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Towards non-destructive estimation of tree age

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ABSTRACT

Accurate tree age information is required in many contexts ranging from nature conservation to forest science and management. Currently available methods for tree age estimation are either destructive or often inaccurate, the latter mostly because they do not tap the full potential of available data and knowledge on tree growth. We compared two new approaches for tree age estimation based on nonlinear age–diameter relationships to a traditional polynomial approach. The nonlinear approaches were based on repeated diameter measurements. One of them included environmental covariates (slope, elevation, aspect, water holding capacity and a drought index) based on the fixed effects of a mixed-effects model. The accuracy of the approaches was evaluated for 237 oaks (*Quercus* spp.) growing along an environmental gradient in Switzerland and comprising ages from 23 to 284 years. The potential of the nonlinear approach with covariates was assessed by additionally including the random effects of the mixed-effects model.

The nonlinear approach with covariates and the polynomial approach were of similar accuracy except for extreme sites, where the polynomial approach performed better. The nonlinear approach without covariates was least accurate. Additionally including the random effects in the nonlinear approach with covariates strongly improved the age estimates and reduced the relative errors below 40% for 98% of the trees.

Including repeated diameter measurements and environmental covariates led to similarly accurate age estimates as the traditional polynomial approach. However, the accuracy of the nonlinear approach with covariates has a high potential for further improvements. Additionally, the nonlinearity and the site information that is explicitly included allow for applications beyond currently represented ages and sites. This transferability and the potential for extrapolation obviate the need for model fitting in further applications, making it entirely non-destructive, which is a large advantage over the polynomial approach, which requires new fitting for new sites. Thus, applying the nonlinear approach with covariates is highly suitable e.g. in protected forests, where destructive age determination is not allowed.

1. Introduction

Knowledge of tree age is important for several scientific and practical reasons. Tree age information is needed in many forest growth models, e.g. for projections of expected timber yield and carbon sequestration in forests (Hall and Clutter, 2004; Thürig et al., 2005). Nature conservation uses age information of trees, e.g. to determine subsidies for the non-utilization of protected trees. Additionally, tree age is an indicator for a tree's ecological value, since structural diversity and the associated biodiversity generally increase with tree age (Michel and Winter, 2009).

A range of methods have been developed to determine tree age. Identifying the number of annual growth rings proved to be an accurate method for trees in the temperate zone (Rozas, 2003; Villalba and Veblen, 1997; Wong and Lertzman, 2001). However, such dendrochronological methods are invasive if based on increment cores and even destructive if based on stem cross sections. Therefore, dendrochronological age determination is not applicable in many cases, for example in the context of quality timber production or nature conservation. Non-invasive methods based on satellite data have evolved during the last decade, but have usually concentrated on stand age rather than tree age (e.g. Sivanpillai et al., 2006). Alternative attempts have focussed on the relationship between tree characteristics and tree age (e.g. Abrams, 1985; Kalliovirta and Tokola, 2005; Rozas, 2003). In particular, the relationship between a tree's diameter and its age has usually been modeled empirically based on polynomials (Abrams, 1985; Loewenstein et al., 2000; Rozas, 2003; Trotsiuk et al., 2012) although there is no biological

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motivation for using polynomials. In fact, these models, which are linear in their coefficients, are invalid outside the range of ages and diameters used for fitting (Pinheiro and Bates, 2000; Rozas, 2003). Furthermore, the age–diameter relationship is mostly tainted with high variability (Loewenstein et al., 2000; Nagel et al., 2007; Piovesan et al., 2005; Tyrrell and Crow, 1994).

Various site and stand characteristics are known to influence tree growth and, consequently, the relationship between the diameter and age of trees. Regarding site characteristics, topographic attributes such as elevation, slope and aspect as well as soil properties such as water holding capacity are usually considered as key variables influencing tree growth (Oberhuber and Kofler, 2000; Parker, 1982; Rohner et al., 2013). Furthermore, tree growth responds sensitively to climatic conditions, i.e. temperature, precipitation or drought (Fritts, 1976). Regarding stand characteristics, competition is thought to be the main growth-limiting feature (Biging and Dobbertin, 1995).

Although site and stand variables have been shown to strongly influence tree growth, common practice is not to consider them for tree age estimation (exceptions: Abrams, 1985; Suarez et al., 2008). In fact, empirical age–diameter relations (e.g. polynomials) have mostly been fitted for individual sites with rather homogeneous environmental conditions (e.g. Loewenstein et al., 2000; Rozas, 2003; Veblen, 1986). Although being highly accurate for a specific site, such models are usually of limited generality and cannot be easily transferred to other conditions. Thus, including site characteristics in addition to diameter for the estimation of tree age should increase both its accuracy and generality.

Further potential to improve tree age estimation arises from repeated diameter measurements. In comparison to single diameter measurements, they provide additional, biologically relevant information in terms of the temporal development of diameter. The growth change within a sequence of repeated diameter measurements in combination with the absolute diameter data might be used to infer the position of the sequence along an age–diameter curve predicted for the respective tree. However, we are not aware of studies that have used this information to estimate tree age. Repeated diameter measurements are available for many forests all over the world, e.g. from national forest inventories or from monitoring in forest reserves (e.g. Brändli, 2010; Brang et al., 2011). Such data sets often cover broad spatial and temporal ranges, and it would be desirable to use them to improve tree age estimations.

We compare a traditional polynomial approach with two new approaches for tree age estimation based on tree-specific nonlinear age–diameter relationships, which include repeated diameter measurements. The two nonlinear approaches differ insofar as one of them considers environmental influences on tree growth as covariates (cf. Table 1). We focus on oak species in Switzerland because of their high conservation value and role in current Payment for Ecosystem Services schemes (Bolliger et al., 2008) as well as their proposed role in the adaptation of forest management to climate change (Mühlethaler, 2008). Our study aims at (1) comparing the accuracy of the age estimates arising from the three approaches for oaks in forest reserves along a large environmental gradient in Switzerland, and (2) quantifying the potential that lies in the nonlinear approach with covariates if knowledge about growth-influencing processes was increased. Thus, our study provides entirely new prospects for the long-standing need of accurate tree age estimation.

2. Methods

2.1. Study sites and tree species

All study sites belong to the Swiss forest reserve network, a joint project of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL Birmensdorf), ETH Zurich and the Swiss Federal Office for the Environment (for details see Brang et al., 2011; Rohner et al., 2012, 2013). Hence, the forests considered in this study have not been managed for decades. We considered the same 10 study sites as in Rohner et al. (2013). All of the forests contain >10% oak (calculated as the importance value = [relative density + relative basal area]/2 × 100; Parker and Leopold, 1983), whereas the composition of the further tree species differs strongly, ranging from *Pinus sylvestris*-dominated sites in the dry, inner-Alpine southwest of Switzerland to *Fagus sylvatica*-dominated sites under mesic conditions in northern Switzerland. Thus, the sites cover a variety of environmental conditions regarding topography, soil properties and climate (see Rohner et al., 2013) and represent a broad range of oak habitats in central Europe.

The most frequent oak species in Switzerland is *Quercus petraea* with 61%, followed by *Quercus robur* with 24% and *Quercus pubescens* with 15% (based on stem numbers; Brändli, 2010). *Q. petraea* and *Q. robur* overlap in many physiological and morphological attributes (Aas, 1998). In addition, hybridization is frequent among the three species, leading to various intermediate forms (Aas, 1998; Kissling, 1980). Because a reliable distinction in the field is not feasible, we conducted the age estimation for the three oak species collectively.

2.2. Data collection and processing

Every forest reserve comprises permanent plots in which all trees are tagged individually. At regular intervals of 8–10 years, the diameter at breast height (DBH) of all living tagged trees is recorded (cf. Brang et al., 2011). We considered the same sample of trees (total of 303 oaks) as in Rohner et al. (2013), where 30–31 tagged oaks per reserve had been selected according to the DBH distribution observed in the last inventory campaign. For every selected oak tree, a sequence of at least three DBH measurements was available from the inventory campaigns. One additional DBH measurement was collected during our field work.

The field work was conducted in summer 2009 and 2010 (for details see Rohner et al., 2013). To determine the age of the selected oaks, one increment core per tree was taken parallel to the contour line at 1.2 m above ground. The core samples were cut with a core microtome (Gärtner and Nievergelt, 2010). Tree-ring widths were measured with a Lintab 5 measuring system using the software TSAP-Win (RINNTECH, Heidelberg, Germany) and cross-dated visually and quantitatively with the software COFECHA (Holmes, 1983). For cores that missed the pith, the missed distance and the missed number of rings were determined according to the graphical method by Rozas (2003). The age at 1.2 m height of the individual oaks was approximated as the sum of the number of tree rings on the core and the estimated number of missed rings to the pith.

2.3. Samples for modeling and validation

After excluding some trees due to difficulties related to cross-dating and estimating the missed distance to the pith, Rohner et al. (2013) had eventually used 243 trees for estimating a nonlinear model that forms the basis of the nonlinear approach with covariates in the present study. In the development of their model, Rohner et al. (2013) had divided the trees into a modeling sample of 200 randomly selected trees (20 trees per reserve) and a validation sample comprising the remaining 43 trees. In the present study, we used the same modeling sample in the development of all approaches for tree age estimation, such that comparability among the approaches was guaranteed. Consequently, all approaches were evaluated based on the same sample of validation trees. However, five modeling trees and