The Soil Profile Database for the National Forest Inventory Plots in Germany Derived from Site Survey Systems

Raphael BENNING [a (*)], Bernd AHRENDS [b], Hagen AMBERGER [c], Johanna DANIGEL [d], Jürgen GAUER [c], Silke HAFNER [b], Franziska HEINZ [h], Michael JANOTT [e], Simon MAYER [d], Tobias METTE [f], Andreas PIEPER [g], Heike PUHLMANN [h], Winfried RIEK [i], Christian STEINICKE [b], Evelyn WALLOR [i], Rainer PETZOLD [a]

* Corresponding author

[a] Staatsbetrieb Sachsenforst, Kompetenzzentrum Wald und Forstwirtschaft, Referat Standortserkundung, Bodenmonitoring und Labor, Bonnewitzer Str. 34, D-01796 Pirna

[b] Nordwestdeutsche Forstliche Versuchsanstalt, Abteilung Umweltkontrolle, Grätzelstr. 2, D-37079 Göttingen

[c] Landesforsten Rheinland-Pfalz, Forschungsanstalt für Waldökologie und Waldwirtschaft, Außenstelle Forsteinrichtung Koblenz, Standortskartierung, Südallee 15-19, D-56068 Koblenz

[d] ThüringenForst, Forstliches Forschungs- und Kompetenzzentrum Gotha, Jägerstrasse 1, 99867 Gotha

[e] Landesbetrieb Wald und Holz NRW, Lehr- und Versuchsforstamt Arnsberger Wald, Schwerpunktaufgabe Waldplanung, Waldinventuren, Waldbewertung, Brößweg 40, D-45897 Gelsenkirchen

[f] Bayerische Landesanstalt für Wald und Forstwirtschaft (LWF), Abteilung 2 Boden und Klima, Hans-Carl-von-Carlowitz-Platz 1, D-85354 Freising

[g] Landesforst Mecklenburg-Vorpommern, Betriebsteil FVI, FG 031, Schlossallee 9, D-19306 Friedrichsmoor

[h] Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, Abteilung Boden und Umwelt, Wonnhaldestr. 4, D-79100 Freiburg

[i] Landesbetrieb Forst Brandenburg, Landeskompetenzzentrum Forst Eberswalde (LFE), Fachbereich 2 Waldentwicklung und Monitoring, Fachteam Bodenkunde, Alfred-Möller-Str. 1, D-16225 Eberswalde

Email address of all the authors: raphael.benning@smul.sachsen.de, rainer.petzold@smul.sachsen.de, bernd.ahrends@nw-fva.de, silke.hafner@nw-fva.de, christian.steinicke@hlug.hessen.de, juergen.gauer@wald-rlp.de, johanna.danigel@lwf.bayern.de, michael.janott@wald-und-holz.nrw.de, tobias.mette@lwf.bayern.de, andreas.pieper@lfoa-mv.de, heike.puhlmann@forst.bwl.de, evelyn.wallor@zalf.de

Keywords soil profile data, legacy data, National Forest Inventory, site mapping

Funding

The work is part of the WP-KS-KW project which was funded within the frame of the Waldklimafonds by the Federal Ministry of Food and Agriculture and the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (support code 28WC1003).

Data availability:

The datasets generated during the current study are available in the OpenAgrar repository via the URL https://www.openagrar.de/receive/openagrar_mods_00049873. DOI: 10.3220/DATA20190625100522

Abstract

Key message The soil database covers data about forest site conditions and detailed soil physical data of characteristic soil profiles for the National Forest Inventory (NFI) plots in Germany. It can be used for modelling forest growth depending on soil as well as calculating water or air capacity of soils.

Context The NFI is used for policy advice and increasingly for research on climate change, tree growth and their interrelationship. Detailed soil data for modelling site dependent tree growth at the NFI plots was missing.

Aims One goal of the *Waldklimafonds* project "*Forest productivity, carbon sequestration, climate change"* was to create a harmonized database containing forest site conditions, associated soil profiles and related physical data at the NFI plots.

Methods We used legacy soil data from forest site mapping, soil mapping of regional authorities, and particularly data from the National Forest Soil Survey. The collected information was harmonized by regional site survey experts according to a mandatory manual.

Results For about 92 % of the NFI plots the current soil database contains detailed soil physical data for horizons: depths of horizons, texture, bulk density, skeletal content, base material, stratification, and others.

Conclusion Now a unique database with precise soil data for the NFI plots is available.

Background

The German National Forest Inventory (NFI) plays a key role in forest policy in Germany and its federal states, and has gained increased importance for scientific research on tree species distribution under conditions of climate change (Kölling et al. 2016, Brandl et al. 2014, Albert & Schmidt 2010, Polley et al. 2010). The NFI covers the entire national territory of Germany on a permanent 4 × 4 km sampling grid (basic grid), with some regions (federal states) sampled at higher resolutions (grids condensed to 2.83 × 2.83 km or even 2 × 2 km). At each grid node, an inventory cluster (German: *Trakt*) is installed and given a unique identifier number (TNR). Each inventory cluster consists of four plots which receive a code from 1 to 4 (ENR). The WP-KS-KW selection criteria (German: *Waldproduktivität – Kohlenstoffspeicherung – Klimawandel*; English: 'Forest Productivity – Carbon Sequestration – Climate Change) for the NFI soil database refers to the data of the second NFI published in 2009 (Thünen-Institut 2009). The selection includes all inventory plots on the 4 × 4 km grid belonging to the forest classes of: productive, unproductive, and temporarily unstocked forest land; and the accessibility class (details on class definitions of site accessability available in BMELV 2011). These criteria were met by 26,450 inventory plots of 9,381 inventory clusters. One inventory cluster consists of four plots. In contrast to the detailed data on forest composition, forest structure and forest growth at the NFI plots, soil data are available only very coarse and heterogeneous. Within the framework of the WP-KS-KW project, the 'Soil Profile' module was focused on the collection and harmonisation of detailed soil profile data at the NFI plots from the federal forests site survey. The scale in forest site mapping is 1:10,000 to 1:5,000, while general soil maps are available at a resolution of 1:25,000 up to 1:100,000. A site unit is the mapping unit in forest site survey, which represents a spatial unit with distinct physical and ecological characteristics (AK Standortskartierung 2016). The representative soil profile for the site unit can be either a single soil profile from field data, or an artificial soil profile compiled from several field measured soil profiles (e.g. legacy soil profiles) which are representative of the specific site unit. This soil profile data is a key input for site and soil dependent growth modelling at the NFI plots, which is the ultimate goal of the WP-KS-KW project. Data collection and harmonisation was coordinated by an expert group of site survey and soil scientists, while regional professionals of the federal forestry administrations compiled data from the specific site survey systems. The WP-KS-KW soil profile database (Benning et al. 2019) contains site characteristics such as: nutrient status (potential status depending on parent material), hydromorphic level, and terrain water status; as well as discrete soil profiles with horizons, texture, stone content, bulk density, and calculated available water capacity in different soil layers.

Methods

Overview of Data Collection and Harmonisation

Forest site surveys in Germany are the responsibility of each individual federal state. As a result, eight different site survey systems exist, each with their own classification schemes. Due to their different levels of soil information quality, a direct derivation of comparable soil data at the national scale is not possible (Petzold et al. 2016). Therefore, an expert group of soil scientists from all participating institutions has developed guidelines for the collection of regional soil data. Following these guidelines, regional professionals have transformed and compiled regional soil datasets of forest site information systems into standardized soil profile datasets. These datasets were subsequently repeatedly checked by the module coordinating team and merged into a uniform national database. The next section provides the developed guidelines for these data sets, and the following sections present the individual methods of each federal state (or region).

The geographical coordinates of the NFI plots were provided by the 'Thünen Institute of Forest Ecosystems'. To account for small scale soil heterogeneity, the geographical coordinates were buffered with a radius of 20 m, which was used to clip the mapped information from the forest site survey or soil maps. The mapped site units were then linked with representative soil profiles of the unit. Details about the federal basis data are presented in the following sections which cover the individual federal states. Each record in the database is comprised of three different levels, which contain the following information:

1. **Plot Level (table 'KOPFDATEN' in database):** accuracy of the geographical coordinates, past liming campaigns (number, year of last campaign, amount of lime applied over one or more campaigns).
2. **Site Unit Level (table 'KARTIEREINHEITEN' in database):** number of units at the plot, mapped unit, abbreviation of the unit, subtype of the unit, area proportion of the unit, soil type, nutrient status, and terrain water status.
3. **Representative Soil Profile Level (table 'LEITPROFIL' in database):** unique identifier for the soil profile, link to the site unit / legend unit, layer number, horizon designation, top and bottom boundaries of the horizon, stratigraphy, bedding, geology, soil texture (i.e. sand, silt, clay, fine sand, medium sand, coarse sand), stone content, bulk density, an indicator for groundwater and/or stagnant moisture conditions, soil organic carbon content, carbonate content, base saturation, and C/N-ratio. See also data description in metadata-sheet "technical" of attached xlsx-file)

Each record in the database was given a quality flag for the different parameters, which indicates the quality or origin of information (i.e. analysed vs. estimated parameter, derived from maps or digital soil mapping approaches …). This indicator was included to ensure reproducibility and to improve the interpretation of parameter values.

Due to the high variability in time, the content of soil organic matter was derived by a nationwide standardised approach. The data of soil organic carbon was taken from the results of the National Forest Soil Inventory / NFSI2 (Grüneberg et al. 2014) and predicted by methods of digital soil mapping (Wilpert et al. 2016).

Methods of the Individual Federal States

Baden-Württemberg

In Baden-Württemberg, soil profile information was assembled based on data from the forest site survey (see in Barnes et al. 1982). A summary is given in table 1.

Table 1: Summary about processed data for the derivation of soil profile data in Baden-Württemberg

forest area	1.372 mha (3,231 NFI plots)
system for soil information (mapped forest area)	vegetation-oriented, homogenous within 7 subunits (78 %)
legacy soil profiles (total/digitized)	7000/1000
methodology for derivation of soil profile data	expert-based

Bavaria

In Bavaria, the data sources for the assignation of soil profiles are (1) the digital Bavarian Site Information System (BaSIS; Taeger & Kölling 2016) and (2) the second National Forest Soil Inventory (NFSI2, BMELV 2006).

Table 2: Summary about processed data for the derivation of soil profile data in Bavaria

forest area	2.606 mha (6,110 NFI plots)
site survey system for soil information (mapped forest area)	soil map at a scale of 1:25,000 (BaSIS) (100 %)
methodology for derivation of soil profile data	median of measured profiles per soil unit, 421 different soil units were processed and related to 5.730 NFI plots; directly measured via NFSI2 at 369 NFI plots

Hesse

In Hesse there are two regional soil maps available which contain information required for the project: (1) at a scale of 1:50,000, covering the whole federal state (HLUG 2006); and (2) at a scale 1:25,000 covering southern Hesse (about 6% of the federal state; HLUG 2011). Consequently, we utilized the two BFD soil maps, which contain representative soil profile information for the different soil mapping units (Table 3).

Table 3: Summary about processed data for the derivation of soil profile data in Hesse

forest area	0.894 mha (2,079 NFI plots)
system for soil information (mapped forest area)	general soil maps at a scale of 1:50.000 (100 %) and 1:25,000 (South of Hesse)
methodology for derivation of soil profile data	representative soil profile information per mapped soil unit

Lower Saxony

In Lower Saxony several modelling approaches from digital soil mapping were combined. An overview of input data is given in table 4. Site information of unmapped forest areas was predicted within the modelling framework from Köhler et al. (2016). Groundwater levels were modelled according to Ahrends et al. (2016) using the general soil map of Lower Saxony (1:50,000), terrain attributes of a DEM (10 m resolution), geological maps (1:25,000 and 1:50,000), and climate and vegetation maps. Bulk density estimation was performed by pedotransfer function (PTF) for forest soils (Steinicke et al. 2016).

Table 4: Summary about processed data for the derivation of soil profile data in Lower Saxony

forest area	1.205 mha (2,792 NFI plots)
system for soil information (mapped forest area)	forest site maps at a scale of 1:25,000 (50%) and general soil maps at a scale of 1:50,000 (100%)
legacy soil profiles, digitized and analyzed	6,343
methodology for derivation of soil profile data	modelling and digital forest site mapping and representative soil profile information per mapped soil unit

Schleswig-Holstein

In Schleswig-Holstein, a modelling approach similar to Lower Saxony was used to extract soil profile information. Input data and overview is given in table 5.

Table 5: Summary about processed data for the derivation of soil profile data in Schleswig Holstein

forest area	0.173 mha (4,38 NFI plots)
site survey system for soil information (mapped forest area)	forest site maps at a scale of 1:25,000 (80 %) and general soil maps 1:25,000/1:200.000 (100%)
legacy soil profiles; digitized	4,759
methodology for derivation of soil profile data	median of measured profile information per site unit (60 %) and representative soil profile information per mapped soil unit from general soil map (40 %)

Hamburg and Bremen

Soil information for the NFI plots were supplied using the soil profile information from general forest soil map 1:1 Mio. in Hamburg and general soil map 1:25,000. Summary is given in table 6.

Table 6: Summary about processed data for the derivation of soil profile data in Hamburg and Bremen

forest area	0.014 mha (13 NFI plots)
system for soil information (mapped forest area)	general soil map at a scale of 1:1 Mio. and 1:50,000 (100%)
methodology for derivation of soil profile data	representative soil profile information per mapped soil unit

North Rhine-Westphalia

In North Rhine Westphalia the soil data at the NFI plots were extracted from detailed soil maps at a scale of 1:5,000 and a general soil map at a scale of 1:50,000.

Table 7: Summary about processed data for the derivation of soil profile data in North Rhine-Westphalia

forest area	0.910 mha (2,141 NFI plots)
system for soil information (mapped forest area)	general soil maps at a scale of 1:5,000 (66%) and 1:50,000 (100 %)
methodology for derivation of soil profile data	representative soil profile information per mapped soil unit

Rhineland-Palatinate

In Rhineland-Palatinate, soil data were gathered from the forest site survey (table 8). This comprised the latest digital dataset of the site survey (site survey map, 9,500 soil profiles with georeferencing), with the addition of results from digital site predictions made following the methods of Gauer et al. (2016), and the results of a simplified site estimation for municipal forest areas (Gauer 2015).

Table 8: Summary about processed data for the derivation of soil profile data in Rhineland-Palatine

forest area	0.840 mha (2,024 NFI plots)
site survey system for soil information (mapped forest area)	three systems of different quality (n.a.)
legacy soil profiles (total/digitized/analyzed)	9,500/6,300/2,700
methodology for derivation of soil profile data	expert-based with legacy soil profiles and terrain analysis of DEM

Saarland

Only a scarce amount of data was available for the derivation of soil information in Saarland (see table 9). Given this data scarcity, additional sources had to be utilized, including a 1:100,000 scale soil map, a 12.5 m DEM, and a subset of forest soil profiles from the Saarland soil information system (SAARBIS).

Table 9: Summary about processed data for the derivation of soil profile data in Saarland

forest area	0.103 mha (243 NFI plots)
system for soil information (mapped forest area)	forest site maps at a scale of 1:10,000 (39 %) and general soil map 1:100,000 (100%)
legacy soil profile information	2357 mainly from Pürckhauer soil sampler
methodology for derivation of soil profile data	expert-based derivation of representative soil profiles via GIS and Terrain analysis

Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt and Thuringia

In the federal states Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt, Thuringia and also Brandenburg, there exists a consistent practice of forest site mapping. This is due to the fundamental works of Dietrich Kopp in the lowland of north-eastern Germany and Walther Schwanecke in the hilly and mountainous region of middle and south-eastern Germany respectively. Since 1963 they formed a one-level and supra-regional system of forest site mapping (Eberhardt et al. 1967). The forest site survey map at a scale of 1:5,000 to 1:10,000 provides site units with detailed vertical soil information which is documented in a catalogue of local soil forms (Schulze 1998, Schwanecke 1994). Besides aggregated information there exists a remarkable amount of legacy soil profiles with both original field estimations and laboratory measurements respectively, as well as additional explanatory material. The assembly of soil profiles was based on the digital forest site survey map and related explanatory volumes, as well as legacy and latest soil profiles and soil auger holes. Soil profiles or auger holes within a distance of 500 m around the NFI plots were used as representative profiles for the plot if their assigned local soil form was identical with the mapped local soil form. Otherwise if the distance was greater and there was more than one soil profile for a local soil form available, then they were aggregated by statistical methods (Beaudette et al. 2013, Benning et al. 2016), taken from data base (Kopp & Jochheim 2002) or derived by expert knowledge of soil professionals.

Table 10: Summary about forest area and processed data for the derivation of soil profile data in Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt and Thuringia

Mecklenburg-Western Pommerania	
forest area	0.558 mha (1,127 NFI plots)
system for soil information (mapped forest area)	forest site soil maps at a scale of 1:10,000 (94 %)
legacy soil profiles (total/digitized/analyzed)	20,000/-/-
methodology for derivation of soil profile data	representative soil profile information per mapped soil unit
Saxony	
forest area	0.553 mha (1,164)
system for soil information (mapped forest area)	forest site soil maps at a scale of 1:10,000 (90 %)
legacy soil profiles (total/digitized/analyzed)	10,000/10,000/1,000
methodology for derivation of soil profile data	statistical modelling of representative soil profile information per mapped soil unit
Saxony-Anhalt	
forest area	0,532 mha (1,190 NFI plots)
system for soil information (mapped forest area)	forest site soil maps at a scale of 1:10,000 (62 %) and general soil map at a scale of 1:25,000 (100 %)
legacy soil profiles (total/digitized/analyzed)	n.a./500/n.a.
methodology for derivation of soil profile data	representative soil profile information per mapped soil unit
Thuringia	
forest area	0,549 mha (1,284 NFI plots)
system for soil information (mapped forest area)	forest site soil maps at a scale of 1:10,000 (90 %)
legacy soil profiles (total/digitized/analyzed)	7,000/1,800/1800
methodology for derivation of soil profile data	statistical modelling of representative soil profile information per mapped soil unit

Brandenburg and Berlin

The soil profile information for the NFI plots in Brandenburg was compiled via a combination of modelling approaches. Soil data input was taken from forest site survey (Schulze 1998, Konopatzky 2012, Kopp & Jochheim 2002) and national forest soil inventory (see table 11). For the majority of NFI plots a modelling framework was applied using the regionalisation approach of Russ (2015), prediction of ground water dynamics according to Hannappel and Riek (2011) and pedotransfer functions (Russ 2015, Adams 1973). Forecast quality was determined through a comprehensive comparison of the NFSI2 data pool of Brandenburg, and the output generated by Russ (2015) and Wallor et al. (2016).

In Berlin, the data was extracted from site survey system for the eastern part and other soil information systems for the western part (SenStadtUm 2010).

Table 11: Summary about processed data for the derivation of soil profile data in Brandenburg and Berlin

forest area	0.1,131 mha (2,435 + 35 NFI plots)
system for soil information (mapped forest area)	forest site maps (80%) and general soil map 1:300,000 (100%)
soil profiles with detailed analytic results	315 (NFSI2)
methodology for derivation of soil profile data	direct information at NFI plots (153), derivation via modelling approach (2,300) and representative soil profile information per mapped soil unit from soil information system (35)

Data Access and Metadata Description

The soil database developed in this project was compiled as a Microsoft Access database (*.mdb) and archived at the Open Agrar server. Access to the database is provided via the URL: https://www.openagrar.de/receive/openagrar_mods_00049873. The database consists primarily of five data tables (as shown in Fig. 1), plus seventeen explanatory tables. The metadata are provided by the Microsoft Excel spreadsheet "*M1_Data_paper_v1.xlsx"* in the supplements.

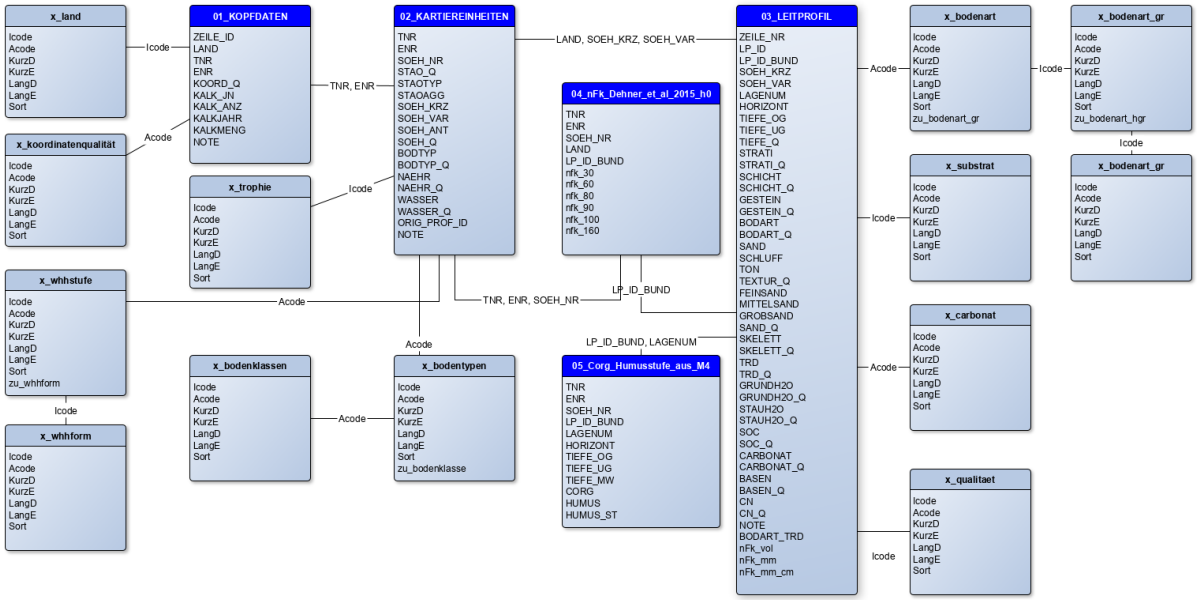

Fig. 1 Scheme of the relationships between the data tables (visualised as boxes) of the soil database. Main tables are indicated by darkblue headers with white titles, whereas explanatory tables('x_parameter') have light blue headers. The key parameters for linking the tables are written near the arrow bars. The term 'Icode' means numerical code and the term 'Acode' stands for alphanumerical code.

Technical Validation

The individual datasets for each federal state were collected by the module coordinating team, and extensively checked for technical and soil science-specific consistency. For this validation, first it was determined if each dataset covered all NFI plots of the respective federal state, and if all specified parameters were reported. In addition, the plot coordinates used for data derivation were checked for accuracy. Extensive plausibility checks were then conducted to verify the value ranges for the following parameters: year of last liming, number and total dosage of all liming campaigns, nutrient status, geological mapping unit, parent material, sand / silt / clay content, fine sand fractions, stone content, bulk density, soil organic carbon content, carbonate content, base saturation, and C/N ratio.

Further, the soil type classification, the horizon designations, and the depth-wise numeration were examined, in order to validate the layering. Texture sums were checked for completeness (100 % ± 0.1 %), and the upper and lower boundaries of the horizons were checked to prevent horizon gaps and overlapping or missing horizons. The congruence between the soil texture class of a record and its contents of sand, silt, and clay were also checked. The labelling of stagnant conditions or groundwater in a horizon was cross-validated with the horizon designation. Finally, the datasets were examined for redundancy, and approximately 20 % of each federal state dataset was validated visually to identify potential irregularities in the soil physical parameters or federal state specific values. Particular attention was paid to the vertical gradients of stone content and bulk density, which are likely to increase with depth (cf. Steinicke et al. 2016).

This dataset validation procedure was conducted iteratively together with the regional professionals until all requirements were successfully fulfilled. After the validation was complete, the final federal states datasets were joined into the nationwide WP-KS-KW soil profile database. To ensure the technical operability of this database, each individual soil profile was matched with an individual soil profile identification number (LP_ID_BUND), and the relationships between the data tables were verified.

Reuse Potential and Usage Limitations

The WP-KS-KW soil profile database was developed to make forest site survey data and detailed representative soil profile data together with data on climate (Dietrich et al. 2019) available at the NFI plots. Thus, it provides a comprehensive basis for investigations of the impacts and relationships between sites, soil conditions, and forest growth; including water budget modelling (Schmidt-Walter et al. 2019) and site dependent growth modelling (Brandl et al. 2019). The soil profile data enables the calculation of soil physical properties, such as available water capacity (e.g. Dehner et al. 2015), field capacity, air capacity, potential cation exchange capacity (e.g. Ad-hoc-AG Boden 2005), surface area exposed to chemical weathering (e.g. Phelan et al. 2004), weathering rates (e.g. Posch et al. 2015), or cation exchange constants (e.g. Spranger et al. 2004). Additionally, the soil database has enormous potential for future harmonization of site classification systems (i.e. estimation of regular nutrient status / terrain water status).

However, there are also some limitations to the database, which could reduce its usability for some applications. In particular, the inclusion of values for nutrient status, soil organic carbon, base saturation, and C/N ratio, were not obligatory to the individual federal states, and were not subjected to the same level of verification as other database parameters. For example, nutrient status was only estimated in terms of the potential status depending on the parent material, and hence it is not a suitable indicator for current nutrient conditions, which will be affected both by previous and current element inputs (e.g. sulphur, nitrogen). In addition, the primary data used for the derivation of representative soil profiles was largely comprised of legacy soil profile data collected since the 1960s, for which there are no timestamps available to indicate the date of sampling or laboratory analysis. Given the environmental changes and advances in laboratory analysis methods which have occurred since the 1960s, there is relatively high uncertainty in the values of soil organic carbon, base saturation, and C/N ratio at different points in time. Therefore these values are not suitable for the calculation of soil carbon storage or other conditional properties. A more suitable data source for these calculations may be the soil database created by a regionalization approach, based on the data of the National Forest Soil Inventory (Wilpert et al. 2016).

Acknowledgements

We thank the German Waldklimafonds, an initiative of the German Federal Ministry of Food and Agriculture and the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, for the funding within the frame of the project '*Forest Productivity, Carbon Sequestration, Climate Change'* (German: '*Waldproduktivität – Kohlenstoffspeicherung – Klimawandel'*).

References

Adams WA (1973) The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. J Soil Sci 24(1):10–17. http://dx.doi.org/10.1111/j.1365-2389.1973.tb00737.x

Ad-hoc-AG Boden (2005): Bodenkundliche Kartieranleitung. vol 5, Hannover: p 438

Ahrends B, Steinicke C, Köhler M, Meesenburg H (2016) Estimation of depth to groundwater level for forest sites in the lowlands of Lower Saxony. For Ecol Landsc Res Nat Conserv 16: 69-81

AK Standortskartierung (2016) Forstliche Standortsaufnahme [engl.: forest site survey], vol 7. IHW-Verlag, Eching bei München, p 400

Albert M, Schmidt M (2010) Climate-sensitive modelling of site-productivity relationships for Norway spruce (Picea abies (L.) Karst.) and common beech (Fagus sylvatica L.). For Ecol Manage 259(4):739-749. doi: org/10.1016/j.foreco.2009.04.039

Barnes, VB, Pregitzer, KS, Spies, TA, Spooner, VH (1982) Ecological Forest Site Classification. Journal of Forestry 80: 493-498

Beaudette DE, Roudier P, O'Green AT (2013) Algorithms for quantitative pedology: A toolkit for soil scientists. Comput Geosci 52:258-268. doi: 10.1016/j.cageo.2012.10.020

Benning R, Ahrends B, Amberger H, Danigel J, Gauer J, Hafner S, Heinz F, Janott M, Mayer S, Mette T, Pieper A, Puhlmann H, Riek W, Steinicke C, Wallor E., Petzold R (2019) Soil data for the National Forest Inventory plots in Germany. Microsoft Access Database. doi: 10.3220/DATA20190625100522

Benning R, Petzold R, Danigel J, Gemballa R, Andreae H (2016) Generating characteristic soil profiles for the plots of the National Forest Inventory in Saxony and Thuringia. For Ecol Landsc Res Nat Conserv 16: 35-42

BMELV (2011) Aufnahmeanweisung für die dritte Bundeswaldinventur (BWI³) (2011 – 2012) [engl.: Survey instructions for the 3rd National Forest Inventory (NFI)], vol 2. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, Bonn

BMELV (2006) Arbeitsanleitung für die zweite bundesweite Bodenzustandserhebung im Wald (BZE II) [engl.: survey instructions for the second National Forest Soil Inventory (NFSI2)], vol 2. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, Berlin

Brandl S, Falk W, Klemmt HJ, Stricker G, Bender A, Rötzer T, Pretzsch H (2014) Possibilities and Limitations of Spatially Explicit Site Index Modelling for Spruce Based on National Forest Inventory Data and Digital Maps of Soil and Climate in Bavaria (SE Germany). Forests 5:2626-2646. doi: 10.3390/f5112626

Brandl, S., Mette, T., Falk, W. et al. (2018) Static site indices from different national forest inventories: harmonization and prediction from site conditions. Ann For Sci 75: 56. https://doi.org/10.1007/s13595-018-0737-3

Dehner U, Renger M, Bräunig A, Lamparter A, Bauriegel A, Burbaum B, Hartmann K-J, Hennings V, Idler F, Krone F, Martin W, Meyer K, Waldmann F (2015) Neue Kennwerte für die Wasserbindung in Böden – Ergebnisse der Abstimmung zwischen dem Personenkreis Wasserhaushaltstabellen der Ad-hoc-AG Boden und dem DWA. Berichte der DBG. Available via: http://eprints.dbges.de/1160/

Dietrich, H, Wolof, T, Kawohl, T, Wehberg, J, Kändler, G, Mette, T, Röder, A, Böhner, J (2019) Temporal and spatial high-resolution climate data from 1961 to 2100 for the German National Forestry Inventory (NFI). Ann For Sci 76: 6. doi: https://doi.org/10.1007/s13595-018-0788-5

Eberhardt E, Kopp D, Passarge H (1967) Site and vegetation of the forest of Kirchleerau in the Swiss lowland, Canton Aargau. IN: Ellenberg H (ed.) Ecological and pedological methods of forest site mapping - Results of an international comparison of methods in the Swiss lowland. Veröffentlichungen des Geobotanischen Instituts der ETH Zürich 39: 280-281

Gauer J, Behrens T, Steinrücken U (2016) Digital Forest Site Mapping – an effective procedure for the acquisition of site information. Forstarchiv 87:121-131. doi: 10.4432/0300-4112-87-121

Gauer J (2015) Dokumentation zur Ableitung der Bodendaten an den BWI-Traktecken des Bundeslandes Rheinland-Pfalz (RLP, Modul 1). Project report. Supplementary material

Grüneberg E, Ziche D, Wellbrock, N. (2014) Organic carbon stocks and sequestration rates of forest soils in Germany. Global Change Biology 20: 2644-2662

Hannappel S, Riek W (2011) Berechnung des Flurabstandes des oberflächennahen Grundwassers der Waldfläche Brandenburgs für hydrologisch typische Zeiträume. Hydrol Wasserwirtsch 55(1):4-15

HLUG (2006) Digitale Bodenflächendaten von Hessen 1:50,000 (BFD50). Hessisches Landesamt für Umwelt und Geologie; Fachinformationssystem Boden/Bodenschutz. Stand 18. August 2006

HLUG (2011) Digitale Bodenflächendaten von Hessen 1:25,000 (BFD25). Hessisches Landesamt für Umwelt und Geologie; Fachinformationssystem Boden/Bodenschutz. Stand 02. September 2011

Köhler M, Steinicke C, Evers J, Meesenburg H, Ahrends B (2016) Modelling water and nutrient regime of forests in the framework of the forest site map of Lower Saxony. For Ecol Landsc Res Nat Conserv 16: 83-94

Kölling C, Mette T, Knoke T (2016) Forest productivity and cultivation risk in an uncertain climate future. Swiss For J 167:29-38. doi: 10.3188/szf.2016.0029

Konopatzky A (2012) Das Wasser macht's - Substratfeuchte in der forstlichen Standortsgliederung - erste Skalierungs- und Bewertungsansätze in Brandenburg. In: Wissenstransfer in die Praxis - Beiträge zum 7. Winterkolloquium. Eberswalder Forstliche Schriftenreihe, vol 49, pp 73-82. http://www.mil.brandenburg.de/sixcms/detail.php/bb1.c.231253.de

Kopp D, Jochheim H (2002) Forstliche Boden- und Standortsdaten des Nordostdeutschen Tieflands als Datenbasis für die Landschaftsmodellierung. Verlag Dr. Kessel, Remagen-Oberwinter, p 207

Petzold R, Benning R, Gauer J (2016) Soil information in the different forest site mapping systems of Germany: current state and perspectives. For Ecol Landsc Res Nat Conserv 16: 7-17

Phelan J, Belyazid S, Kurz D, Guthrie S, Cajka J, Sverdrup H., Waite R (2014) Estimation of Soil Base Cation Weathering Rates with the PROFILE Model to Determine Critical Loads of Acidity for Forested Ecosystems in Pennsylvania, USA: Pilot Application of a Potential National Methodology. Water Air Soil Pollut 225: 2109

Polley H, Schmitz F, Hennig P, Kroiher F (2010) Chapter 13 Germany. In: Tomppo E, Gschwantner T, Lawrence M, McRoberts R (ed): National Forest Inventories. Pathways for Common Reporting. Springer, Heidelberg, p 594

Posch M, Vries de W, Sverdrup H (2015) Mass Balance models to derive critical loads of nitrogen and acidity for terrestrial and aquatic ecosystems. In: Vries de W, Hettelingh J-P, Posch M: Critical Loads and Dynamic Risk Assessments. Environmental Pollution, 25. Springer. Dordrecht, Heidelberg, New York, London. pp 171-205

Russ A (2015) Regionalisierung des Wasser- und Kohlenstoffhaushalts für die Waldfläche Brandenburgs - Entwicklung von Regionalisierungsansätzen unter besonderer Berücksichtigung der forstlichen Standortskarte. Bodenökologie und Bodengenese, vol 44. p 164

Schmidt-Walter P, Ahrends B, Mette T, Puhlmann H, Meesenburg H (in review) NFIWADS: the water budget, soil moisture, and drought stress indicator database for the German National Forest Inventory (NFI). Ann For Sci 76: 39. https://doi.org/10.1007/s13595-019-0822-2

Schulze G (1998) Anleitung für die forstliche Standortserkundung im nordostdeutschen Tiefland (Standortserkundungsanleitung) SEA 95, Bd. D. Bodenformen-Katalog. Merkmalsübersichten und -tabellen für Haupt- und Feinbodenformen, vol 3. Schwerin, p 252

Schwanecke W (1994) Merkmalstabellen für Haupt- und Lokalbodenformen der forstlichen Standortserkundung in den Standortsregionen Mittelgebirge und Hügelland der ostdeutschen Länder (Bodenformen-Katalog), Weimar, 200 p

SenStadtUm (2010) Konzeptkarte der Bodengesellschaften, Senatsverwaltung für Stadtentwicklung und Umwelt Berlin. http://fbinter.stadt-berlin.de/fb/wms/senstadt/k01_01boges2010?. Accessed 8 Apr 2015

Spranger T, Lorenz K, Gregor H D (2004) Manual on methodologies and criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends. Texte Umweltbundesamt, Federal Environmental Agency (Umweltbundesamt). Berlin, p 266

Steinicke C, Köhler M, Ahrends B, Wellbrock N, Evers J, Hilbrig L, Meesenburg H (2016) Pedotransfer functions for estimation of bulk density of forest soils in Germany. For Ecol Landsc Res Nat Conserv 16: 95-107

Taeger S, Kölling C (2016) Standortsinformationssystem BaSIS [engl.: Site information system BaSIS]. AFZ-DerWald 71(4):10-13

Thünen-Institut (2009) Zweite Bundeswaldinventur - Basisdaten (Stand 2009). https://bwi.info/Download/de/BWI-Basisdaten/ThuenenGDI/ Accessed 20 Sep 2016

Wilpert von K, Zirlewagen D, Puhlmann H. (2016) Regionalization of soil data for Germany – data basis, target variables, model performance for two exemplary test regions. For Ecol Landsc Res Nat Conserv 16: 109-120

Wallor E, Russ A, Riek W (2016) Validation of regionalised soil information of forest soils by examining site specific growth performance of Scots pine in Brandenburg. For Ecol Landsc Res Nat Conserv 16: 121-129