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Methodology to assess and map the potential development of forest ecosystems exposed to climate change and atmospheric nitrogen deposition: A pilot study in Germany

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HIGHLIGHTS

- A spatial explicit methodology for evaluating integrity of forests was developed.
- Data on vegetation, soil condition, climate change and atmospheric were used.
- Forest types were classified based on data from 21,600 stands.
- Integrity was investigated by comparing current, future and reference states.
- Potential future conditions of forests were proved to be positive and negative.

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ABSTRACT

A methodology for mapping ecosystems and their potential development under climate change and atmospheric nitrogen deposition was developed using examples from Germany. The methodology integrated data on vegetation, soil, climate change and atmospheric nitrogen deposition. These data were used to classify ecosystem types regarding six ecological functions and interrelated structures. Respective data covering 1961–1990 were used for reference. The assessment of functional and structural integrity relies on comparing a current or future state with an ecosystem type-specific reference. While current functions and structures of ecosystems were quantified by measurements, potential future developments were projected by geochemical soil modelling and data from a regional climate change model.

The ecosystem types referenced the potential natural vegetation and were mapped using data on current tree species coverage and land use. In this manner, current ecosystem types were derived, which were related to data on elevation, soil texture, and climate for the years 1961–1990. These relations were quantified by Classification and Regression Trees, which were used to map the spatial patterns of ecosystem type clusters for 1961–1990. The climate data for these years were subsequently replaced by the results of a regional climate model for 1991–2010, 2011–2040, and 2041–2070. For each of these periods, one map of ecosystem type clusters was produced and evaluated with regard to the development of areal coverage of ecosystem type clusters over time. This evaluation of the structural aspects of ecological integrity at the national level was added by projecting potential future values of indicators for ecological functions at the site level by using the Very Simple Dynamic soil modelling technique based on climate data and two scenarios of nitrogen deposition as input. The results were compared to the reference and enabled an evaluation of site-specific ecosystem changes over time which proved to be both, positive and negative.

1. Background and goal

Approximately 30% and 40% of the German and European land surface, respectively, are covered by forests (EU, 2014). Their structures and functions and, subsequently, their service to human societies may be influenced by climate change and air pollution as structures and functions are reconstructed and other ecosystem types evolve (Allen, 2009; Allen et al., 2010; Bobbink et al., 2010; de Vries et al., 2014; de Vries and Posch, 2011; EEA, 2012; EUROSTAT, 2012; FAO, 2009, 2010; FOREST EUROPE, UNECE, FAO, 2011; Gobiet et al., 2014; Luedeling et al., 2013; Manion, 1991; Maroschek et al., 2009; Nagajyoti et al., 2010; Paoletti et al., 2010; Richardson et al., 2013; Stankovic et al., 2014; Tanino et al., 2010; Vitasse et al., 2009a,b, 2011; Vose et al.,

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2012; Wulff et al., 2012). Simpson et al. (2014) were able to show that climate and emission changes impact nitrogen (N) deposition. Changes in ecosystems often are noted in references to ecosystem quality, ecosystem state, ecosystem condition, ecosystem health, and ecosystem integrity (Holyoak and Hochberg, 2013) and linked to various diversity/stability and scaling concepts (Fränzle, 1994; Chase and Knight, 2013; Chave, 2013; Ives and Carpenter, 2007; Loreau and de Mazancourt, 2013; Saint-Béat et al., 2015; Thibaut and Connolly, 2013).

Certain functions and structures of ecosystems are valued by people because they serve to regulate ecosystem conditions and the related aspects mentioned above, provide material products and contribute non-material human benefits. To safeguard the regulating, provisioning and cultural services of ecosystems, their structures and functions need to be monitored and protected. This is the aim of environmental directives and conventions such as the EU Biodiversity Strategy to 2020 and the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention, UNECE, 2013). The framework of the Air Convention, and the activities therein that refer to climate change and ecological structures and functions, comprises the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) and the Working Group on Effects, which manage six International Cooperative Programmes (ICP). The ICP Forests, ICP Vegetation and ICP Integrated Monitoring are of special relevance for assessing the impacts of climate change and air pollution on ecological structures and functions.

Theoretical models and empirical studies have identified linkages between changes in biodiversity and ecological functions (Balvanera et al., 2006; Doherty et al., 2000; Hooper et al., 2005). Even minor losses in the number of species may reduce ecosystem functions and stability aspects such as resilience when faced with environmental change. This is especially true for those species that each uniquely contributes to the functioning of the ecosystem. The possibility of reduced ecosystem function is increased as more species are lost due to reductions in substitutability. Thus, biodiversity and ecosystem functions are co-dependent, and therefore, biodiversity is vital to maintaining functioning ecosystems and vice versa (Maynard et al., 2010, 2011; Midgley, 2012; Petter et al., 2013). Under action 5 of the EU Biodiversity Strategy to 2020, the condition of ecosystems and their services should be mapped and assessed across Europe. To this end, information about drivers and pressures, such as, for instance, air pollution and climate change, as well as their "impacts on structure and function of each ecosystem type," should be assessed by using *available* data (EU, 2014:20). Thus, a strategy for the Mapping and Assessment of Ecosystems and their Services (EU, 2014) was developed. This Europe-wide approach addresses ecological structures and functions and encompasses ecosystem type and ecosystem condition mapping. Mapping ecosystem condition is used to deliver information about the services each ecosystem type can provide while taking into account climate, geology and other natural factors, as well as the drivers and pressures to which the ecosystem types are exposed. Changes in ecosystem condition due to environmental changes such as land use, air pollution or climate change provide further information about the ecosystem's capacity to deliver services over time. Mapping ecosystems provides information about the spatial extension and distribution of the main ecosystem types and is regarded as the starting point for assessing the condition of each ecosystem type. The ecosystem typology differentiates at three levels and takes into account mapping feasibility at the European scale while aiming at compatibility with national mapping approaches. Additionally, national and sub-national data sources should be used in pilot studies to detail the ecosystem coverage and condition across Europe (EU, 2014).

In Germany, an integrative approach that can cope with potential modifications in ecological structures and functions due to climate change and atmospheric N deposition is still lacking. Therefore, the objective of the study at hand was to develop a comprehensive and spatially explicit methodology for generating and verifying hypotheses on the integrity of forest ecosystems using available data. The methodology should enable an evaluation of *ecosystem integrity* (*ESi*) both at the site level and across Germany.

2. Materials and methods

Focusing on forest ecosystems, the methodology, which was quantitatively developed, achieves the following six objectives: 1. defining ESi; 2. classifying (forest) ecosystem types and establishing an indicator-based reference system; 3. mapping ecosystem types (EsT); 4. generating spatial hypotheses (predictive maps) on potential patterns of EsT regions across time (1961–2070); 5. generating hypotheses (projections) on potential developments of site-specific ESi indicators for the years 2011–2070 by numeric modelling; and 6. evaluating potential developments in ESi.

2.1. Defining ecosystem integrity (ESi)

Ecosystems are dynamic open systems encompassing plant, animal, and microorganism communities and components such as air, water, soil, and bedrock that interact through fluxes of energy, information and matter that serve as functional units (Fränzle, 1994; Hassan et al., 2005; White et al., 1992). From the interactions among the above-mentioned compartment-specific biophysical structures – the 'architecture' of ecosystems in terms of their horizontal and vertical setting, geographical location, and topographical features – functions (processes) emerge. For scientific understanding environmental policies affecting the physical, chemical and biological conditions (state) of an ecosystem across time need to be monitored and compared to reference systems. These reference systems could be agreed-upon targets in environmental directives such as, at the European level, the Habitats Directive, the Water Framework Directive or the Marine Strategy Framework Directive (European Commission, 2014), or historical or projected potential future conditions. Because many ecological phenomena such as biodiversity or theoretical concepts such as ecosystem integrity are too complex for direct measurements, they are subdivided into measurable units, which serve, when each is taken as a part of the whole, as indicators (Pesch and Schröder, 2006).

We are aware that a multitude of definitions of ecosystem integrity exists, each regarding specific aspects of ecosystem structure

Table 1
Ecosystem functions, corresponding indicators and respective data for quantification of ecosystem integrity.

Ecosystem function	Indicators	Data
(1) Habitat function	Deviations of compositions of species to reference condition, e.g., Kullback-distance (Kullback, 1951; Jenssen, 2010)	Vegetation databases ICP Level 2
(2) Net primary production (NPP)	Deviation of NPP to reference condition	NPP models Forest management
(3) Carbon sequestration	Deviation of biomass and humus condition to reference conditions	Forest management ICP Level 2 Forest soil data Long-term soil observation Atmospheric deposition
(4) Nutrient flow	Deviation of C/N ratio, soil acidity, base saturation and nutrients concentration in needles and leaves to reference conditions	Indicator value models Forest soil data Long-term soil observation Atmospheric deposition
(5) Water flow	Deviation of soil moisture index to reference conditions	Indicator value models Forest soil data Long-term soil observation ICP Level 2
(6) Resilience	Deviation of tree species composition from reference conditions	Potential natural vegetation Forest management Agriculture management