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*Supplement of*

# Climate and geology overwrite land use effects on soil organic nitrogen cycling on a continental scale

**Lisa Noll et al.**

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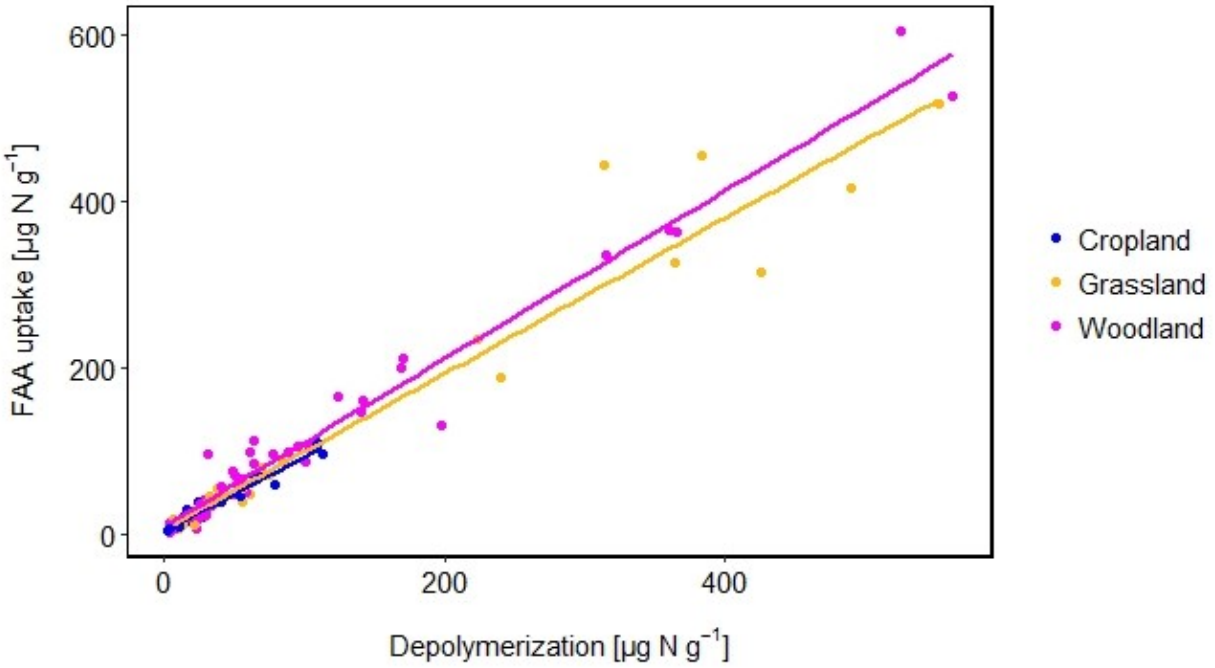


**Fig. S1.** Relationship of gross protein depolymerization and gross microbial amino acid uptake in cropland($r=0.9451$, $p<0.001$), grassland ($r=0.983$, $p<0.001$) and woodland ($r=0.965$, $p<0.001$) soils.

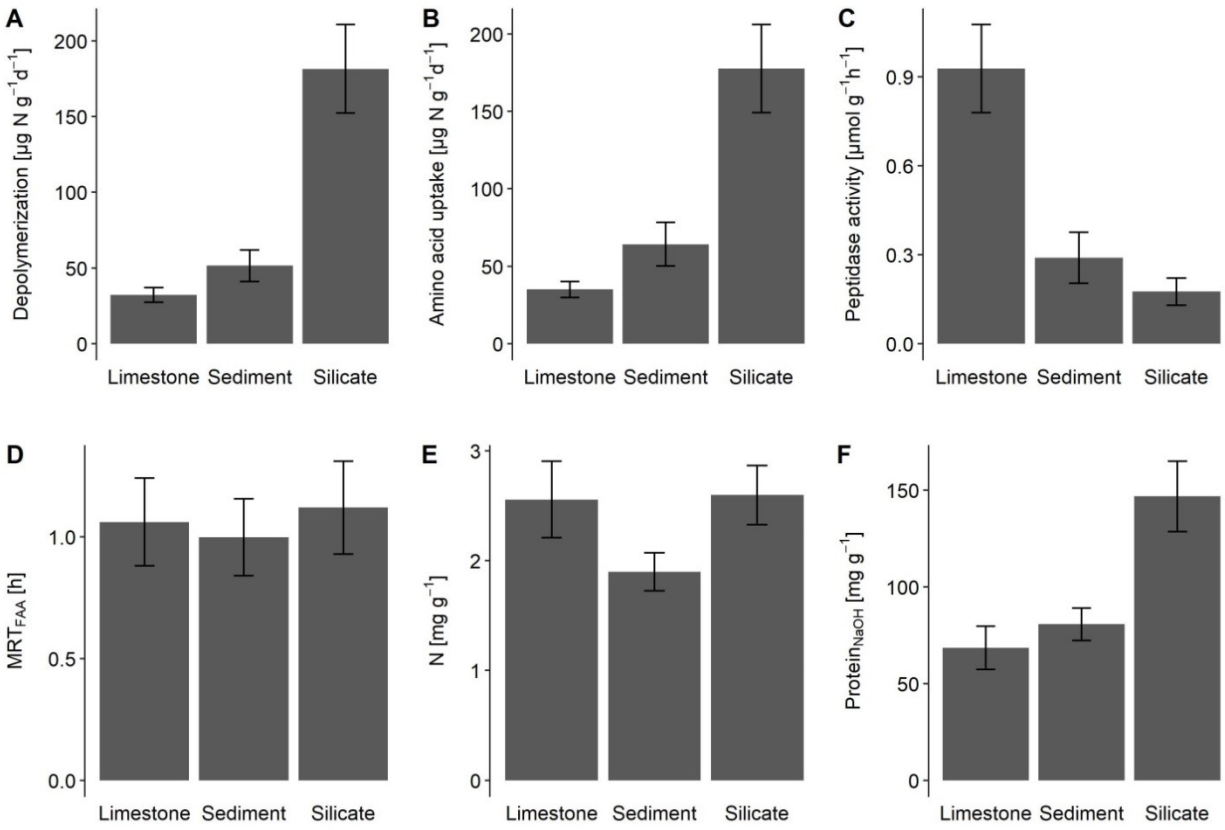


**Fig. S2.** Protein depolymerization rate (A), microbial amino acid uptake (B), leucine amino-peptidase activity (C), mean residence time of free amino acids ($MRT_{FAA}$, D), total soil N (E) and NaOH-extractable protein (F) for three different b bedrock types (limestone, sediment, silicate, mean±1SE, n = 26, 33, 36). Statistics are shown in Table S2.

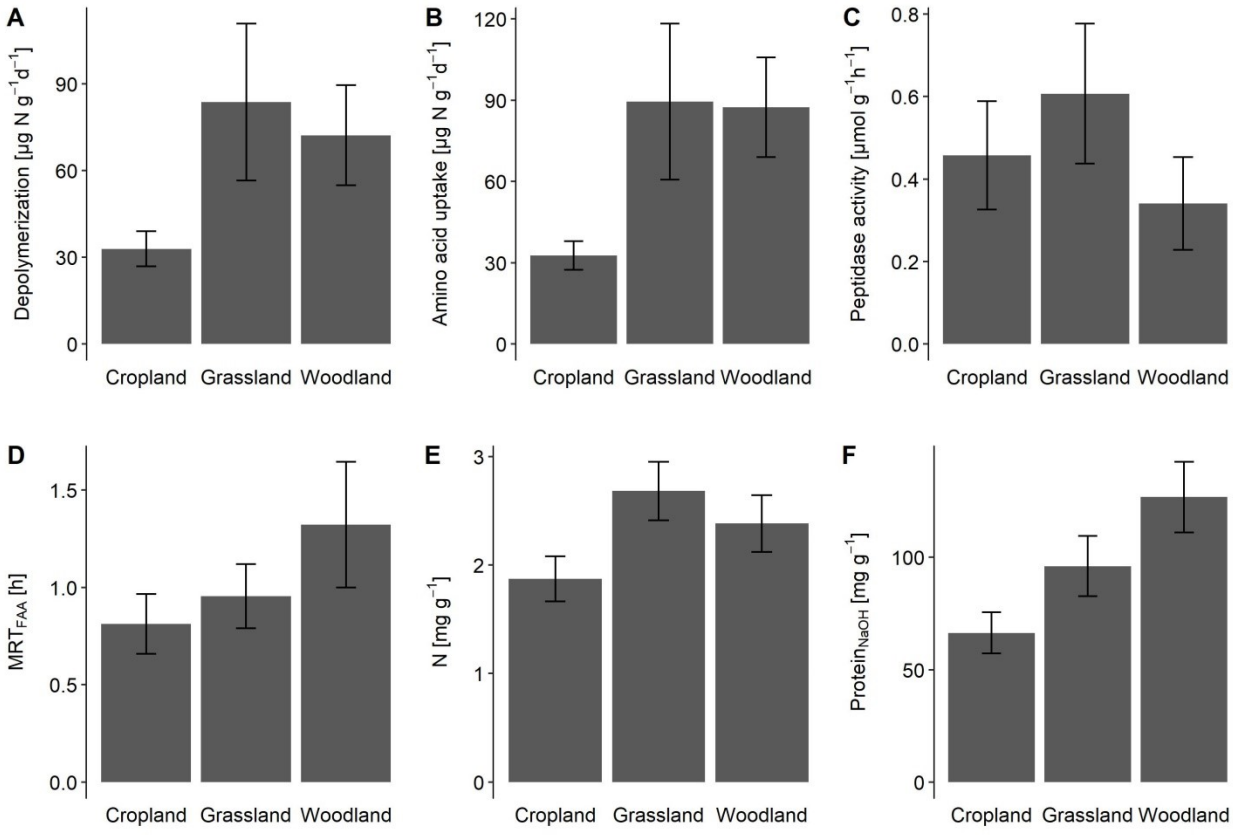


**Fig. S3.** Protein depolymerization (A), microbial amino acid uptake (B), leucine amino-peptidase activity (C), mean residence time of free amino acids ($MRT_{FAA}$, D), total soil N (E) and NaOH-extractable protein (F) for three different land use types (cropland, grassland, woodland, mean±1SE, n = 22, 22, 22). Statistics are shown in Table S2.

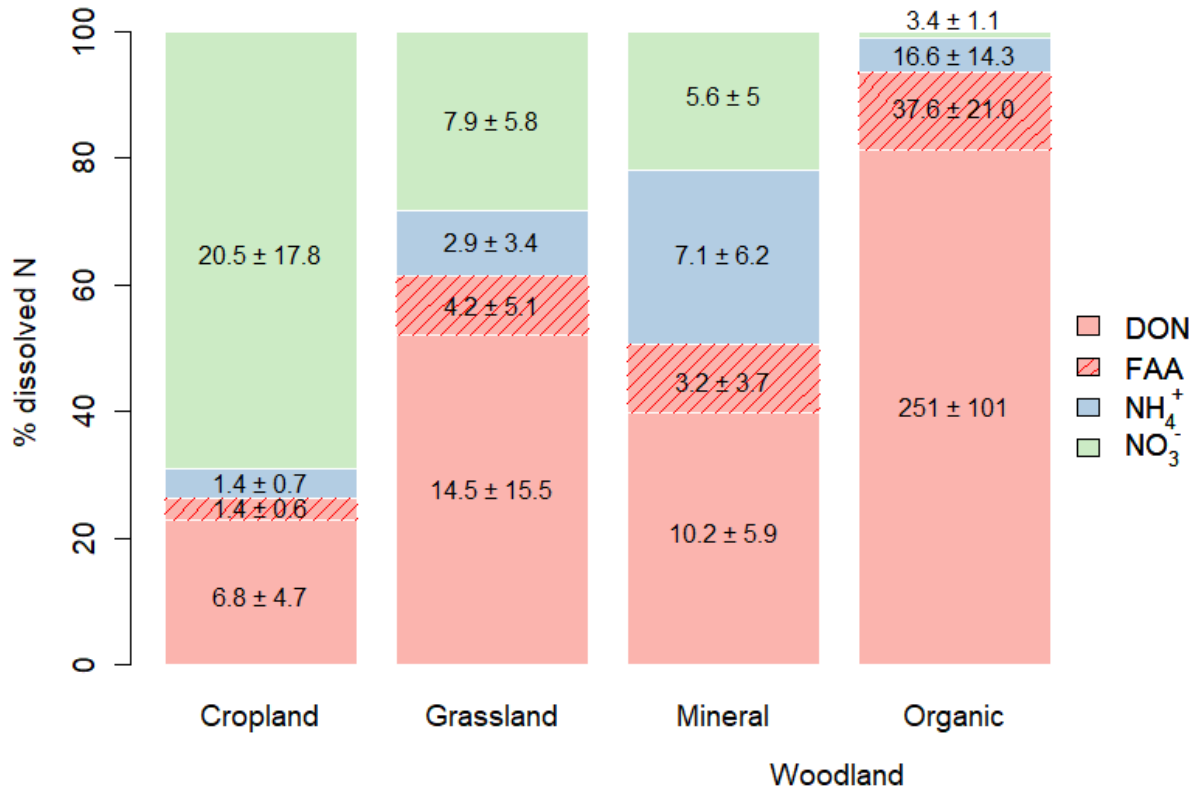


**Fig. S4.** Percentage of dissolved N species in total dissolved N. Composition of dissolved organic N in cropland (n = 24), grassland (n = 28) and woodland mineral soils (n = 48) as well as in woodland organic soil horizons (n =13). Numbers indicate the average N content (mean± 1sd) in µg N $g^{-1}$ d.w..

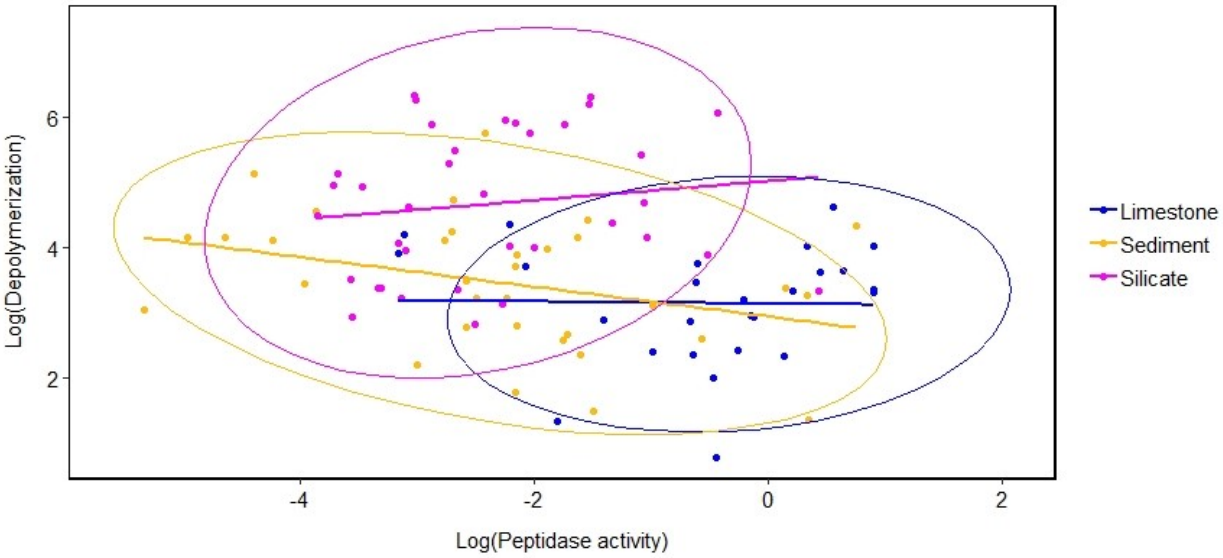


**Fig. S5.** Relationship of Log(peptidase activity) measured at native soil pH and log(gross protein depolymerization) in soils developed on limestone (r=-0.021, n.s.), sediment (r=-0.337, n.s.) and silicate(r=0.139, n.s.). Ellipses indicate the 95% confidence interval.

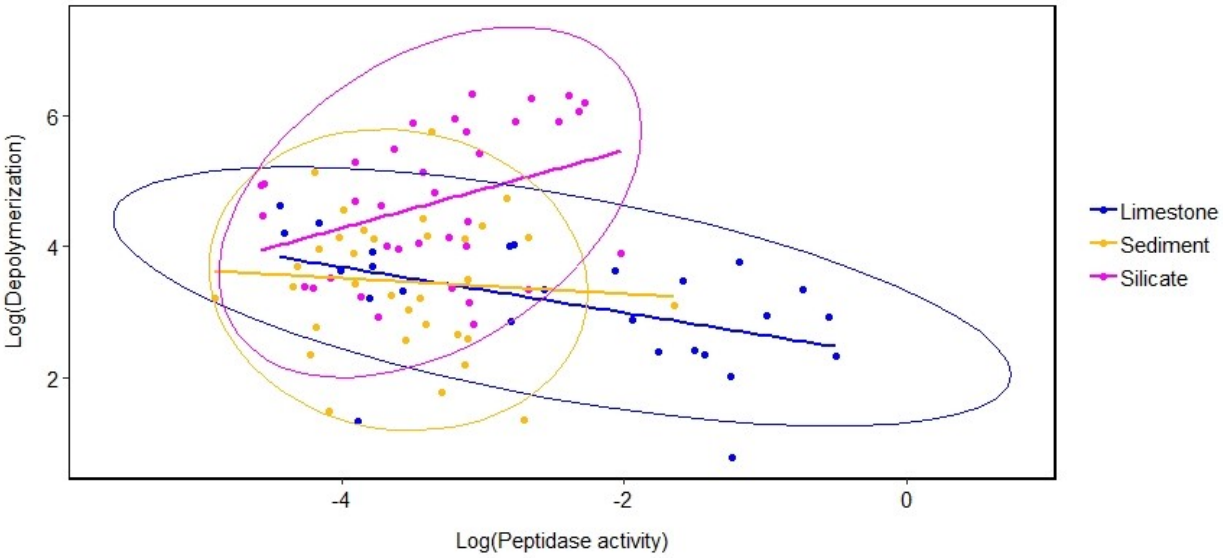


**Fig. S6.** Relationship of log(peptidase activity) measured at pH 5.5 and log(gross protein depolymerization) measured at natural soil pH developed in limestone ($r=-0.495$, $p<0.05$), sediment ($r=-0.070$, n.s.) and silicate($r=0.354$, $p<0.05$) soils. Ellipses indicate the 95% confidence interval.

| Site | Country | Latitude (°N) | Longitude (°E) | Elevation (m a.s.l.) | MAT (°C) | MAP (mm $y^{-1}$) | Parent material | Vegetation class | Soil type | horizon | Land use |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S-J1 | Spain | 36.8 | -5.2 | 684 | 15.1 | 728 | Carbonate | mediterreanen | Calcisol | mineral | W, G, C |
| S-J7 | Spain | 36.4 | -6.0 | 33 | 17.7 | 620 | Carbonate | mediterreanen | Calcisol | mineral | W, G, C |
| S-F1a | Spain | 43.4 | -5.7 | 250 | 13.2 | 842 | Carbonate | mesophytic (deciduous) | Leptosol | mineral | W, G |
| S-G3 | Spain | 42.6 | -0.3 | 824 | 9.9 | 737 | Sediment | thermophil | Leptosol | mineral | W, G, C |
| S-J4 | Spain | 42.0 | -0.3 | 473 | 12.2 | 449 | Carbonate | mediterreanen | Gypsisol | mineral | W, G, C |
| S-K3 | Spain | 41.7 | -0.2 | 418 | 13.2 | 415 | Carbonate | xerophytic | Gypsisol | mineral | W, C |
| S-J6 | Spain | 40.6 | 0.5 | 170 | 16.2 | 549 | Carbonate | mediterreanen | Calcisol | mineral | W, G, C |
| P-J5 | Portugal | 38.1 | -8.4 | 53 | 17 | 550 | Sediment | mediterreanen | Regosol | mineral | W, G, C |
| P-J3 | Portugal | 39.5 | -8.3 | 48 | 16.8 | 711 | Sediment | mediterreanen | Podzol | mineral | W, G, C |
| P-G4 | Portugal | 40.2 | -7.4 | 596 | 13.9 | 1050 | Silicate | thermophil | Regosol | mineral | W, G, C |
| D-1 | Germany | 53.0 | 13.9 | 94 | 8.6 | 565 | Sediment | mesophytic (deciduous) | Luvisol | mineral | W, G, C |
| D-2 | Germany | 54.1 | 11.9 | 6 | 8.7 | 590 | Sediment | mesophytic (deciduous) | Luvisol | mineral | W, G, C |
| D-3 | Germany | 51.1 | 10.4 | 445 | 7.3 | 745 | Carbonate | mesophytic (deciduous) | Cambisol | mineral | W, G, C |
| D-4 | Germany | 50.6 | 12.0 | 468 | 7.5 | 666 | Sediment | mesophytic (deciduous) | Cambisol | mineral | W, G, C |
| D-5 | Germany | 48.4 | 9.5 | 796 | 7.2 | 958 | Carbonate | mesophytic (deciduous) | Leptosol | mineral | W, G, C |
| R-1 | Romania | 45.8 | 25.5 | 542 | 8 | 620 | Sediment | mesophytic (deciduous) | Podzol | mineral | W, G, C |
| R-2 | Romania | 45.9 | 25.7 | 707 | 7.2 | 656 | Sediment | mesophytic (deciduous) | Podzol | mineral | W, G, C |
| R-3 | Romania | 47.0 | 26.3 | 428 | 7.6 | 585 | Sediment | mesophytic (deciduous) | Podzol | mineral | W, G, C |
| R-4 | Romania | 47.1 | 26.5 | 415 | 7.5 | 601 | Sediment | mesophytic (deciduous) | Luvisol | mineral | W, G, C |
| R-5 | Romania | 46.4 | 27.0 | 164 | 9.3 | 546 | Sediment | mesophytic (deciduous) | Luvisol | mineral | W, G, C |
| R-6 | Romania | 45.0 | 28.5 | 98 | 10.7 | 460 | Carbonate | Forest steppe | Chernozem | mineral | W, G, C |

| Site | Country | Latitude (°N) | Longitude (°E) | Elevation (m a.s.l.) | MAT (°C) | MAP (mm $y^{-1}$) | Parent material | Vegetation class | Soil type | horizon | Land use |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A-1 | Austria | 47.4 | 14.2 | 1572 | 2.4 | 1380 | Silicate | mesophytic (coniferous) | Podzol | mineral, organic | W, G |
| A-2 | Austria | 47.4 | 14.2 | 1350 | 3.5 | 1246 | Silicate | mesophytic (coniferous) | Podzol | mineral, organic | W, G |
| A-3 | Austria | 47.5 | 14.1 | 912 | 5.7 | 973 | Silicate | mesophytic (coniferous) | Cambisol | mineral, organic | W, G, C |
| SE-01 | Sweden | 68.3 | 18.8 | 422 | 2 | 440 | Silicate | subarctic | Podzol | mineral, organic | W |
| SE-02 | Sweden | 68.3 | 19.3 | 602 | -1.2 | 490 | Silicate | subarctic | Leptosol | mineral, organic | W |
| SE-03 | Sweden | 68.3 | 19.3 | 795 | -2.1 | 524 | Silicate | subarctic | Leptosol | mineral, organic | W |
| SE-04 | Sweden | 68.3 | 19.3 | 1012 | -3.4 | 568 | Silicate | subarctic | Leptosol | mineral | W |
| SE-05 | Sweden | 66.0 | 19.7 | 328 | -0.3 | 537 | Silicate | mires | Histosol | organic | |
| SE-06 | Sweden | 64.0 | 18.1 | 330 | 1 | 537 | Silicate | mesophytic (coniferous) | Podzol | mineral, organic | W, G |
| SE-07 | Sweden | 60.4 | 15.2 | 369 | 4.8 | 657 | Silicate | mesophytic (coniferous) | Podzol | mineral, organic | W, G, C |
| SE-08 | Sweden | 58.1 | 15.8 | 130 | 6.5 | 566 | Silicate | mesophytic (coniferous) | Regosol | mineral, organic | W, G, C |
| SE-09 | Sweden | 57.7 | 13.7 | 331 | 6.4 | 572 | Silicate | mires | Regosol | organic | W |
| FIN-01 | Finland | 67.9 | 24.4 | 309 | -2 | 504 | Silicate | mesophytic (coniferous) | Histosol | mineral, organic | W |
| FIN-02 | Finland | 67.2 | 26.9 | 249 | -1.3 | 539 | Silicate | mesophytic (coniferous) | Histosol | mineral, organic | W |
| FIN-03 | Finland | 67.8 | 29.6 | 300 | 7.2 | 749 | Silicate | subarctic | Podzol | mineral, organic | W |
| FIN-04 | Finland | 67.8 | 29.6 | 300 | -1 | 538 | Silicate | subarctic | Podzol | mineral, organic | W |
| FIN-05 | Finland | 67.8 | 29.6 | 300 | -1 | 538 | Silicate | subarctic | Podzol | mineral, organic | W |
| FIN-06 | Finland | 67.8 | 29.6 | 300 | -1 | 592 | Silicate | subarctic | Podzols | mineral, organic | W |
| NO-01 | Norway | 71.0 | 25.8 | 270 | -2.1 | 555 | Silicate | arctic | Leptosol | mineral | W |
| NO-02 | Norway | 68.4 | 14.9 | 17 | 4.4 | 1283 | Silicate | heaths | Leptosol | mineral, organic | W, G |
| NO-03 | Norway | 59.1 | 10.9 | 31 | 7.3 | 745 | Silicate | heaths | Podzol | mineral, organic | (W), G, C |

**Table S1.** Selected study sites across the different countries comprising the European transect, with the corresponding spatial coordinates (latitude, longitude), elevation, mean annual temperature (MAT), mean annual precipitation (MAP), soil parent material, vegetation zone, reference soil type, collected horizons (organic (o), mineral (m)) and collected land use types (woodland (W), grassland (G), cropland (C)) along the transect.

| | Between bedrock | | | | Between land use | | | | Between horizons |
|---|---|---|---|---|---|---|---|---|---|
| | F value | Limestone | Sediment | Silicate | F value | Cropland | Grassland | Woodland | F value |
| pH | 37.52*** | c | b | a | 15.63*** | b | b | a | 3.30** |
| roots | 4.07* | a | ab | b | 17.54*** | a | b | b | -3.35** |
| root C:N | n.s. | | | | 19.50*** | a | a | b | n.s. |
| Clay | 17.58*** | c | b | a | n.s. | | | | NA |
| Silt | 4.90** | b | ab | a | 6.40** | ab | b | a | NA |
| CEC | 27.86*** | b | a | a | n.s. | | | | -10.75*** |
| $Fe_{oxalate}$ | 65.35*** | a | b | c | n.s. | | | | NA |
| $Al_{oxalate}$ | 14.45*** | a | a | b | n.s. | | | | NA |
| Fed-o | 11.89*** | b | a | a | n.s. | | | | NA |
| SOC | 9.48*** | a | a | b | 8.65*** | a | ab | b | -11.12*** |
| Total N | 1.67* | n.s. | n.s. | n.s. | n.s. | | | | -10.07*** |
| $Protein_{NaOH}$ | 15.19*** | a | a | b | 6.41** | a | ab | b | -3.68** |
| % $Protein_{NaOH}$ | 24.26*** | a | b | c | 7.76** | a | a | b | 5.00*** |
| Total P | n.s. | | | | 19.36*** | b | b | a | -3.66** |
| TOP | 3.63** | ab | a | b | 6.14** | ab | b | a | -5.59*** |
| DOC | 4.02* | ab | a | b | 13.81*** | a | a | b | -12.90*** |
| DON | 5.35** | a | a | b | 5.79** | a | ab | b | -10.06*** |
| DOP | 36.02*** | a | b | c | n.s. | | | | -5.78*** |
| FAA-N | 22.93*** | a | a | b | 21.44*** | a | b | b | -7.96*** |
| NH4+ | 7.19*** | a | b | b | 17.91*** | a | b | c | -12.17*** |
| NO3- | n.s. | | | | 9.94*** | b | ab | a | -5.13*** |
| microbial C | 7.43** | b | a | b | 4.96* | a | b | ab | -11.22*** |
| C:N imbalance | 9.66*** | b | a | b | 8.51*** | a | a | b | -6.57*** |
| N:P imbalance | 22.6*** | b | a | a | 3.72* | a | ab | b | -3.91** |
| $PLFA_{gram+}$ | 7.30** | a | a | b | 11.41*** | a | a | b | n.s. |
| $PLFA_{gram-}$ | n.s. | | | | 6.27** | a | a | b | n.s. |
| $PLFA_{Bacteria}$ | n.s. | | | | 8.85*** | a | a | b | n.s. |
| $PLFA_{Fungi}$ | n.s. | | | | n.s. | | | | n.s. |
| $PLFA_{Fungi:Bacteria}$ | n.s. | | | | n.s. | | | | n.s. |
| Peptidase | 19.31*** | b | a | a | 5.26** | b | b | a | -9.73*** |
| $Peptidase_{buffer}$ | 12.94*** | b | a | a | 4.98** | ab | b | a | |
| Depoly | 19.66*** | a | b | b | 4.69* | a | b | b | -9.67*** |
| FAA uptake | 15.51*** | a | b | b | 5.37** | a | b | b | -8.00*** |
| $MRT_{FAA}$ | n.s. | | | | n.s. | | | | n.s. |

Levels of significance: p>0.05 n.s., p<0.05 *, p<0.01**, p<0.001***

**Table S2.** Effect of bedrock, land use and soil horizon on various soil parameters, peptidase activity at natural pH, gross protein depolymerization rates (Depoly), gross microbial amino acid uptake rates (FAA uptake) and mean residence time of free amino acids ($MRT_{FAA}$). Bedrock (limestones, sediments, silicates, n = 95) effects were ontained from one-way ANOVA and land use effects (woodland, grassland, cropland, n = 22) were obtained from two-way ANOVA. Asterisks indicate levels of significance. Significant differences between individual land use or bedrock types obtained from Tukey HSD are

indicated by different letters. Differences between mineral and organic soil horizons were obtained from paired t-tests (n = 13). Soil texture and mineralogy were not analyzed in organic soils (NA).

| | all | | | cropland | | | grassland | | | woodland | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mineral | | | mineral | | | mineral | | | mineral | | | organic | | |
| | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein |
| pH | -0.417*** | 0.663*** | -0.415*** | -0.342 | 0.563** | -0.208 | -0.502*** | 0.720*** | -0.503** | -0.371* | 0.722*** | -0.313 | 0.057 | 0.483 | 0.318 |
| roots | 0.202 | -0.111 | 0.307** | 0.617** | -0.175 | 0.207 | 0.169 | -0.144 | 0.477* | 0.064 | 0.035 | 0.103 | 0.305 | -0.603** | -0.541** |
| root C:N | -0.14 | -0.196 | -0.061 | -0.243 | -0.033 | -0.278 | -0.605*** | -0.118 | -0.484** | -0.034 | -0.193 | -0.198 | -0.242 | -0.016 | -0.129 |
| Clay | -0.224* | 0.284** | -0.167 | 0.269 | 0.295 | 0.181 | -0.473* | 0.315 | -0.319 | -0.225 | 0.226 | -0.118 | NA | NA | NA |
| Silt | -0.115 | 0.315** | -0.148 | 0.342 | 0.154 | 0.319 | -0.143 | 0.404* | -0.261 | -0.272 | 0.27 | -0.172 | NA | NA | NA |
| $CEC_{eff}$ | -0.219* | 0.695*** | 0.022 | 0.126 | 0.681*** | 0.363 | -0.429* | 0.746*** | -0.213 | -0.098 | 0.694*** | 0.121 | 0.402 | 0.619** | 0.642** |
| $Fe_{oxalate}$ | 0.524*** | -0.273* | 0.384*** | 0.524** | -0.238 | 0.653*** | 0.642*** | -0.324 | 0.369 | 0.366* | -0.248 | 0.351* | NA | NA | NA |
| $Al_{oxalate}$ | 0.459*** | -0.194 | 0.275** | 0.498* | 0.162 | 0.680*** | 0.681*** | -0.232 | 0.402* | 0.312 | -0.299 | 0.063 | NA | NA | NA |
| $Fe_{d-o}$ | -0.096 | 0.310** | -0.075 | -0.098 | 0.538** | 0.078 | -0.128 | 0.169 | -0.385* | -0.107 | 0.421** | -0.034 | NA | NA | NA |
| SOC | 0.438*** | 0.093 | 0.744*** | 0.29 | 0.495* | 0.578** | 0.456* | 0.168 | 0.718*** | 0.492 | 0.102 | 0.651*** | -0.089 | 0.102 | 0.158 |
| Total N | 0.408*** | 0.311** | 0.599*** | 0.366 | 0.529** | 0.607** | 0.523** | 0.138 | 0.727*** | 0.384 | 0.388* | 0.551*** | 0.235 | 0.283 | 0.172 |
| Soil C:N | 0.156 | -0.261* | 0.291** | -0.244 | 0.015 | -0.257 | 0.212 | 0.173 | 0.364 | 0.133 | -0.439** | 0.078 | -0.234 | -0.133 | -0.071 |
| Protein | 0.579*** | -0.078 | | 0.485* | 0.241 | | 0.557** | -0.226 | | 0.699*** | -0.001 | | 0.234 | 0.105 | |
| % Protein | 0.26 | -0.330** | 0.547*** | 0.254 | 0.001 | 0.714*** | 0.246 | -0.464* | 0.622*** | 0.189 | -0.344* | 0.382* | 0.182 | -0.201 | 0.961*** |
| Total P | 0.342*** | 0.250* | 0.220* | 0.241 | 0.278 | 0.532** | 0.613** | 0.143 | 0.480* | 0.234 | 0.229 | 0.287 | 0.025 | 0.239 | -0.025 |
| TOP | 0.510*** | 0.14 | 0.415*** | 0.401 | -0.016 | 0.788*** | 0.741*** | 0.012 | 0.554** | 0.323* | 0.148 | 0.379* | 0.026 | 0.200 | -0.046 |
| DOC | 0.18 | 0.001 | 0.236* | -0.325 | 0.058 | -0.508 | 0.187 | -0.266 | 0.020 | 0.178 | 0.241 | 0.237 | 0.078 | 0.773** | 0.571* |
| DON | 0.675*** | -0.167 | 0.558*** | 0.119 | -0.029 | 0.151 | 0.872*** | -0.309 | 0.548** | 0.672*** | -0.094 | 0.557*** | 0.352 | 0.453 | 0.291 |
| DOP | 0.607*** | -0.358*** | 0.354** | 0.562** | -0.257 | 0.457* | 0.817*** | -0.411* | 0.540** | 0.488** | -0.439** | 0.272 | -0.162 | 0.366 | -0.011 |
| FAA-N | 0.836*** | -0.187 | 0.512*** | 0.475* | -0.130 | 0.588** | 0.874*** | -0.229 | 0.450* | 0.682*** | -0.167 | 0.504** | 0.731*** | 0.512 | 0.667** |
| $NH_4^+$ | 0.222* | -0.213* | 0.422*** | 0.615** | 0.083 | 0.748*** | 0.200 | -0.208 | 0.744*** | 0.111 | -0.244 | 0.243 | 0.897*** | 0.254 | 0.145 |
| $NO_3^-$ | 0.077 | 0.248* | 0.057 | 0.174 | -0.014 | 0.219 | 0.376* | 0.319 | 0.372 | -0.044 | 0.415** | 0.127 | 0.490 | 0.180 | 0.179 |
| microbial C | 0.422*** | 0.282** | 0.677*** | 0.221 | 0.625** | 0.416* | 0.437* | 0.339 | 0.551** | 0.423** | 0.247 | 0.647*** | 0.574* | 0.733** | 0.778** |

| | all | | | cropland | | | grassland | | | woodland | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mineral | | | mineral | | | mineral | | | mineral | | | organic | | |
| | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein | Depoly | Peptidase | Protein |
| $C:N_{imbalance}$ | 0.125 | 0.075 | 0.209* | -0.190 | 0.286 | -0.129 | -0.054 | 0.453* | 0.091 | 0.045 | -0.002 | 0.08 | -0.339 | -0.212 | -0.199 |
| $N:P_{imbalance}$ | -0.124 | 0.517*** | 0.176 | -0.098 | 0.500* | 0.304 | -0.304 | 0.657*** | -0.022 | -0.090 | 0.695*** | 0.148 | -0.093 | -0.448 | -0.153 |
| $PLFA_{gram+}$ | 0.333** | -0.082 | 0.419*** | 0.219 | 0.326 | 0.678*** | 0.692*** | -0.082 | 0.356 | 0.198 | -0.093 | 0.29 | 0.035 | -0.202 | 0.066 |
| $PLFA_{gram-}$ | 0.294** | -0.064 | 0.363*** | 0.197 | 0.581** | 0.532** | 0.520** | -0.119 | 0.302 | 0.128 | -0.084 | 0.212 | -0.027 | -0.184 | 0.037 |
| $PLFA_{Bacteria}$ | 0.317** | -0.074 | 0.405*** | 0.006 | 0.487* | 0.616** | 0.614** | -0.100 | 0.335 | 0.185 | -0.089 | 0.274 | 0.014 | -0.189 | 0.060 |
| $PLFA_{Fungi}$ | 0.186 | -0.049 | 0.307** | -0.068 | 0.540** | 0.554** | -0.068 | -0.161 | -0.061 | 0.111 | -0.055 | 0.191 | 0.205 | -0.202 | -0.010 |
| Fungi:Bacteria | -0.052 | -0.046 | 0.014 | 0.211 | 0.263 | 0.038 | -0.439* | -0.139 | -0.375* | 0.113 | -0.155 | 0.112 | 0.008 | -0.139 | -0.120 |
| Peptidase | -0.199 | | -0.078 | -0.135 | | 0.241 | -0.250 | | -0.226 | -0.243 | | -0.001 | 0.252 | | 0.105 |
| Depoly | | -0.119 | 0.579*** | | -0.135 | 0.485* | | -0.250 | 0.557*** | | -0.243 | 0.699*** | | 0.252 | 0.234 |

Levels of significance: p>0.05 n.s., p<0.05 *, p<0.01**, p<0.001***

**Table S3.** Coefficients of determination (pearson's r) for correlations of gross protein depolymerization rates (Depoly), leucine-amino peptidase activity (Peptidase) and $Protein_{NaOH}$ for all mineral soils (n = 95), mineral horizons of cropland, grassland and woodland soils and organic woodland soil horizons. Asterisks indicate levels of significance. Soil texture and mineralogy was not analyzed n organic horizons (NA).

| | Climate | | Soil properties | |
|---|---|---|---|---|
| | Parameter estimate | p | Parameter estimate | p |
| Intercept | 3.786 | <0.01 | 2.257 | <0.05 |
| | -0.68*MAT | <0.001 | 0.727*Log(ProteinNaOH) | <0.001 |
| | 0.265*MAP | <0.05 | -0.252*pH | <0.01 |
| | -0.212*MAP:MAT | 0.062 | | |
| **$r^2$** | **0.464** | | **0.685** | |

**Table S4.** Linear mixed effect model of log(gross protein depolymerization rate) explained by climate and soil parameters with land use as random effect. Total model fit is given as adjusted $r^2$.

| | Variance explained (%) | F value | p |
|---|---|---|---|
| MAT | 29.1 | 47.8 | <0.001 |
| MAP | 10.1 | 16.5 | <0.001 |
| MAT:MAP | 4.6 | 3.7 | <0.05 |
| Land use | 1.9 | 3.2 | 0.08 |
| **$r^2$** | **0.425** | | |

**Table S5.** Linear model of log(gross protein depolymerization rate) explained by climate, land use and interaction effects. Total model fit is given as adjusted $r^2$.