D09.4 Final model toolkit for cross-site relationships between modelled and observed biodiversity and biogeochemical indicators

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Publishable Executive Summary

Soils and vegetation of terrestrial ecosystems in Europe have been affected by atmospheric deposition of sulphur (S) and nitrogen (N) since at least the 1950’s, at regionally highly varying pressure levels. The soil and vegetation characteristics of the receiving ecosystems show distinct regional variations as well. The pressure of N deposition continues at certain locations, and the ongoing regional climate change manifests itself with different change signals in northern and southern latitudes. The high regional diversity in the pressures as well as in the receiving ecosystems calls for analysis tools which are able to account for site-based data.

In this context the eLTER Project Work Package (WP) 9 or Joint Research Activity 2 (JRA2) concerns “Improving and testing integrated information services for abiotic drivers and ecosystem/biodiversity response”. The Task JRA2.3 focuses on “Integrated services for modelling ecosystem impacts of multiple drivers”, with the objective to develop and apply a modelling toolkit for cross-site relationships between modelled and observed biogeochemical and biodiversity indicators, providing results of application of the models including information on parameters. This objective was met by setting up dynamic modelling tools to forecast and project impacts of multiple drivers: (i) climate change and deposition of N and S impacts on soil variables at 26 diverse sites throughout Europe were simulated, and (ii) the applicability of the model toolkit to long-term data on forest understory vegetation was tested. This Deliverable D09.4 of WP9 Task JRA2.3 provides an overview of the model toolkit with references and links to detailed information on the dynamic models, model application studies, and their results.

Contents

Publishable Executive Summary

1. Introduction

This public report is the eLTER Project Deliverable D09.4 of Task JRA2.3 of the Work Package (WP) 9 or Joint Research Activity 2. WP9 (JRA2) concerns “Improving and testing integrated information services for abiotic drivers and ecosystem/biodiversity response”. Task JRA2.3 focuses on “Integrated services for modelling ecosystem impacts of multiple drivers”, in the context of responses of terrestrial, mainly forested, ecosystems to continuously elevated levels of N deposition, in concert with declining S deposition and on-going regional climate change and warming.

1.1. Objective

The objective of Task JRA2.3 was to develop and present a modelling toolkit to assess cross-site relationships between modelled and observed biogeochemical and biodiversity indicators, providing simulation results and a documentation of the model application including information on parameters. The objective was met by setting up pre-existing dynamic modelling tools to forecast impacts of multiple drivers: regional climate change and deposition of N and S. The key model used was the single-layer soil model VSD+ (Bonten et al. 2016), which accounts for processes of organic C and N turnover as well as charge and mass balances of elements, cation exchange and base cation weathering. We used VSD+ Studio (version 5.6.2, 2017) together with its accompanying pre-processors MetHyd (version 1.9.1, 2017) and GrowUp (version 1.3.2, 2017). We applied the soil dynamic model VSD+ to simulate the impacts of N and S deposition on soil solution pH (pH), soil base saturation (BS) and soil organic carbon to nitrogen ratio (C:N) at 26 sites throughout Europe (Fig. 2, Table A1). The simulations were carried out both under future climate conditions close to current climate, and with 24 regional climate scenarios, representing the two greenhouse gas concentration trajectories (RCP4.5 and RCP8.5) with twelve combinations of a modelling chain of global and regional climate models as well as bias adjustment methods (Supplementary Table A2). The modelling tools were applied to simulate soil responses at 26 diverse sites throughout Europe (Holmberg et al. 2018) and to test the applicability to long-term data on forest understory vegetation (Dirnböck et al. 2018).

2. Modelling tools

We applied the dynamic modelling suite VSD+ (Bonten et al. 2016), using data and services from long-term ecological research infrastructures (Fig. 1). The model chain includes (i) the pre-processor MetHyd for the meteorological and hydrological abiotic inputs, (ii) the GrowUp tool to estimate nutrient turnover, (iii) the single-layer soil model VSD+ to simulate impacts of N and S deposition on soil solution pH, soil base saturation (BS) and soil organic carbon to nitrogen ratio (C:N) (Bonten et al. 2016, Holmberg et al. 2018). These simulated dynamics of soil properties, together with site-based N deposition and climate are input to the statistical plant species niches model PROPS (Dirnböck et al. 2018). The model setup and results are described in detail in Holmberg et al. (2018, open access https://doi.org/10.1016/j.scitotenv.2018.05.299).

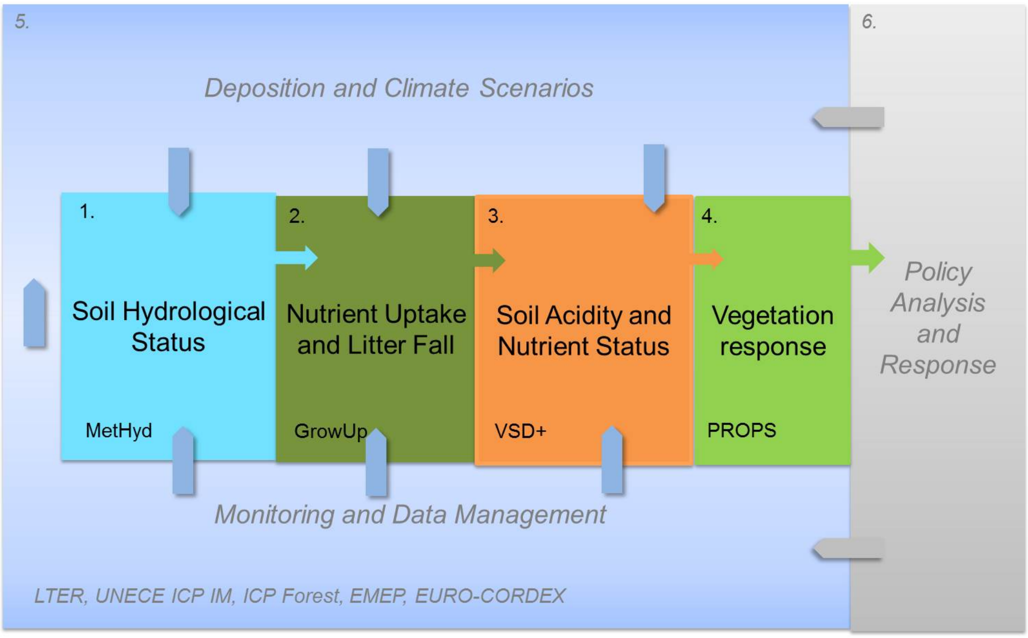

Figure 1: Workflow of ecosystem modelling to forecast impacts of N deposition and climate

2.1 Model results

Future soil conditions improved for about half of the sites in simulations based on current climate and considering only future changes in S and N deposition. In the simulations with current climate conditions and future deposition according to the CLE scenario, soil BS and C:N for the year 2100 were more than 5% higher than for the year 2000 at 16 and 12 sites, respectively, and soil solution pH improved more than 0.02 pH units at 21 sites from 2000 to 2100 (Fig. 6). Not all the sites showed improvement, however, under the CLE deposition scenario, which represents only moderate, although realistic, deposition reductions (Holmberg et al. 2018).

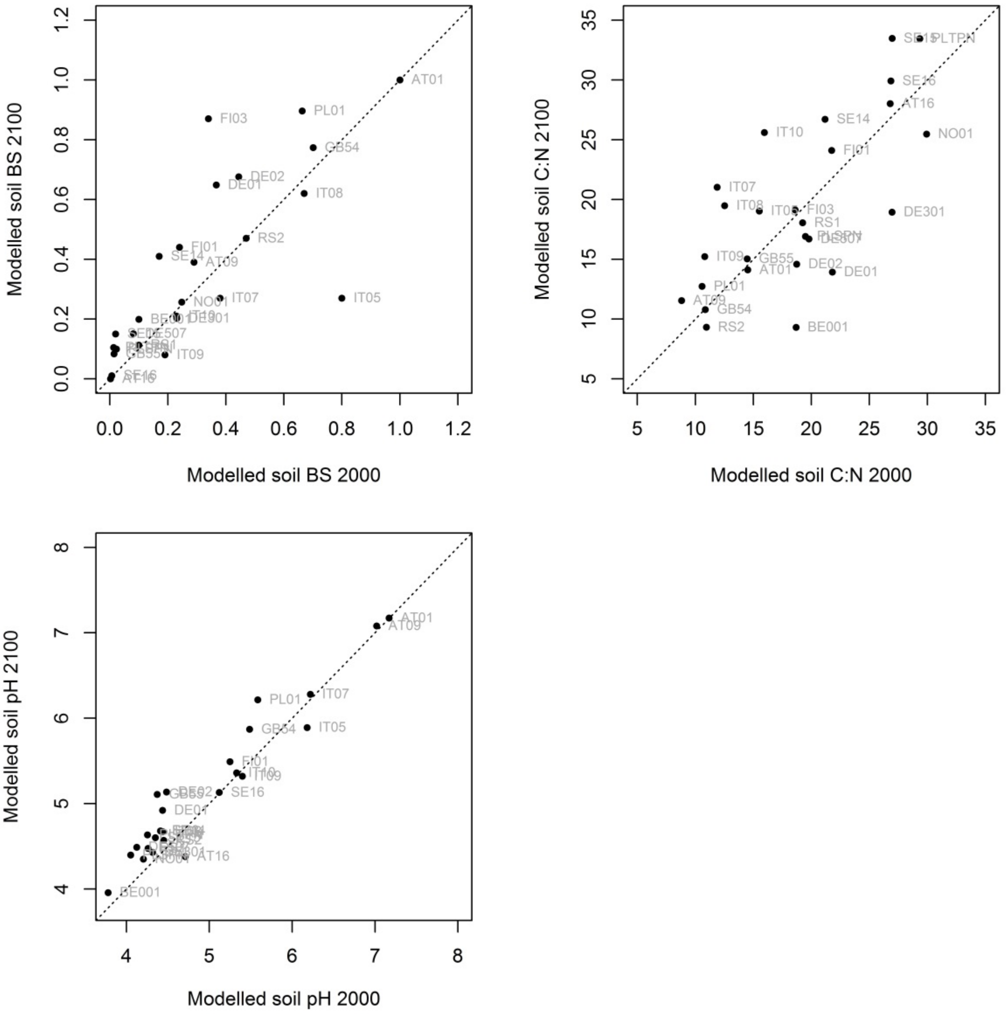

Figure 2. Modelled soil BS, C:N ($g\ g^{-1}$) and pH for the year 2100 versus modelled values for the year 2000. Simulations carried out with the deposition scenario corresponding to current legislation, and with reference climate. Each dot represents the simulated result for one site. Dashed line represents 1:1 line. (From Holmberg et al. 2018). When climate change was included in the scenario analysis, the variability of the results increased. Climate warming clearly had an impact on soil conditions, yielding increases in simulated soil BS, C:N and pH values from the year 2000 to 2100. Especially the increase in C:N was more marked with the climate warming scenarios than with current climate (Fig. 3).

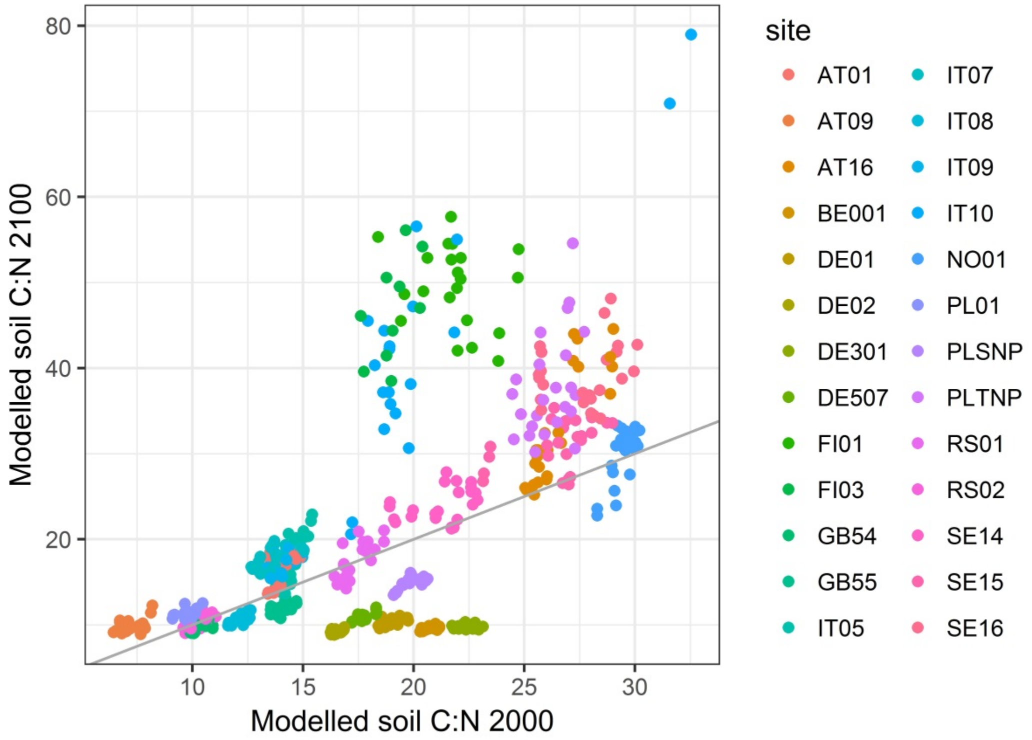

Figure 3. Modelled soil C:N for 2100 versus the value for 2000 for 24 climate scenarios. Each dot represents one simulation driven by a specific downscaling model chain at a particular study site. All simulations with current legislation deposition scenario. The grey line represents 1:1. (From Holmberg et al. 2018).

In climate change simulations, soil solution pH increased for most sites (Fig. 4). Also soil BS increased at many sites on the average. Especially the RCP8.5 scenarios yielded high mean change in C:N, but also RCP4.5 scenarios increased C:N. At nine sites, however, soil C:N decreased for all climate scenarios.

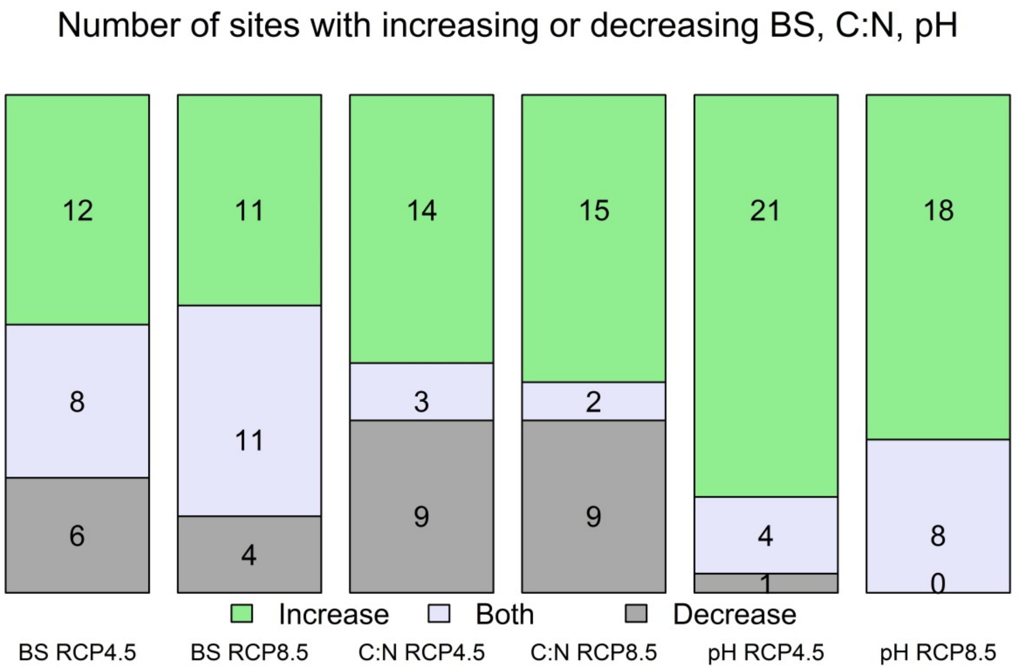

Figure 4. Simulated change in soil variables from the year 2000 to 2100. Number of sites with only increase (top), both increase and decrease (middle) or only decrease (bottom) in BS, C:N or pH. Increase/decrease defined as BS or C:N more than 5% or pH more than 0.02 pH units higher/lower than in 2000. Simulations performed with current legislation deposition scenario and twelve RCP4.5 and twelve RCP8.5 climate scenarios. (From Holmberg et al. 2018).

2.2 Model availability

The MetHyd, GrowUp, VSD+ model software is available for download at no cost from the Coordination Centre for Effects (CCE) at their site dedicated to the VSD+ suite of models: https://www.umweltbundesamt.de/en/cce-data-models. This site includes also four videos on how to use the VSD+ model with details on 1) the use of datafiles; 2) the calibration; 3) interpreting the results and 4) using the vegetation model.

Direct links to the models:

MetHyd: https://cms.umweltbundesamt.de/en/document/methyd-model ;

GrowUp: https://cms.umweltbundesamt.de/en/document/growup-model ;

VSD+ : https://cms.umweltbundesamt.de/en/document/vsdplus-model .

The PROPS model is under further development but available upon request from the main developer Wieger Wamelink, Alterra, Wageningen UR, Wageningen, the Netherlands.

3. Data used for modelling

Site data needed for the modelling included climate data, soil parameters, soil solution chemistry, nutrient cycling variables, and information on ground vegetation. Site-specific information on projected future climate was obtained through the work conducted in Task JRA2.1 by Goergen (2018). This deliverable D09.1 of Goergen (2018) describes also the storage and availability of the climate scenario data. Historic and future scenarios of N and S deposition were obtained from EMEP model results (Schöpp et al. 2003, Simpson et al. 2012). Soil parameters and soil solution chemistry used in the modelling are described in the Supplementary tables of the Appendix A (Holmberg et al. 2018, Supplementary data). The 26 sites of this study are part of the European network for Long Term Ecological Research (LTER Europe), the International Co-operative Programmes on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests), and on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM) under the UNECE LRTAP Convention. The data used for the model applications at the sites are produced by the monitoring and data management infrastructures of these networks. The sites are forested, representing deciduous, evergreen or mixed forest, and boreal forests (taiga). They are located in Europe, in Atlantic, continental, Mediterranean, forested alpine and boreal climate regions. The setup of the PROPS model is described in Dirnböck et al. (2018).

3.1 VSD+ data and parameters

In order to document the integrated ecosystem model structure, Table 1 lists the characteristics of the sites studied in Holmberg et al. (2018). VSD+ is a single layer model, and its input parameters include thickness of soil layer, soil bulk density, clay content and cation exchange capacity (Table 2). Options for simulating cation exchange are the Gaines-Thomas or the Gapon model, which are controlled by the values of the selectivity constants for Al – Bc and H – Bc exchange, where Bc stands for the sum of cations Ca, Mg, K and Na (Bonten et al. 2016). In case organic acids are included in the simulations, one may use either a constant, or a pH dependent dissociation parameter. Other parameters influencing the calculations are the initial values of soil C pool, the initial C:N ratio, and the weathering rates of Ca, Mg, K and Na.

To provide input to the VSD+ model, MetHyd is needed to calculate daily evapotranspiration, soil moisture, precipitation surplus and parameters related to N processes (Bonten et al. 2016). MetHyd reads daily or monthly data on temperature, precipitation and radiation. Input and output variables of MetHyd are listed inTable 3. MetHyd was used with site-specific monthly, or for some sites, daily observed temperature, precipitation, and sunshine or radiation data from local weather stations

GrowUp uses information on forest region, tree species and N deposition. Additional data on litter fall biomass and N concentrations were available. Also, more general area and species specific yield tables were utilized; e.g., information derived from the EFISCEN inventory.

VSD+ can be calibrated using the automatic calibration routine provided with the model. In Holmberg et al. (2018) the final values for the calibrated parameters (Table 4) were obtained through automatic calibration provided with the model, and following visual inspection of the overall performance of the model. The calibration results were evaluated using the normalized mean absolute error (NMAE), the Pearson correlation coefficient, the coefficient of determination (RSqr) and the coefficient of efficiency (CE) evaluation metrics. For each site, observations of soil BS and C:N ratio, soil solution pH and soil solution concentrations [SO42-], [NO3-], [NH4+], [Bc2+] were available for different time periods The key data and parameter values necessary for applying the model toolkit (Tables 1 to 4) are given as illustrations of the application of the model toolkit to guide future studies by individual scientists of the eLTER-sites and the eLTER Research Infrastructure (ESFRI).

3.2 Deposition scenarios

Site-specific values for deposition of S and N were used as input, with deposition values for 2005, 2010, 2020 and 2030 based on the latest EMEP model version using the current legislation scenario (CLE) with revised Gothenburg Protocol emissions. The EMEP model provides receptor-specific deposition, to forest, semi-natural vegetation or as grid-average values at 0.50° × 0.25° resolution. The regional variation in deposition is reflected both in the levels of the historical peak deposition values and those of the cumulative annual deposition values for the period 1880–2100 The levelling off of the decrease in N deposition is reflected in the N deposition projections. Simulations with VSD+ were carried out for the period 1880 to 2100 with the CLE deposition (Holmberg et al. 2018).

3.3 Climate scenarios

For the climate change simulations MetHyd was used with monthly temperature, precipitation and radiation data according to the 12 climate change projections representing RCP4.5 and 12 projections representing RCP8.5. Simulations with the VSD+ model were conducted with climate change projections accounting for the effects of air temperature, drought stress, and N deposition on forest growth by scaling the input to VSD+ resulting from GrowUp. Future warming is more pronounced in some sites than in others, as can be seen from the mean climate change signals (future time span minus past time span) per model combination for the 30-year means of annual average air temperature and annual sum of precipitation for the periods 1980–2009 and 2060–2089, averaged for the 12 ensemble members per RCP (Fig. 5).

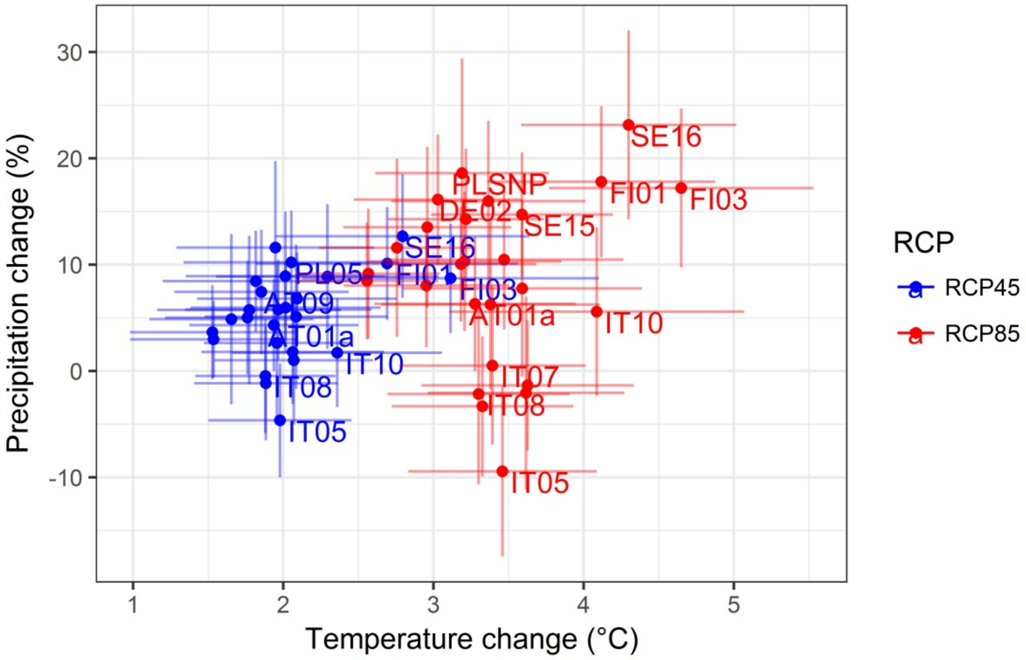

Figure 5. Scatter plot of changes in 30-yr mean values of precipitation (%) versus changes in temperature (°C) from the period 1980 – 2009 to the period 2060 – 2089. Each data point with error bars represents climate change at one site, as average over 12 ensemble members: blue for RCP4.5 and red for RCP8.5. Error bars calculated as standard deviation of 12 ensemble members. Codes AT01 etc. refer to the sites (Table 1).

Table 1. Site characteristics of 26 sites for which the VSD+ model was applied in Holmberg et al. (2018)

Country	Site Code for VSD+ study	Site	Longitude (decimal coord.)	Latitude (decimal coord.)	Altitude (m a.s.l)	Networks[1]	ILTER Biome	Biogeographic region	Soils
Austria	AT01	Zöbelboden IP1	14.44	47.84	895	IM, LTER	Mixed forest	Alpine	Chromic Cambisols and hydromorphic Stagnosols
Austria	AT09	Klausen-Leopoldsdorf	16.05	48.12	510	FO, LTER	Deciduous Forest	Alpine	Endostagnic Endoskeletic Luvisol
Austria	AT16	Murau	14.11	47.06	1540	FO, LTER	Evergreen Forest	Subalpine	Hyperdystric Endoskeletic Cambisol
Belgium	BE001	Brasschaat	4.52	51.31	14	FO, LTER	Evergreen Forest	Atlantic	Moderately wet and sandy Arenosol with distinct horizons of humus and iron, forest floor mor-moder type
Germany	DE01	Forellenbach	13.42	48.94	894	IM, LTER	Deciduous Forest	Continental	Dystric Cambisol
Germany	DE02	Neuglobsow	13.03	53.13	65	IM	Mixed forest	Continental	Eutric Cambisol
Germany	DE301	Lüss	10.28	52.84	125	FO, LTER	Deciduous Forest	Atlantic	Albic Rustic Podzol
Germany	DE507	Monschau	6.15	50.4	445	FO, LTER	Deciduous Forest	Atlantic	Dystric Cambisol
Finland	FI01	Valkea-Kotinen	25.06	61.24	165	IM, FO, LTER	Taiga	Boreal	Cambic Podzol
Finland	FI03	Hietajärvi	30.68	63.15	170	IM, FO	Taiga	Boreal	Haplic Podzol
United Kingdom	GB54	Wytham	-1.33	51.77	138	LTER	Deciduous	Atlantic	Eutric Vertic Stagnosols
United Kingdom	GB55	Alice Holt	-0.85	51.17	125	IM, FO, LTER	Deciduous	Atlantic	Eutric Vertic Stagnosols
Italy	IT05	Selva Piana	13.59	41.85	1500	IM, FO, LTER	Deciduous Forest	Alpine	Orthic Rendzinas
Italy	IT07	Carrega	10.2	44.73	200	IM, FO	Deciduous Forest	Continental	Plano-Gleyic Luvisols
Italy	IT08	Brasimone	11.12	44.11	975	IM, FO	Deciduous Forest	Continental	Calcaric Regosols
Italy	IT09	Monte Rufeno	11.9	42.83	690	IM, FO, LTER	Deciduous Forest	Mediterranean	Calcaric Regosols
Italy	IT10	Val Masino	9.55	46.24	1190	IM, FO, LTER	Evergreen Forest	Alpine	Dystrict Lithosols
Norway	NO01	Birkenes	8.25	58.38	190	IM, FO, LTER	Taiga	Boreal	Podzol and Cambisol
Poland	PL01	Puszcza Borecka	22.05	54.12	170	IM	Deciduous forest	Continental	Luvisol
Poland	PLSNP	Słowiński National Park	17.47	54.7	15	FO, LTER	Evergreen Forest	Continental	Histo-Humic Gleysol
Poland	PLTNP	Tatrzański National Park	19.99	49.27	970	LTER	Evergreen Forest	Alpine	Calcaric Lithosol

Serbia	RS1	Kopaonik	20.81	43.29	1700	FO, LTER	Mixed forest	Continental	Cambic Podzol, Humic Cambisol
Serbia	RS2	Crni vrh	21.98	44.13	940	FO, LTER	Deciduous forest	Continental	Dystric Cambisol
Sweden	SE14	Aneboda	14.53	57.12	230	IM, LTER	Taiga	Boreonemoral	Podzol
Sweden	SE15	Kindla	14.9	59.75	345	IM, LTER	Taiga	Boreal	Podzol
Sweden	SE16	Gammtratten	18.1	63.86	425	IM, LTER	Taiga	Boreal	Podzol and Histosol

[1] Networks:
FO (UNECE ICP Forests, International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests under the United Nation's Economic Commission for Europe);
IM (UNECE ICP IM, International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Ecosystems under the United Nation's Economic Commission for Europe);
LTER (LTER Europe, International Long Term Ecological Research regional network for Europe)

Table 2. Input VSD+ parameter values used in Holmberg et al. (2018).

Site	Thickness (m)	Bulk density (g cm^{-3})	CO_2 pressure	Calcium in parent material (1)	Clay content (%)	CEC (meq kg^{-1})	Exchange model (2)	Organic acids model (3)	Parameters organic acids model (4)	Concentration of organic acids (mol m^{-3})
AT01	0.5	0.611	18	0.5	38.0	511.2	-	Mono-protic organic acid	4.5	0.320
AT09	0.59	1.099	19.2		43.0	68.5	Gaines-Thomas	Mono-protic organic acid	4.5	0.050
AT16	0.45	0.671	15.3		21.0	74.6	Gaines-Thomas	Mono-protic organic acid	2.8	0.066
BE001	0.8	1.450	23		5.0	15.0	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.062
DE01	0.7	1.410	15		3.0	36.2	Gapon	Mono-protic organic acid	4.5	0.500
DE02	0.8	1.300	15		2.3	30.6	Gapon	Mono-protic organic acid	0	0.250
DE301	0.8	1.293	15		5.5	70.3	Gapon	Mono-protic organic acid	0	0.500
DE507	0.8	1.196	15		27.2	93.0	Gapon	Mono-protic organic acid	0	0.500
FI01	0.435	0.954	33		5.3	46.8	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004
FI03	0.435	1.342	33		1.0	6.8	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004
GB54	0.4	1.149	33		80.0	222.2	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004
GB55	0.4	1.149	33		60.0	279.7	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004
IT05	0.2	0.871	19.5		26.0	166.5	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.010
IT07	0.6	1.063	24.3		21.0	125.2	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.010
IT08	0.42	1.269	22.7		30.0	123.8	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.010
IT09	0.53	1.183	24		25.0	178.8	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.010
IT10	0.53	0.905	20.2		15.0	197.5	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.010
NO01	0.4	0.654	33		10.0	311.0	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.065
PL01	1	1.300	30		25.0	250.0	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.005
PLSNP	0.7	1.300	33		5.0	30.0	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004
PLTNP	0.5	1.300	33		5.0	60.0	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.004

RS1	0.8	0.768	20		16.7	351.8	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.050
RS2	0.8	1.190	20		13.3	533.9	Gaines-Thomas	Oliver model	0.96; 0.9; 0.039	0.050
SE14	0.8	0.819	4		27.8	21.3	Gaines-Thomas	Mono-protic organic acid	4.5	0.200
SE15	0.7	0.949	4		25.0	9.5	Gaines-Thomas	Mono-protic organic acid	8	0.050
SE16	0.8	0.819	4		21.9	7.1	Gaines-Thomas	Mono-protic organic acid	4.3	0.500

(1) For calceareous soils, fraction (0 - 1) of Ca in parent material: if 0 pure calcite; if 1 pure dolomite.

(2) Type of model used for cation exchange in non-calcareous soils.

(3) Type of model used for simulating dissociation of organic acids (Bonten et al.2016).

(4) Parameters for organic acid dissociation model.

Table 3. MetHyd input and output used in Holmberg et al. (2018).

site	Albedo (1)	Theta_Sat (2)	Theta_FC (3)	Theta_1bar (4)	Theta_WP (5)	Sand_ct (6)	OrgC_ct (7)	Period of data (8)	rf_nit (9)	rf_denit (10)	rf_miR (11)	Theta (12)	Percolation (13)	TempC (14)	Precip (15)
AT01	0.11	0.58	0.43	0.36	0.24	8.80	2.71	1997-2013	0.80	0.80	0.83	0.49	1.23	6.16	1.77
AT09	0.14	0.55			0.24	6.60	1.50	1985-2013	0.92	0.92	1.08	0.40	0.32	8.88	0.72
AT16	0.11	0.65			0.24	43.00	7.30	1985-2013	0.58	0.58	0.63	0.43	0.86	4.22	1.16
BE01								1930-2008	1.10	0.003	1.10				
DE01	0.14	0.56	0.31	0.21	0.08	62.00	0.20	1991-2012	0.74	0.01	0.40	0.32	0.46	5.80	0.97
DE02	0.14	0.42	0.10	0.06	0.02	90.44	0.80	1991-2012	1.06	0.00	0.50	0.11	0.10	7.90	0.60
DE301	0.14	0.45	0.15	0.10	0.04	84.88	1.33	1991-2012	1.01	0.00	0.20	0.13	0.17	8.58	0.70
DE507	0.14	0.50	0.35	0.30	0.20	11.75	2.12	1991-2012	1.02	0.04	0.20	0.35	0.37	8.93	0.98
FI01	0.11	0.55	0.33	0.25	0.14	65.80	0.31	1963-2015							
FI03	0.11	0.45	0.20	0.14	0.06	89.97	0.14	1971-2015							
GB54	0.14	0.52	0.46	0.40	0.28	10.00	3.31	1993-2012	0.49	0.15	0.73	0.38	0.12	9.94	0.73
GB55	0.14	0.52	0.46	0.40	0.28	15.00	2.64	1995-2012	0.50	0.17	0.79	0.39	0.22	10.73	0.83
IT05	0.14	0.59	0.41	0.35	0.23	31.00	3.54	1998-2011							
IT07	0.14	0.53	0.37	0.31	0.21	37.00	3.52	1998-2011							
IT08	0.14	0.48	0.33	0.28	0.19	34.00	1.45	1999-2010							
IT09	0.14	0.50	0.35	0.30	0.20	31.00	2.56	1998-2011							
IT10	0.11	0.58	0.35	0.26	0.12	55.00	1.31	1997-2008							
NO01								1993-2014	0.56	0.07	0.65	0.26	1.02	4.91	1.52
PL01	0.14	0.38	0.26	0.24	0.08			1993-2013	0.76	0.01	0.62	0.19	0.12	6.64	0.66
PLSNP	0.11	0.45	0.14	0.09	0.04	85.00	1.00	1960-2010	0.86	0.00	0.90	0.12	0.23	7.51	0.65
PLTNP	0.11	0.45	0.14	0.09	0.04	85.00	1.00	1960-2010	0.40	0.00	0.42	0.14	1.03	1.46	1.33
RS1	0.11	0.63	0.40	0.31	0.16	59.16	3.90	1990-2014	0.52	0.0001	0.55	0.34	0.47	3.98	0.99
RS2	0.11	0.49	0.29	0.23	0.13	43.58	2.17	1990-2014	0.59	0.00	0.65	0.22	0.20	7.01	0.79
SE14	0.11	0.60	0.43	0.38	0.28	38.84	7.00	1901-2013							
SE15	0.11	0.57	0.40	0.35	0.25	38.01	5.00	1901-2013							
SE16	0.11	0.60	0.42	0.36	0.26	44.43	7.00	1901-2013							

MetHyd inputs

1) Albedo (0 - 1) defaults: conifer 0.11, deciduous 0.14, grassland 0.22
2) Water content at saturation as a volume fraction (0-1), given or computed in MetHyd from soil properties
3) Water content at field capacity (pF 2.0) as a volume fraction (0-1), given or computed in MetHyd from soil properties
4) Water content at -1 bar (pF 3.0) as a volume fraction (0-1), given or computed in MetHyd from soil properties
5) Water content at wilting point (pF 4.2) as a volume fraction (0-1), given or computed in MetHyd from soil properties
6) Sand content of the soil (%)

7) Organic carbon content of the soil (%)
8) Period of meteorological data (monthly or daily values of air temperature, precipitation and radiation) used as input to MetHyd
In addition, MetHyd inputs include site longitude and latitude (Suppl Table A1), bulk density and clay content (%) of the soil (Suppl. Table A3)
MetHyd outputs read by VSD+, either as period average values, or as annual or monthly values
9) Reduction factor of nitrification rates due to moisture and temperatue (-)
10) Reduction factor of denitrification rates due to moisture and temperatue (-)
11) Reduction factor of mineralisation rates due to moisture and temperature (-)
12) Water content of the soil (m3 m3)
13) Precipitation surplus (m/yr)
14) Average temperature T (oC)
15) Precipitation P (m/yr)

Table 4. Calibrated VSD+ parameter values from Holmberg et al. (2018).

Site	Initial C pool (g m^{-2})	Initial C:N (g g^{-1})	lgK_AlBc (1)	lgK_HBc (2)	lgK_Alox (3)	Initial BS (4)	Ca weathering (eq m^3 yr^{-1})	Mg weathering (eq m^3 yr^{-1})	K weathering (eq m^3 yr^{-1})	Na weathering (eq m^3 yr^{-1})
AT01	6015	5	-	-	6.15	-	10.000	10.000		
AT09	9000	8	16.43	2.57	8.90	-	0.468	0.304	0.309	
AT16	28000	23	6.82	3.47	8.00	-	0.010	0.010	0.100	
BE001	14657	35	-0.89	-1.09	7.46	-	0.010	0.001	0.001	0.003
DE01	7000	28	0.17	2.03	7.90	0.60	0.150	0.200	0.150	
DE02	27516	21	0.14	2.00	7.89	0.67	0.200	0.010	0.093	0.0004
DE301	10000	34	0.10	2.67	7.90	0.26	0.006	0.006	0.011	
DE507	10370	22	0.75	2.08	7.90	0.20	0.108	0.053	0.116	
FI01	1200	5	0.50	6.30	6.00	0.35	0.060	0.070	0.020	0.020
FI03	300	2	-5.00	1.00	7.00	0.45	0.025	0.008	0.008	0.008
GB54	11850	10	0.16	6.73	7.90	-	0.173	0.035	0.025	0.025
GB55	15032	18	0.16	6.73	7.90	-	0.294	0.148	0.025	0.025
IT05	4480	10	8.50	2.00	8.00	0.70	0.014	0.007	0.004	0.002
IT07	2000	15	12.00	3.00	8.00	0.60	0.055	0.022	0.014	0.024
IT08	8000	15	-5.00	0.21	8.00	0.60	0.011	0.004	0.005	0.049
IT09	14000	8	6.97	3.77	8.00	0.33	0.032	0.013	0.008	0.014
IT10	3033	20	4.26	2.53	8.00	0.34	0.023	0.009	0.006	0.010
NO01	10453	52	0.10	1.98	6.22	0.29	0.050	0.004	0.004	0.012
PL01	7000	8	3.00	7.00	6.00	0.40	0.800	0.100		
PLSNP	5093	25	0.001	0.07	7.90	0.10	0.005		0.001	0.001
PLTNP	6650	20	0.003	0.003	7.90	0.20	0.020		0.001	0.001
RS1	6358	10	5.02	2.21	6.00	0.07	0.083			
RS2	5793	10	0.30	2.08	8.00	0.46	0.100			
SE14	8000	25	0.16	3.80	7.90	0.20	0.020	0.030	0.010	0.010
SE15	10000	25	0.16	3.80	7.90	-	0.020	0.012	0.002	0.010
SE16	5000	25	0.16	4.00	7.90	0.10	0.020	0.010	0.001	0.010

(1) Log10 of selectivity constant for Al-Bc exchange
(2) Log10 of selectivity constant for H-Bc exchange
(3) Log10 of Al equilibrium constant ((mol/l) $^{-2}$)
(4) Initial base saturation. If missing, its value is determined by the model assuming equilibrium conditions at the start.

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