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Silvicultural climatic turning point for European beech and sessile oak in Western Europe derived from national forest inventories

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ABSTRACT

Forests of temperate Europe are climate sensitive ecosystems, and the current balance between the tree species will shift as climate becomes warmer and potentially drier. Especially changes in the dominant species have a strong impact on forest ecosystems because they fundamentally change life conditions of plants and animals living in the forest. Mette et al. (2013) introduced the climatic turning point (CTP) as a concept that marks the climatic conditions where such a change in species dominance is expected to occur. While they modelled the CTP for European beech (*Fagus sylvatica*) and sessile oak (*Quercus petraea*) from environmentally sensitive forest growth models, this study determined the CTP between beech and oak from national forest inventories in Western Europe. We ask (1) under which climate conditions the inventory-based CTP occurs, (2) whether it is modified by soil type and (3) how it differs from other CTP references like the Ellenberg quotient (Ellenberg, 1963).

The CTP from beech to oak occurred approximately at mean annual temperatures above 8–9 °C if annual precipitation was below 600 mm and rose to 11–12 °C for annual precipitation exceeding 900 mm. This relation was strongly modified by soil type. Compared to Ellenberg (1963) and Mette et al. (2013), oak replaced beech at far more moderate climatic conditions (EQ 20–30). This can be attributed to the silvicultural history of forest stands: the inventory-based CTP signal carries the century old anthropogenic preference for oak.

We expand the CTP concept that was until now based on natural competition by a "silvicultural" CTP that is contained in large-scale inventory data. It thereby implicitly incorporates the question how silviculture and social-cultural values impact the balance between species. Climate change projections indeed suggested that large parts of Western Europe will cross the silvicultural CTP.

1. Introduction

European beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Mattuschka) Liebl.) both are major stand-forming forestry species in temperate Europe. The two species have almost identical distributions and often form mixtures, still, oak forests (*Quercetalia robori-petraeae* and *Qu. pubescenti-petraeae*) typically replace beech forests (*Fagetalia sylvaticae*) on warmer and drier sites (Ellenberg, 2009; Hein and Dhôte, 2006; Pretzsch et al., 2013). As climatic conditions in Europe are projected to become warmer and potentially also drier, the competition dynamics between beech and oak will change and favour oak where critical climatic conditions are passed. Ecologically, a change of the dominant species alters living conditions for all forest plants and animals. Given the long production span of traditional forestry, the climatic turning point (CTP) where European beech is replaced by sessile oak, is of high interest also for forest management (Bolte et al., 2009; Hanewinkel et al., 2012). Currently, beech stands are discussed to be supplemented or even replaced by oak to adapt to climate change risk (Köhl et al., 2010; Mette et al., 2013).

Until now the climatic turning point (CTP) between beech and oak was derived both from phyto-sociological relevés (Ellenberg, 2009, 1963) and from empirically parametrized forest growth models (Mette et al., 2013). In both approaches the CTP is defined by the temperature and precipitation at which a reversal in the species dominance is observed. The famous Ellenberg quotient EQ (1000 × July temperature/annual precipitation) was derived from sites where forests had supposedly developed without disturbance.

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European beech clearly dominated for EQ < 20; the oak share increased for 20 < EQ < 30, but oak dominated only beyond EQ > 30 (~500–600 mm annual precipitation). The capability of EQ to predict beech and oak dominance has been assessed in other studies and has been found to be useful (Czúcz et al., 2011; Stojanović et al., 2013). Mette et al. (2013) evaluated simulations of the empirically parameterised forest growth model SILVA and the forest landscape model LandClim for climate trajectories of a warm dry study site. With a mean annual temperature of 11–12 °C and an annual precipitation of 500–530 mm, the resulting CTP ranged at the upper extreme of the Ellenberg quotient.

This study employed a third approach in which the CTP was determined by intersecting large-scale forest inventories with climate and soil data over a great part of the distribution range of both species. So far, especially species distribution models (SDMs) make use of such data sets (Cortés Montaño et al., 2012; Dolos et al., 2015; Falk and Hempelmann, 2013; Meier et al., 2011). Other than SDMs which regard a general prevalence of individual species and have no information on transitions between species, the CTP focuses on the coexistence between two species (or possibly groups of species) and the factors that control it. This is a very straightforward approach particularly when management decisions between two species need to be evaluated.

The search for the climatic turning point between European beech and sessile oak is complicated by two factors. On the one hand, oak was for centuries silviculturally favoured (Aas, 2008; Camus, 1938; Krahl-Urban, 1959; LWF, 2014). Ellenberg (2009) therefore based his temperature-precipitation limit between the species only on "near natural" grown forests and showed that even the core areas of south-German oak silviculture Spessart and Pfalz would climatically be dominated by beech (Gauer and Aldinger, 2005). The same was confirmed for formerly beech-poor mixed oak forests of Fontainebleau (Lemée et al., 1992) or the mighty oak stands of Futaie des Clos (Lebourgeois et al., 2004) which are currently reconquered by beech. Studies prove many cases where beech outperforms oak on even drier sites (Bolte et al., 2007; Gómez-Aparicio et al., 2011; Scharnweber et al., 2011). On the other hand, a certain incompatibility in the ecology of beech and oak makes a clear delineation of a climatic turning point difficult. Due to a strong juvenile growth advance oaks hold out on succession sites after disturbances for at least 20–30 years, even in a clear beech climate (Brouillard, 1911; Lemée et al., 1992). At the same time, established beech stands can delay a transition to oak in an increasingly beech-unfavorable climate through their extremely shading canopy (Mette et al., 2013). As a consequence, the transition from beech to oak is often described as "abrupt" and "no continuous series" (Ellenberg, 2009).

Another issue in the determination of the CTP is the choice of a measure for species dominance. Species dominance and changes in species dominance are the result of different demographic processes such as seed production and their dispersal, establishment and survival of seedling and saplings, growth rate and finally mortality (Dolos et al., 2015; Schurr et al., 2012; Thuiller et al., 2014). All these processes affect the species coexistence and thus, the determination whether or not species switch performance ranks between contrasting environments contributes to developing a mechanistic understanding of species coexistence (Kitajima and Bolker, 2003). A comparably simple but also robust measure which was used by Mette et al. (2013) is the basal area or rather the basal area share of the species. Basal area is measured very precisely via circumference or diameter and is one the most reliable and accessible parameters of forest inventories even in first or singular surveys. Of course, basal area will also show a temporary successional oak dominance in beech climates and, of course, basal area does not spontaneously switch from beech to oak if the climate passes the climatic turning point (the reason to distinguish potential and actual CTP in Mette et al., 2013). Yet, in large-scale inventories the climatic turning point represents a statistical probability which can be expected to balance these effects to a certain degree.

In Ellenberg (1963, p. 19) and Mette et al. (2013) the influence of soil on the CTP could not be derived from the data. Yet, especially when droughts or aridity may tip the balance between one and the other species, soils with high water capacity probably make a difference. Different tolerances of stagnic horizons, heavy clay or acidity are among other soil factors that may shift the CTP or even exclude one species. What makes the inclusion of soil data so difficult is the fact that species preferences are often expressed very vague, soil units themselves are often heterogeneous, and small-scale changes can often not be resolved. In spite of these challenges, studies on species distribution have derived nutrient or fertility indices, texture, and other attributes from thematic maps of soil type or geology and used them in modelling (Brandl et al., 2014; Dolos et al., 2015; Franklin, 1995; Meier et al., 2011).

Compared to the phytosociological (Ellenberg, 1963) and model-based CTP (Mette et al., 2013) the determination of a CTP from a large empirical data set such as national forest inventories permits a more objective and statistically sound analysis. Also, we can stratify according to soil classes as long as they are sufficiently represented in the data. The aims of our study can be formulated in the following questions:

(1) Which temperature and precipitation are empirically determined as the CTP between beech and oak from the inventory data?
(2) Does soil type have an influence on the CTP?
(3) Does the CTP from the inventory data differ from the phytosociological (Ellenberg, 1963) or model-based CTP (Mette et al., 2013)?

The last question allows us identifying methodology-related inconsistencies and contradictions in the CTP and interpreting the reasons for them. This is also important for SDMs, especially, when they are used to take decisions on silvicultural species suitability under climate change.

2. Methods

2.1. Study site and data

The study area covered the distribution area of European beech (*F. sylvatica*) and sessile oak (*Qu. petraea*) in Germany, France and Spain encompassing temperate to submediterranean and oceanic to subcontinental climates. For these three countries, national forest inventory data were openly available providing a great data basis for studies on forest processes (Tomppo, 2009). We filtered all sites where either European beech or sessile oak was dominant, i.e. possessing the largest basal area share of all present tree species. Due to the inventory method, only tree individuals above 7 cm diameter at breast height (DBH) were considered. The information whether beech or sessile oak was dominant served as response variable in the statistical model.

In Germany, the first inventory was conducted between 1986 and 1988 in the federal states of West Germany, the second between 2001 and 2002 for entire Germany and the third between 2011 and 2012. Within this study the second inventory was used. In the German NFI, sites were located in a regular 4 km grid (which was refined in some federal states). At each grid point 1–4 permanent satellites (depending if there was forest) were established in a rectangular with edge length 150 m. At each grid edge stand information based on angle count sampling was recorded (factor 4, syn.