.1202 0.4137 0.5059 0.4081**

**Number of observations:**

**lat long elev area Ca TN TP T.av**

**long 720**

**elev 716 716**

**area 713 713 709**

**Ca 695 695 692 691**

**TN 505 505 501 505 504**

**TP 643 643 639 640 640 493**

**T.av 720 720 716 713 695 505 643**

**colour 371 371 368 371 370 324 354 371**

**Pairwise two-sided adjusted p-values (Holm's method)**

**lat long elev area Ca TN TP T.av**

**long <.0001**

**elev <.0001 1.0000**

**area 0.8725 0.8725 1.0000**

**Ca 0.0001 <.0001 0.0709 <.0001**

**TN <.0001 <.0001 0.0155 0.0021 <.0001**

**TP <.0001 0.0873 <.0001 <.0001 <.0001 <.0001**

**T.av <.0001 <.0001 0.0016 1.0000 <.0001 <.0001 <.0001**

**colour <.0001 <.0001 <.0001 1.0000 0.1455 <.0001 <.0001 <.0001**

**Table S3.** Area (km2), observed richness, expected richness and its standard deviation (from species accumulation curves, Fig. 2) for standardised sampling efforts: 37 sites for biogeographical zones, 58 sites for geographical regions and 76 sites for latitudinal bands.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Area (km2) | Observed  richness | Expected  richness | ±sd |
| **Biogeographical zones** |  |  |  |  |
| Boreo-nemoral | 25000 | 82 | 59 | 4.7 |
| South-boreal | 40000 | 85 | 62 | 5.2 |
| Mid-boreal | 65000 | 71 | 55 | 2.7 |
| North-boreal | 90000 | 54 | 45 | 2.8 |
| \*Alpine | 100000 | 25 | 25 | 0.6 |
| **Geographical regions** |  |  |  |  |
| Southeast | 79277 | 83 | 69 | 4.0 |
| South | 31732 | 45 | 45 | 0.8 |
| West | 43461 | 58 | 50 | 2.7 |
| Mid | 56381 | 61 | 59 | 1.1 |
| North | 64333 | 62 | 55 | 2.9 |
| Northeast | 48618 | 45 | 44 | 0.6 |
| **Latitudinal bands** |  |  |  |  |
| <60°N | 55900 | 86 | 70 | 4.5 |
| [60-63[ °N | 120199 | 79 | 68 | 3.5 |
| [63-66[ °N | 45515 | 67 | 65 | 1.6 |
| [66-69[ °N | 39411 | 54 | 53 | 0.8 |
| ≥69 °N | 63109 | 52 | 52 | 0.6 |

\* since we only sampled low alpine and included sub-arctic area, alpine zone was excluded of the species-area relationship (SAR)

**Table S4.** GAMs for species richness.

|  |  |  |
| --- | --- | --- |
| GAM model predictors | *df* | AIC |
| area+Ca+TP+T.av+(latitude:longitude) | 47 | 3464 |
| area+Ca+TP+T.av | 25 | 3545 |
| area+Ca+TP+(latitude:longitude) | 42 | 3580 |
| area+TP+T.av+(latitude:longitude) | 39 | 3476 |
| area+T.av+(latitude:longitude) | 33 | 3554 |
| area+(latitude:longitude) | 29 | 3715 |
| area | 5 | 3868 |

**Table S5.** GAMs for beta-diversity (Sorensen)

|  |  |  |
| --- | --- | --- |
| GAM model predictors | *df* | AIC |
| area+Ca+TP+T.av+latitude | 46 | -167918 |
| Ca+TP+T.av+latitude | 37 | -167441 |
| Ca+TP+latitude | 29 | -165667 |
| Ca+latitude | 20 | -154716 |
| Ca | 11 | -133830 |

**Table S6.** Generalised additive model (GAM) where Sørensen index (βsor), species turnover (βsim) and species net loss or gain (nestedness, βsne) were predicted as a function of differences in lake area, calcium, total phosphorus, average summer temperature and latitude between pairs of lakes. Estimated degrees of freedom (*edf*) are related to the complexity of trend lines.

beta.sor ~ s(log1p(d.area)) + s(log1p(d.Ca)) + s(log1p(d.TP)) + s(d.T.av) + s(d.lat)

Gaussian distribution with identity function; REML

|  |  |  |  |
| --- | --- | --- | --- |
|  | **estimate** | **se** | ***P*** |
| intercept | 0.78 | 4 × 10-4 | <2 × 10-16 |
|  | ***edf*** | **F** | ***P*** |
| log (d.area+1) | 8.8 | 54 | <2 × 10-16 |
| log (d.Ca+1) | 8.6 | 3667 | <2 × 10-16 |
| log (d.TP+1) | 8.5 | 1126 | <2 × 10-16 |
| d.T.av | 7.9 | 213 | <2 × 10-16 |
| d.Lat | 8.9 | 1714 | <2 × 10-16 |

R2 (adj) = 0.29, deviance 29%, n=193131

beta.sim ~ s(log1p(d.area)) + s(log1p(d.Ca)) + s(log1p(d.TP)) + s(d.T.av) + s(d.lat)

Gaussian distribution with identity function; REML

|  |  |  |  |
| --- | --- | --- | --- |
|  | **estimate** | **se** | ***P*** |
| intercept | 0.66 | 5 × 10-4 | <2 × 10-16 |
|  | ***edf*** | **F** | ***P*** |
| log (d.area+1) | 8.9 | 340 | <2 × 10-16 |
| log (d.Ca+1) | 8.5 | 2905 | <2 × 10-16 |
| log (d.TP+1) | 8.5 | 789 | <2 × 10-16 |
| d.T.av | 7.5 | 113 | <2 × 10-16 |
| d.Lat | 8.8 | 1378 | <2 × 10-16 |

R2 (adj) = 0.25, deviance 25%, n=193131

beta.sne ~ s(log1p(d.area)) + s(log1p(d.Ca)) + s(log1p(d.TP)) + s(d.T.av) + s(d.lat)

Gaussian distribution with identity function; REML

|  |  |  |  |
| --- | --- | --- | --- |
|  | **estimate** | **se** | ***P*** |
| intercept | 0.12 | 4 × 10-4 | <2 × 10-16 |
|  | ***edf*** | **F** | ***P*** |
| log (d.area+1) | 9.0 | 638 | <2 × 10-16 |
| log (d.Ca+1) | 8.6 | 586 | <2 × 10-16 |
| log (d.TP+1) | 7.8 | 109 | <2 × 10-16 |
| d.T.av | 5.7 | 12 | <2 × 10-16 |
| d.Lat | 8.4 | 317 | <2 × 10-16 |

R2 (adj) = 0.09, deviance 9%, n=193131

**Table S7.** Generalised additive model (GAM) where Sørensen index (βsor), species turnover (βsim) and species net loss or gain (nestedness, βsne) were predicted as a function of differences in lake area, calcium, total phosphorus, average summer temperature and **distance (km) between pairs of lakes**. Estimated degrees of freedom (*edf*) are related to the complexity of trend lines.

beta.sor ~ s(log1p(d.area)) + s(log1p(d.Ca)) + s(log1p(d.TP)) + s(d.T.av) + s(**distkm**)

Gaussian distribution with identity function; REML

|  |  |  |  |
| --- | --- | --- | --- |
|  | **estimate** | **se** | ***P*** |
| intercept | 0.78 | 4 × 10-4 | <2 × 10-16 |
|  | ***edf*** | **F** | ***P*** |
| log (d.area+1) | 8.8 | 47 | <2 × 10-16 |
| log (d.Ca+1) | 8.6 | 3703 | <2 × 10-16 |
| log (d.TP+1) | 8.5 | 1197 | <2 × 10-16 |
| d.T.av | 7.9 | 164 | <2 × 10-16 |
| **distkm** | 8.9 | 1875 | <2 × 10-16 |

R2 (adj) = 0.295, deviance 29.5%, n=193131

Chart

Description automatically generated

**Fig. S1.** GAM diagnostic plots for species richness with Poisson distribution (log link)

Graphical user interface

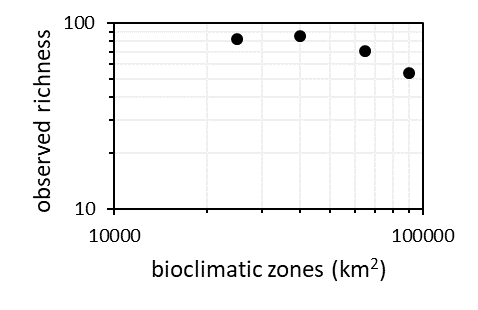
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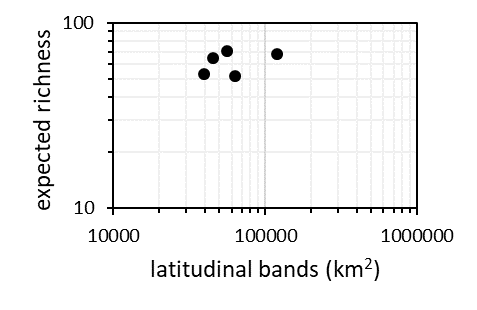
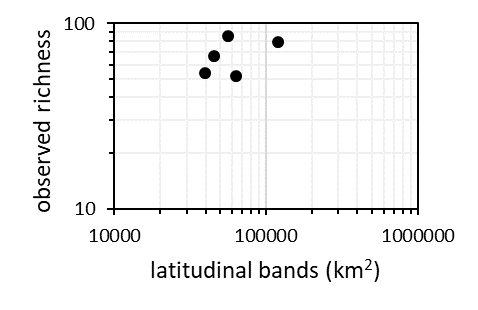
**Fig. S2.** GAM diagnostic plots for beta-diversity (Sorensen) with beta distribution (logit link)

Chart

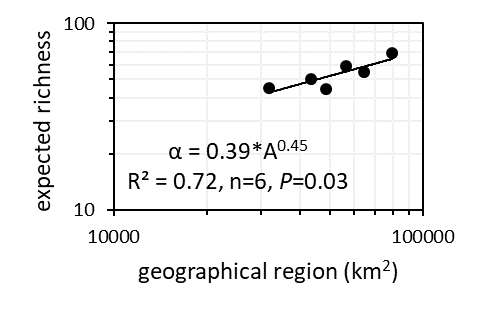
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**Fig. S3.** GAM diagnostic plots with Gaussian distribution (identity link) for beta-diversity (Sorensen)

**Chart, scatter chart

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**Chart, scatter chart

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**Fig. S4.** Species-area relationships. Observed or uncorrected (left) and expected (right) species richness as a function of area for bioclimatic zones (top), latitudinal bands (middle) and geographical regions (bottom). Data from Table S3.

Chart, line chart, histogram

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**Fig. S5.** Species turnover (βsim) predicted by pairwise differences in Ca, TP, latitude, average summer temperature and lake area. Same legend as Fig. 5. See Table S4.

Chart, line chart, histogram

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**Fig. S6.** Nestedness (βsne): net species gain or loss predicted by pairwise differences in Ca, TP, latitude, average summer temperature and lake area. Same legend as Fig. 5. The rug represents the distribution of datapoints along the x axis. See Table S4.

**Chart, line chart

Description automatically generated**

**Fig. S7.** Sørensen index (βsor): beta-diversity predicted by distance between lakes (km) assuming average pairwise differences in Ca, TP, average summer temperature and lake area. Note the similarity with latitude in Fig. 5. See Table S5.

Graphical user interface, chart

Description automatically generated

**Fig. S8**. Generalized dissimilarity modelling (GDM) results for compositional dissimilarity (Sorensen beta-diversity). The results were similar to GAM with explained deviance of 27% (29% for GAM). Both TP (total phosphorus) and Ca were strong predictors in GDM and GAM. TP seemed to be a stronger factor than Ca in GDM (unlike in GAM) but the analyses were based on untransformed differences for GDM and log-transformed differences for Ca, TP and area in GAM.