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Modelling study of soil C, N and pH response to air pollution and climate change using European LTER site observations

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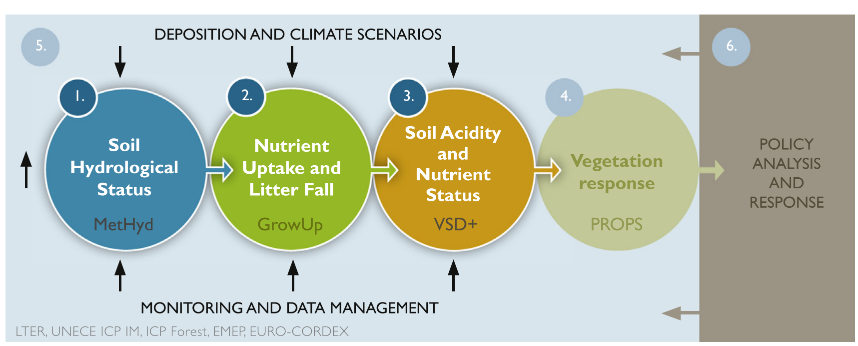
HIGHLIGHTS

- VSD+ dynamic soil model was applied at diverse LTER-Europe sites.
- We employ data from LTER, UNECE ICP IM and ICP Forest networks.
- Soil pH and BS were projected to increase under decrease in S, N deposition.
- Simulations with climate warming gave more variable results.
- Climate warming led to higher soil C:N at half of the sites, lower at one third.

GRAPHICAL ABSTRACT



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ABSTRACT

Current climate warming is expected to continue in coming decades, whereas high N deposition may stabilize, in contrast to the clear decrease in S deposition. These pressures have distinctive regional patterns and their resulting impact on soil conditions is modified by local site characteristics. We have applied the VSD+ soil

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dynamic model to study impacts of deposition and climate change on soil properties, using MetHyd and GrowUp as pre-processors to provide input to VSD+. The single-layer soil model VSD+ 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 calibrated VSD+ at 26 ecosystem study sites throughout Europe using observed conditions, and simulated key soil properties: soil solution pH (pH), soil base saturation (BS) and soil organic carbon and nitrogen ratio (C:N) under projected deposition of N and S, and climate warming until 2100. The sites are forested, located in the Mediterranean, forested alpine, Atlantic, continental and boreal regions. They represent the long-term ecological research (LTER) Europe network, including sites of the ICP Forests and ICP Integrated Monitoring (IM) programmes under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), providing high quality long-term data on ecosystem response. Simulated future soil conditions improved under projected decrease in deposition and current climate conditions: higher pH, BS and C:N at 21, 16 and 12 of the sites, respectively. When climate change was included in the scenario analysis, the variability of the results increased. Climate warming resulted in higher simulated pH in most cases, and higher BS and C:N in roughly half of the cases. Especially the increase in C:N was more marked with climate warming. The study illustrates the value of LTER sites for applying models to predict soil responses to multiple environmental changes.

1. Introduction

Current climate warming is expected to continue in coming decades, while high European nitrogen (N) deposition may stabilize, in contrast to the clear decrease in sulphur (S) deposition (Tørseth et al., 2012; Waldner et al., 2014; Fagerli et al., 2016). The long-term impacts of N on vegetation and biodiversity in terrestrial ecosystems have been identified (Bobbink et al., 2010; Dirnböck et al., 2014; Ferretti et al., 2014) and are likely to continue unless deposition rates decline. Impacts of N on leaching water quality continue, while those of S decline with deposition (De Wit et al., 2015; Vuorenmaa et al., 2018). Climate warming and air pollution have distinctive regional patterns and their resulting impact on soil conditions and vegetation is modified by local site characteristics (Jones et al., 2004; Bertini et al., 2011; Pardo et al., 2011; Merilä et al., 2014; Jonard et al., 2015). There is increasing recognition that anthropogenic pressures and consequent environmental responses are best studied in concert in a multidisciplinary setting (e.g., De Vries et al., 2017; Mirtl et al., 2018). The direct effects of air pollution on ecosystems and habitats have been addressed through research and policy development underpinning the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP Convention) (e.g., Holmberg et al., 2013; De Wit et al., 2015; Vuorenmaa et al., 2017). Informed use of science to promote sustainable development is advanced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (e.g., Barnosky et al., 2012; Honrado et al., 2016). Climate change effects on ecosystems and biodiversity have been studied extensively (e.g., McMahon et al., 2011; Corlett and Westcott, 2013; Garcia et al., 2014; He et al., 2016). Air pollution and climate change interact in numerous ways, and can mitigate effects, e.g., through increased CO_2 uptake in N-polluted forests (De Vries et al., 2006), or worsen them, e.g., through increased N_2O fluxes under N pollution, or the combined acidifying effects of N and S deposition (e.g., Forsius et al., 2005; Garmo et al., 2014). Understanding and predicting ecosystem responses to 21st century environmental change requires the capacity to simulate the combined effects of different drivers on soils, vegetation and species diversity. Combined models that include soil and species responses may provide this capacity (De Vries et al., 2010). The coupled biogeochemical and vegetation community model VSD + PROPS has been applied in the United States by McDonnell et al. (2018), who found that historical changes in N deposition had pronounced impacts on simulated HSI, a biodiversity metric (Rowe et al., 2016).

In this study we demonstrate an application of the VSD+ model (Bonten et al., 2016), with its pre-processors MetHyd and GrowUp, to 26 ecosystem study sites throughout Europe. The objectives of this work were i) to compile and report the necessary data to apply the model chain at 26 sites; ii) to evaluate the VSD+ calibration to current observations; iii) to describe future projections of soil solution pH, soil BS, C:N at 26 sites. The presented VSD+ calibrations are intended to be used for further modelling including vegetation responses. This paper provides the first phase for a demonstration of the use of a model chain that may ultimately provide input to policy analysis (Fig. 1). The sites where the models were applied represent the LTER-Europe site network (Haase et al., 2018; Mollenhauer et al., 2018), covering a wide range of environmental conditions within several distinct biomes. By including (partly co-located) sites of the ICP Forests and ICP Integrated Monitoring programmes under the LRTAP Convention (ICP Forests, 2018; ICP IM, 2018), we were able to make use of high quality long-term data on ecosystem response. We also used data provided by the European Monitoring and Evaluation Programme (EMEP, 2018). To our knowledge, this is the first multi-site application of the VSD+ model chain at such a broad regional extent in Europe.

2. Methods

2.1. Modelling approach

We used a systems approach in applying a detailed model chain employing data and services from long-term ecological research infrastructures (Fig. 1). The single-layer soil model VSD+ (Bonten et al., 2016) 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, Supplementary Table A1). The simulations were carried out both under future climate conditions close to current climate, and with 24 regional climate scenarios, representing 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).

2.2. Models

2.2.1. MetHyd

MetHyd is the meteo-hydrological pre-processor for hydro-meteorological data of VSD+ to calculate daily evapotranspiration, soil moisture, precipitation surplus and parameters related to N processes (Bonten et al., 2016). MetHyd reads daily data on temperature,