Mapping and evaluation of potential future developments of forests due to climatic changes at the national level with regard to nature protection by example of Germany

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Abstract

According to the principles of the German Strategy for Adaptation to Climate Change nature conservation programmes and instruments should take more account of the findings of climate research, including the relevant uncertainties. In this context, a method for mapping climate-induced changes of natural ecosystem types is presented. It is built on a classification system for natural and near-natural ecosystems in Germany. The modelling approach is based on Classification and Regression Trees and geographic information on climate, soil and vegetation features available with blanket coverage of Germany. This method allows users to produce nationwide maps in a coarse temporal resolution (here: 1961-1990, 1991-2010, 2011-2040, 2041-2070). It is demonstrated how the allocation of the ecosystem types to Habitats Directive Annex I habitat types can be used to estimate potential hazards for the condition of habitat types as a result of climate change.

Keywords: Climate change, ecosystem classification, Germany, monitoring data, potential natural vegetation, reference condition

1. Introduction

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 condition of forest ecosystems using available data. The methodology should enable an evaluation of ecosystem condition both at the site level and across Germany. Focusing on forest ecosystems, the methodology, which was quantitatively developed, achieves the following objectives: 1. classifying forest ecosystem types and generating spatial hypotheses (rule-based maps, predictive maps) on potential patterns of EsT regions across time (1961-2070) at the *national level*; 2. generating hypotheses (projections) on potential developments of *site-specific* forest condition indicators for the years 2011-2070 by numeric modelling; and 3. evaluating potential developments of forest condition at the site and the national level. The paper at hand concentrates on the national level while Schröder *et al*. (submitted for CEST 2017) additionally deal with site-specific geo-chemical modelling.

2. Materials and methods

Indicators of ecological condition should be based on an understanding of the structure and functions of ecosystems. Ecological classifications can help to categorize the variability within and among ecosystem types so that differences among several grades of ecosystem condition can be more clearly recognized (Faber-Langendoen *et al*. 2012 a, 2012 b). According to Hofmann (1997), ecosystem types should be classified as entities characterized by certain homogeneity of significant features of their structures and functions. Accordingly, ecosystem types were categorized using data collected for 21600 forest sites across Germany during the years 1961-1990. The data quantify site factors (soil type, topography, and climate) as well as ecological functions and related structures in terms of habitat function, net primary production, carbon sequestration, nutrient and water flow, in addition to adaptability to climate change and atmospheric N deposition (resilience). With respect to these functions, structures were selected according to their ecological significance (Hofmann 1997; Jenssen *et al*. 2013) and the availability of data for the quantification of corresponding indicators. These data should not only allow for classifying ecosystem types but also enable a comparison of the condition of these ecosystem types over the years from 1961-1990, referred to herein as reference condition. The comparison will involve i) the current ecosystem condition as defined in this investigation by the years 1991-2010, and ii) the potential future ecosystem conditions (2011-2040, 2041-2070), calculated with climate change projections, and with decision tree-based nationwide mapping (this paper) and site-specific numerical modelling (Schröder *et al*. 2015) being applied to both current and future conditions. The data representing the reference condition of ecosystem types (EsT) were derived from and referred to the potential natural vegetation (Bohn *et al*. 2000 / 2003; Suck *et al*. 2010, 2013) and the European Habitats Directive Annex I habitat types (EEC 1992) . According to the respective parameter value interval of the particular ecological function, and by application of a vegetation similarity measure developed by Hofmann and Passarge (1964), each ecosystem type was assigned a code that comprehensively addressed the geographic region, the soil water budget and the biogeochemical budget as indicated by the humus condition. In this way, 135 semi-natural forest ecosystem types and 45 cultivated forest ecosystem types classified and detailed quantitatively by Jenssen *et al*. (2013). The classification system includes not only ecosystem type-specific reference conditions but also potential succession. This is of significance inasmuch, at present, future conditions for only three of the six functional indicators could be estimated by numerical modelling (Schröder *et al*. 2015). Linking the potential natural vegetation (pnV) map (Suck *et al*. 2010) with the dominating ecosystem type that is spatially included in the pnV complexes within a geographic system (GIS) and applying a vegetation similarity measure according to Jenssen (2010) enabled mapping of the potential natural ecosystem types across Germany. Then, the GIS map of potential natural ecosystem types was connected with GIS maps of recent tree species coverage and actual land use, and current ecosystem types were identified by application of the following conditional statements to the aforementioned geodata and mapped: 1. IF dominating land use categories are consistent with current ecosystem types AND tree species coincide with current ecosystem types, THEN current ecosystem types are mapped as current semi-natural ecosystem type. 2. ELSE IF dominating tree species correspond to a cultivated ecosystem type that takes the place of the current ecosystem types on the particular site, THEN this cultivated ecosystem type is mapped as current semi-natural ecosystem type. 3. ELSE the ecosystem is mapped as current non-natural ecosystem type. For identifying potential areal shifts of ecosystem types over time due to climate change, the map of ecosystem types (reference condition 1961-1990) was related to geodata on elevation a.s.l., soil texture, and climate (average monthly minimum, maximum and mean of air temperature, monthly means of relative air humidity, evapotranspiration and precipitation) collected within the reference period 1961-1990. The multiple statistical relations were modelled by Classification and Regression Trees (CART; Breiman *et al*. 1984). The resulting if-then rules identified for the reference period 1961-1990 were then applied to the above-mentioned geodata on escosystem types, elevation a.s.l., soil texture and, iteratively, climate in terms of the aforementioned meteorological phenomena for the periods 1991-2010, 2011-2040, and 2041-2070. These data were computed by the Potsdam Institute for Climate Impact Research for two climate change scenarios with a regional climate model. The application of the CART rules describing the statistical relation between the ecosystem types (reference condition 1961-1990), climate (1961-1990, 1991-2010, 2011-2040, and 2041-2070), elevation above sea level (a.s.l.) and soil texture to the geodata enabled predictive mapping of regions for ecosystem types. Each of these spatial clusters contained ecosystem types with similar relations to elevation a.s.l., soil texture, and climate.

3. Results

The CART model describing the statistical relations between the spatial patterns of current semi-natural ecosystem types with maps on elevation a.s.l., climate and soil texture (Section 2) yielded 44 spatial clusters detailed by Jenssen *et al*. (2013). Each of these regions contains one dominant ecosystem type and several other ecosystems with lower percentages. Nevertheless, the areal percentages of the ecosystem types joined to one region, and all cluster members feature the same relations to elevation, climate and soil texture. The application of the CART rules describing the relations between ecosystem types, elevation and soil texture to the climate projections for the representative concentration pathway RCP 8.5 (IPCC 2013) resulted in the maps depicting the shift of spatial patterns of ecosystem type regions due to climate change. Taking regions 9 and 32 as examples, their areas changed from 9,2 % and 1,1 % of the German territory (1961-1990) to 28,5 % and 0 % (2041-2070), respectively (Fig. 1). Grouping the ecosystem types by their hypsometric and horizontal allocation comprehensively corroborates spatial trends (Table 1). Accordingly, the areal percentages of subalpine knee timber (B) and (high) mountain forests (C, D) was estimated to decrease from approximately 20 % to 14 %, while the coverage of the forest ecosystem types in the low mountains and in the lowlands is expected to increase from ca. 80 % to 87 % (1961-2070). Furthermore, northern European (En), subcontinental (Ed) and central European (Ec) ecosystem types potentially could decrease contrary to the (sub)Atlantic (Ea, Eb) and sub-Mediterranean (Ee) types. Most of these temporal trends were significant with p < 0,1 according to Mann Kendall. Up to now, the weakness of this statistical analysis is that ecosystem types not yet existing in Germany, but, for instance, existing in countries with sub-Mediterranean climates (e.g., central France), should be included in further computations because they could potentially develop with ongoing climate change.

Considering nature protection measures, the ecosystem types were referred to habitat types as defined by the European Habitats Directive (Table 2), enabling an analysis of the areal shifts due to climate change. Compared to the habitat types, the ecosystem types are characterized by a relatively high degree of differentiation and internal homogeneity with respect to specific aspects of ecosystem structure and functioning. For example, the ecosystem type predominantly represents a specific vegetation-related characteristic of a corresponding habitat type.

Table 1. Climate change-induced spatial shifting of ecosystem types grouped by their hypsometric and horizontal allocation

Ecoclimatic classification	1961 -1990	1991 - 2010	2011 - 2040	2041 - 2070	Trend
B – Subalpine knee timber	0,10 %	0,10 %	0,08 %	0,05 %	⬂
C – Higher montane level	5,37 %	4,98 %	4,02 %	3,27 %	⬂⬂
D – Montane level	14,82 %	13,93 %	12,40 %	10,23 %	⬂⬂
E – Lowland to lower montane level	79,71 %	80,99 %	83,50 %	86,45 %	⬀
En – Northern European	0,04 %	0,00 %	0,00 %	0,00 %	⬂⬂
Ea – Atlantic	7,02 %	14,17 %	10,58 %	17,60 %	⬀
Eb – Sub-Atlantic	25,61 %	29,65 %	27,94 %	34,77 %	⬀⬀
Ec – Middle European	16,97 %	8,34 %	10,34 %	8,02 %	⬂⬂
Ed – Subcontinental	4,81 %	4,11 %	8,12 %	0,39 %	⬂⬂
Ee – Sub-Mediterranean	0,05 %	0,10 %	0,07 %	0,15 %	⬀⬀
Eg – Generally	25,23 %	24,63 %	26,46 %	25,53 %	⬀⬀

Explanation: ⬀ = increase; ⬀⬀ = significant increase with p-value according to Mann Kendall < 0,1; ⬂ = decrease; ⬂⬂ = significant decrease with p-value according to Mann Kendall < 0,1

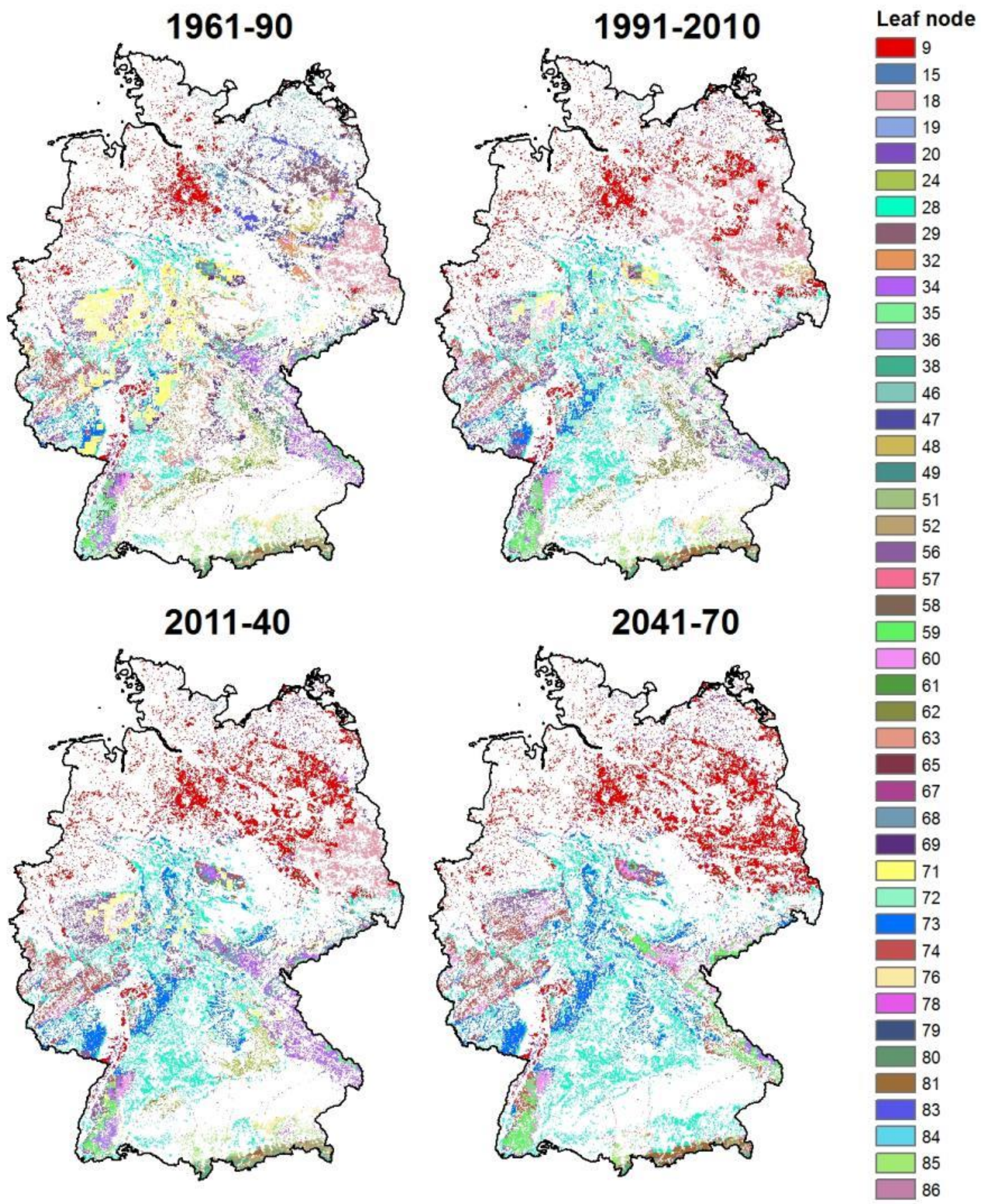

Figure 1. Regions of ecosystem types 1961-1990, 1991-2010, 2011-2040, and 2041-2070.

Explanation: The map shows the spatial distribution of the EsT regions (= spatial EsT classes) with a grid size of 500 by 500 m for the periods 1961-1990, 1991-2010, 2011-2040 and 2041-2070. The underlying CART model consists of 44 leaf nodes (= EsT classes) with a characteristic variance and a predominant csnEsT: 9, 15 = Ea-5n-c2 Atlantic moder pine forest; 18 = Ed-3n-b1 Subcontinental raw-humus pine forest; 19, 28 = Eb-7n-D1 Hygrophilous brown mull beech forest; 20 = Eb-5n-D1 Brown mull beech forest; 24 = Eg-5n-c3 Calciphilous spruce forest; 29, 32, 48, 65, 78 = Ebc-4n-c2 Moder pine forest; 34 = Dg-5n-c2 Moder spruce forest of the mountain level; 35 = C3-6d-B2 Raw-humus spruce, fir and beech forest of the altimontane level; 36 = D2-7s-B2 Hygrophilous raw-humus fir forest of the montane level; 38 = C4-6d-Ta1N Calciphilous spruce forest of the altimontane level; 46, 63, 74 = Eb-5n-D1 Brown mull beech forest; 47 = Ebc-3n-c2 Thermophilous moder pine forest; 49, 69, 72 = Eg-5n-b1 Raw-humus spruce forest; 51, 85 = C3-7n-C2 Hygrophilous moder spruce, fir and beech forest of the altimontane level; 52, 81 = C2-6d-Ta1L Calciphilous spruce, fir and beech forest of the altimontane level; 56, 71, 73 = Eb-5n-C2 Moder beech forest on bunter; 57, 67 = D1-6d-C2 Moder beech forest of the montane level; 58, 68, 79 = Dg-5n-c2 Moder spruce forest of the montane level; 59, 60 = D2-6d-C1 Moder Douglas-fir forest of the montane level; 61 = Eg-5n-c3 Calciphilous spruce forest; 62 = Eb-5r-E2 Calciphilous mull beech forests on slopes; 76 = Eg-5n-c2 Moder spruce forest; 80, 83 = Ebc-4n-c1 Raw humus-moder pine forest; 84 = Ea-5n-c2 - Sandy moder oak and beech forest; 86 = D2-6d-C2 Moder fir and beech forest of the montane level.

Table 2. Climate change-induced spatial shifting of ecosystem types grouped according to assigned European Habitat Directive Annex I habitat types

Habitat type	1961 -1990	1991 – 2010	2011 - 2040	2041 - 2070	Trend
*4070	0,10 %	0,10 %	0,08 %	0,05 %	⬂
9110	12,76 %	14,54 %	13,88 %	16,03 %	⬀
9130	27,01 %	28,96 %	29,38 %	35,11 %	⬀⬀
*91G0	0,16 %	0,09 %	0,15 %	0,02 %	⬂⬂
9410	1,40 %	1,57 %	1,18 %	0,95 %	⬂⬂

Explanation: *4070 = Bushes with *Pinus mugo* and *Rhododendron hirsutum* (Mugo – Rhododendretum hirsutii); 9110 = Luzulo-Fagetum (beech forests); 9130 = Asperulo-Fagetum beech forests; 9410 = Acidophilous Picea forests of the montane to alpine levels (Vaccinio-Piceetea); *91G0 = Pannonic Woods with *Quercus petraea* and *Carpinus betulus* (Tilio-Carpinetum); ⬀ = increase; ⬀⬀ = significant increase with p-value according to Mann Kendall < 0,1; ⬂ = decrease; ⬂⬂ = significant decrease with p-value according to Mann Kendall < 0,1

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