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ORIGINAL ARTICLE

Age estimation of Norway spruce using incomplete increment cores: Testing new and improved methods

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ABSTRACT

Information on tree age is often vital for dendrochronological studies, especially when the Regional Curve Standardisation technique is used. Several linear and non-linear methods of tree age estimation using partial increment cores (without the presence of pith) were evaluated and modified to provide more accurate estimations than are currently used. To achieve the objective, core samples from 142 Norway spruce trees (*Picea abies* [L.] Karst.) were collected from an altitudinal gradient in the Western Carpathians. The samples in which the pith was included were then used for further analyses. Several known age estimation approaches were adjusted to combine the advantages of direct increment- and indirect age-diameter-based methods. Inverse differential forms of non-linear growth functions were tested and proposed as a new advanced approach for age estimation. The results show that most of the modified linear methods achieved a mean square error of less than 10% when the length of the partial core exceeded 90% of the stem radius and less than 20% when the length of the core was at least 60% of the stem radius. Using an appropriate differential form of the non-linear growth functions, a mean square error of less than 20% was reached, even when the core length was shorter than 60% of the radius. The results show that current linear methods for age estimation can only be used if the missing part of the core sample is very short, with only a few rings absent. In the case of a large number of missing rings, a differential form of non-linear functions should preferably be used instead.

Introduction

The accurate and effective determination of tree age is a key methodological issue in research on plant population dynamics (Rozas, 2003). Correct age determination is essential for studies on forest growth and yield (Pretzsch, 2009), growth response after forest disturbance (Van Bogaert et al., 2011), long-term regional climate/growth variations detected by the Regional Curve Standardisation method (e.g. Cook et al., 1995; Briffa and Melvin, 2008; Esper et al., 2009) and for quantifying temporal aspects of changing forest dynamics due to anthropogenic impact (Lorimer, 1985; Daniels et al., 2007).

Age-estimation methods can be divided into two main groups (Villalba and Veblen, 1997; Wong and Lertzman, 2001; Ranius et al., 2009): direct methods using tree rings from increment cores or discs; and indirect methods based on age-diameter regression. Direct counting of the number of tree rings on increment cores represents a relatively accurate technique; however, it is invasive and rather costly. Age-diameter methods are generally less time consuming, but on the other hand are also substantially less accurate. For this reason the ages of different size trees have for the most part, been determined using the more accurate core methods, and from this, sample regression age-diameter equations are calculated and used to estimate the ages of other, similar sized trees (Norton et al., 1987).

In practice, using increment cores for accurate age determination includes several potential issues. The first major limitation is

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a tree ring wedged around the stem bole and/or the existence of locally false or absent tree rings causing over- or under-estimation of the true tree age (Norton et al., 1987; Duncan, 1989; Norton and Ogden, 1990). The detection and removal of such anomalies on the increment cores requires additional core samples, collected from neighbouring trees, as well as the application of time-demanding cross-dating techniques (Frelich and Graumlich, 1994; Lorimer et al., 1999).

The second major limitation of using increment cores is the difficulty in intercepting the pith as a chronological tree centre at the root collar (Villalba and Veblen, 1997). The absence of the pith in the core, i.e. the existence of partial cores, is often caused by; insufficient length of the borer relative to the radius of the tree, butt swelling, rotten wood, hollow tree centre and incorrect alignment of an increment borer combined with eccentricities of the pith. The influence of some of these negative factors can be partially reduced by taking the samples at breast height, but practical experience shows that many cores are still not able to precisely intercept the pith and, at the same time, further uncertainty related to the age estimation of a tree comes from the unknown number of years between tree germination and sampling height (Wong and Lertzman, 2001; Fraver et al., 2011).

There are many approaches to reduce the uncertain position of the chronological centre in the case of partial cores, usually representing the majority of all collected samples (Rozas, 2003). A common feature of all methods is determining the length of the missing radius and the number of rings missing from the segment. For partial cores with visible arcs of inner rings, the length of the missing radius can be determined using either geometric (Norton et al., 1987; Duncan, 1989) or graphical methods (Villalba and Veblen, 1997; Rozas, 2003).

The missing radius of a partial core with no visible inner arcs can usually be estimated as the absent distance to the geometric centre of the tree. To further estimate the number of missing rings on partial cores, various methods may be used; for instance, extrapolation of the mean growth rate from the innermost rings on the core (Norton et al., 1987; Duncan, 1989), age-diameter regression curves (Lorimer, 1980), cumulative curves of radial growth (Villalba and Veblen, 1997) or non-linear regression methods (Stephenson and Demetry, 1995).

This study examines several age-estimation methods for partial increment cores taken at breast height with no visible arcs of inner rings. For this purpose, several modifications of existing methods are proposed and alternative approaches, based on differential forms of non-linear growth functions are examined. The evaluation is done in regards to different lengths of missing portions of the radius simulated on complete core samples with known pith position. The cores were taken from Norway spruce (*Picea abies* Karst.) trees, one of the most widespread species of conifer in Europe (Bošel'a et al., 2014).

The general aim is to select the method which: (i) does not systematically over- or under-estimate tree age, (ii) offers the highest possible accuracy and (iii) is easy to use. An attempt to combine the advantages of indirect and direct methods was carried out in order to explore whether it is possible to estimate tree age with sufficient accuracy, even using very short increment cores.

Materials and methods

Study area

The study area, Pol'ana (48°38′ N, 19°29′ E), is part of the Slovak Ore Mountains and belongs to the Western Carpathians. As an extinct stratovolcano, the region is characterised by diverse topography and by high vertical elevation of around 1000 m. Fertile mesophilous soils, average annual air temperatures between 3 and 5 °C, average precipitation totals between 600 and 1100 mm and very high relative air humidity are characteristic for the area. As a result, very favourable growth conditions are present and the region encompasses one of the most productive forest sites in Slovakia with growing stock volumes varying between 700 and 1200 m^3 ha^{-1} at 100 years of age.

About 90% of the selected study area is covered by temperate mixed stands. The location, in the southern part of the Carpathian Arc, where the warm Pannonian climate intersects with the Carpathian mountain climate, facilitated diverse forest vegetation. Within a few kilometres there are six forest vegetation zones (FVZ) in the Western Carpathians ranging from beech-oak and beech to spruce dominated communities.

The majority of forest stands are managed even-aged stands maintained by intensive thinning and natural regenerated is encouraged by shelterwood cuttings. Stands growing at low and high altitudes have a relatively well-preserved natural tree species composition. However, in the vicinity of human settlements and at mid-level altitudes, it is relatively common to find dense stands of Norway spruce that have been artificially increased through planting. In the highest parts of the mountain range (7th FVZ), spruce primaeval forests is located at the southernmost border of their distribution range in the Western Carpathians. These stands are unmanaged, fully protected and comprise part of the national natural reserve. Generally, the health status of spruce stands is presently experiencing rapid deterioration, irrespective of their degree of naturalness, due to climate change.

Sampling, field and tree-ring measurements

The empirical material used in the study was collected along the altitudinal vegetation gradient passing through the southern slopes of the mountain range in 2012. The core samples were taken from spruce trees older than 80 years. The stands were stratified according the FVZ and within each FVZ, a random sampling method, proportional to size of sample unit, was applied. The sample unit size was measured by stand area covered by Norway spruce, i.e. stands with large areas and higher representation of spruce had higher probability of sampling than smaller stands with marginal spruce populations.

One sample point within each chosen stand was randomly selected near the stand centre. At each sampling point, the mean diameter and top diameter tree was determined according to the Weise rule (Weise, 1880). The Wiese rule is a rule of thumb for estimating the quadratic mean stand diameter d_w as the 60th percentile of an ordered set of diameters. Practical procedure of estimation at a given sampling point is based on the visual ranking of 10 proximal trees. Trees are ranked in ascending order according to diameter size and the measurement of the 6th order stem is accepted as corresponding to the mean diameter. Similarly, the maximum diameter is determined as corresponding to the mean of 10% of the thickest trees, i.e. the diameter of the largest tree out of 10 trees.

From the two selected trees, one core per tree was taken at breast height at a 45° angle towards the slope line, alternately from the left and right side of the trunk, with the intention of avoiding the reaction wood and partly to cover the variability of annual rings around the stem.

The number of sampled trees for each FVZ was calculated according to the classic formula for a statistical calculation of sample size where the variability of tree radial increments between and within stands for a given natural conditions were estimated. The sample size was set to attain an accuracy of 10% with 95%