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Original article

New insights into estimating the age of old Scots pine from increment cores with stem rot

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ABSTRACT

Trunk inner rot is a common phenomenon in some old-growth pine dominated forests, making it impossible to determine tree age by counting annual rings. We compared the efficiency of five methods to estimate the age of hollow pine trees (*Pinus sylvestris* L.). Our main aims were to select the best-performing method and to test whether the age of the tree or the proportion of rot influences the accuracy of estimation. We used full increment cores (reaching the pith or within 1 cm of it) from 100 trees (54–562 years old) collected in northern Sweden and simulated rotten centres of three different sizes in order to test the methods. The lowest error rates were obtained when less than a third of the sample was missing (down to 5.0 % error rate), and by using a method based on the growth pattern of a set of healthy trees. Using linear extrapolation of the mean radial growth led to large overestimates (up to three times the number of absent rings) with error rates up to 27.3 %. We also found that the performance of all methods was reduced in cores from older trees. Our main conclusion is that non-linear methods should be preferred for age estimation of hollow pines. We also argue that more precision in the age estimation could be gained already in the field by collecting multiple cores from rotten trees or by developing alternative coring methods.

1. Introduction

Old Scots pine (*Pinus sylvestris* L.) trees are keystone features of many North European forested landscapes. The age of such trees is often determined by dating tree-rings from discs or increment cores (Norton et al., 1987; Duncan, 1989), and by applying dendrochronological methods. Not only the age itself of the trees is of interest, but also events such as forest fires (Niklasson and Granström, 2000; Farris et al., 2013), windthrow (Busby et al., 2009; Zielonka et al., 2010), climatic shifts (Sano et al., 2009; Björklund et al., 2013) and land-use activities (Ruffner and Abrams, 2002; Fonti et al., 2006; Josefsson et al., 2010; Omurova et al., 2020) can be dated to the year and sometimes even to season. However, a common problem is having to deal with partial tree-ring sequences due to inner rot destroying part of the core, so that the analysis of the tree-rings is hampered (cf. Groven et al., 2002; Routson et al., 2012). Samples with incomplete tree-ring sequences are often excluded, which can lead to less precision in the data, and sometimes inaccurate conclusions regarding, for example, forest age.

The cores or discs collected can be incomplete because they do not include the chronological centre of the tree (too big a tree), or because of incorrect borer alignment when the tree was cored (Norton et al., 1987). Previous research has provided methods to overcome such problems, and estimate as precisely as possible the age of some deciduous (Rozas, 2003; Ranius et al., 2009; Altman et al., 2016) and coniferous (Norton et al., 1987; Duncan, 1989; Stephenson and Demetry, 1995; Sedmák et al., 2014; Pirie et al., 2015) tree species. So far, no comprehensive study has focused on assessing different methods for age estimation of Scots pine trees with incomplete tree-ring sequences.

Most of the existing literature on incomplete tree cores due to rot deals with widely distributed broadleaved species such as pedunculate oak (*Quercus robur*) and common beech (*Fagus sylvatica*), which commonly suffer from rot, especially if the tree has endured some mechanical damage to the stem or branches. Thanks to the presence of chemical compounds in their heartwood, pine species are often more resistant to stem-rot, even after damage to the stem (Rennerfelt and Nacht, 1955). Pine heartwood produces stilbenes (mainly pinosylvins) which serve as an effective antifungal defence (Gref et al., 2000). Nevertheless, very old pine trees (notably *P. sylvestris*, *P. ponderosa*, and *P. cembra*) do experience stem-rot at ages above c. 400 years. This rot is either a natural decay phenomenon due to advanced age or a

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consequence of the "*red ring rot*" disease, after an infection by the fungus *Phellinus pini*. This tree disease causes pockets of rot in the heartwood of coniferous trees, and has been documented in North American and European pine forests (Renvall, 1995; Blanchette, 1980; Szewczyk, 2008; Lohmus, 2016). Rot makes the use of the inner tree impossible for dendrochronological purposes, therefore the overall aim of this study is to improve age-estimation for coniferous trees suffering from tree rot, with Scots pine as an example. Thus, our approach draws to some extent on a previous study carried out on Norway spruce (*Picea abies* L.) (Sedmák et al., 2014). However, the novelty of this study lies in the fact that we simulated rot conditions (short partial cores and absence of the arc of inner rings) on long cores corresponding to old pine trees in unmanaged forests (Fig. 1). We want to provide tools and discuss their applicability in real-life research situations, with a practical problem-solving approach. Using cores for which we knew the total number of year rings, we simulated a missing inner part and we compared five different methods to estimate how many annual rings were lacking because of the missing radius. We repeated this experiment under three different rot scenarios. The specific questions we want to answer are:

1) Which method can give the better estimate of the number of absent rings in a pine tree affected by tree rot?
2) Is the accuracy of the estimations influenced by the age of the tree, and the proportion of rot?

We also want to provide recommendations on how to deal efficiently with rotten pine trees during fieldwork.

2. Material and methods

2.1. Sampling sites and sampling methods

The tree cores used in this study were collected in two late-successional Scots pine dominated forests, the Stora Sjöfallet National Park (NP) and the Tjeggelvas Nature Reserve (NR), situated in the northernmost part of Sweden (Fig. 2). Stora Sjöfallet NP is situated at

Fig. 1. Photo of a very old Scots pine tree in unmanaged conditions, from the Tjeggelvas Nature Reserve. Photo by Leon Hauenschild.

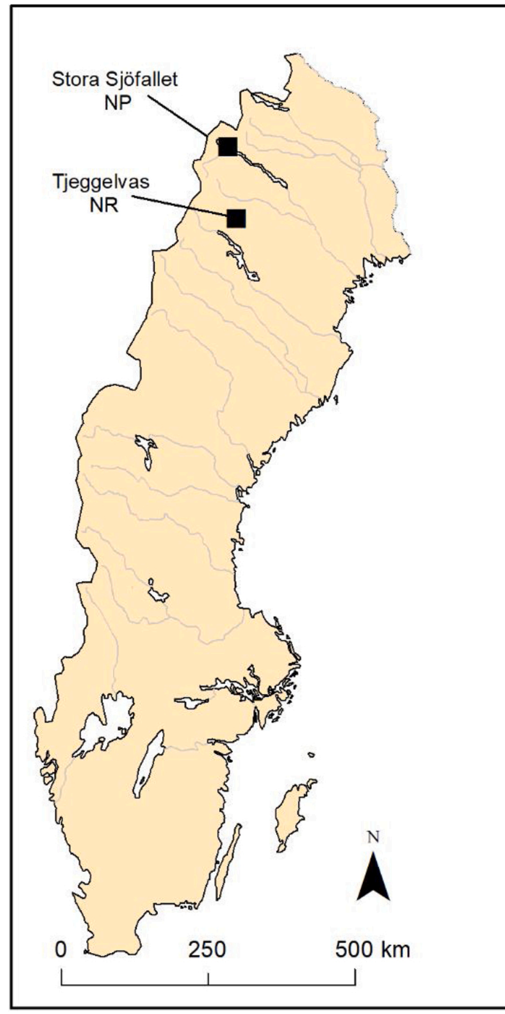

Fig. 2. Map of Sweden and location of the two sampling sites, Stora Sjöfallet National Park (NP) and Tjeggelvas Nature Reserve (NR). Rivers and water bodies are in grey. © Lantmäteriet.

latitude 67° north, and encompasses vast mountainous areas, water courses, mires as well as coniferous and deciduous forests. The area has been used primarily by Sami reindeer herders in the past. Commercial, selective logging has taken place to a very limited extent, and only in the easternmost part of the park. The Tjeggelvas NR is located approximatively 110 km south of Stora Sjöfallet NP, and is characterized by broad undulating landscapes with forests, wetlands, small and large lakes. Past human land-use, including Sami reindeer-herding and small-scale farming, has been documented in this area (e.g. Josefsson et al., 2010; Rautio et al., 2014). The Tjeggelvas NR is unique in the sense that there is a total absence of commercial logging in the northern part of the reserve.

Both sites contain old boreal forests that are generally semi-open and dominated by Scots pine, downy birch (*Betula pubescens*) and Norway spruce (*Picea abies*). The ground vegetation is characterized by dwarf-shrubs (for example *Vaccinium* and *Empetrum* species and dwarf birch *Betula nana*). The bottom layer is rich with ground lichens (*Cladonia* spp., *Cetraria* spp. and *Stereocaulon* spp.) and mosses (*Pleurozium schreberi*, *Hylocomium splendens*). The landscapes are rather rocky with several boulder fields. Thanks to their protected status, both sites are currently used solely for reindeer herding, and for recreational, tourist activities.

The sampling sites (Stora Sjöfallet NP 67°42′ N, 17°33′ E, Tjeggelvas NR 66°36′ N 17°45′ E) were selected based on the presence of a high density of very old and well-preserved Scots pine trees, no history of commercial logging, and because they share many intrinsic features that allow us to make direct comparisons. Both sites also have the advantage of being late-successional forest with known presence of rotten pines, according to previous sampling. At both sites, we collected tree core samples from standing, living trees at breast height using increment borers (4.3 and 12 mm diameter). The sampled trees were selected randomly using a relascope in plots along transects. Sample plots were spaced at 500 m intervals (Stora Sjöfallet) and at 100 m intervals (Tjeggelvas). Only cores from trees with a diameter >20 cm at breast height (DBH) were used for further analyses. For each of the sampled trees, additional data such as tree diameter were collected.

To avoid any potential confusion with the dendrochronological term "*missing ring*", it is important here to define what we will hereafter refer to as an "*absent ring*". What is usually called a missing ring is an anomaly where the tree does not produce a visible annual ring due to poor yearly growth (Schweingruber, 1988). In this paper, absent rings are the innermost rings that are unusable because of tree rot.

2.2. Tree core selection and laboratory procedures

From 469 sampled tree cores, we selected a total of 100 cores (one core per tree, 50 from each site) with a visible or nearly visible (<1 cm missing) pith (Table 1). These samples came from trees within a rather old age class (mean age 232, min. 54 and max. 562). We then split our 100-sample stack into two groups based on random selection, in order to get a similar proportion of shorter and longer cores: 40 cores (20 from Tjeggelvas, 20 from Stora Sjöfallet) were used as a calibration set (i.e. to fit the coefficients of non-linear methods), and 60 cores (30 from each site) were used as a validation set (i.e. to evaluate the error of all methods). The length of each core (bark to pith) as well as the number of rings was measured, using a transparent plastic sheet of concentric circles when the pith was not available.

As a supplement to the 100 complete cores, we established another set of 28 partial cores that were incomplete because of rot (Table 1). These cores were collected in the Tjeggelvas NR, in a specific area where we found that about a third of the cored trees had inner rot (unpublished data). In order to gain a realistic idea of the proportion of sample left on these partial cores, we measured the hollow pines diameter at sampling height (breast height), and we estimated the missing radius of each of these 28 cores by substracting the partial core length from the tree calculated radius. This gave an average of 63.26 % missing tree radius, that we considered representative for old Scots pines in unmanaged old-growth forests.

All cores were mounted and sanded using two different grades of sandpaper (100 and 400) to allow the rings to be seen clearly. All cores were quality-checked to ensure that they did not contain irregularities in the tree-ring sequences caused by disturbances or missing rings due to insufficient annual tree growth. This procedure was carried out by measuring tree-ring width and comparing each tree-ring sequence with a local master chronology for Tjeggelvas NR (Gunnarson et al., 2012), and a regional master chronology for northernmost Sweden (Grudd et al., 2002). Both master chronologies cover a time period more than the last 500 years (the latter 7 200 years). All samples were scanned and tree-rings were measured to the nearest 0.01 mm using CooRecorder and CDendro software and statistics (version 9.3.1, Cybis Elektronik &. Data AB, Sweden). From this procedure we also obtained the core length, number of annual tree rings and the mean radial growth rate, for each sample.

Table 1
Number of core samples for each of the two study sites and their repartition in the different sets.

Site	Complete cores (validation set)	Complete cores (calibration set)	Partial cores	*Total*
Tjeggelvas	30	20	28	*78*
Stora Sjöfallet	30	20	0	*50*
Total	*60*	*40*	*28*	*128*

2.3. Tree-rot scenarios and estimations of total tree age

The number of absent rings in the inner part of a living tree affected by a fungus is dependent on how far the rot has advanced. Early on, only the innermost part of the tree is affected, but with time, the tree rot advances laterally outwards consuming more and more tree rings and making age estimation more and more difficult. In this study, we simulated three different tree rot scenarios: only one third of the radius visible (*1*), one half of the radius visible (*2*) and finally two thirds of the radius visible (*3*). We measured the exact number of annual rings for each sample, which would then serve as a reference for comparison. These different simulations were designed to test the influence of the percentage of rot when estimating the number of absent rings and, more widely, estimating the total age of the tree. It is most common to find core length simulations of 50 %, 60 %, 70 %, 80 % and 90 % of the total radius in similar studies (Norton et al., 1987; Altman et al., 2016), but here we were interested in reproducing the conditions of inner pine rot as realistically as possible. Thanks to previous studies at the Tjeggelvas site we have experience of the amount of rot in older pines, which often covers an area wider than half of the tree basal area (unpublished data).

2.4. Methods for estimating the number of absent rings

Five methods to estimate the number of absent rings were coupled with the three different tree rot scenarios, and applied to the 60 trees of the validation set. Code names were then given to each couple of method/scenario for further analyses (e.g. "A1" corresponds to method A scenario 1). This gave a total of 180 estimates per method. Accordingly, this produced 15 tree-age estimates that were compared with the true tree age for each of the 60 samples. Table 2 shows a summary of all the methods and their equations used to derive the number of absent rings. To assess the total age of the tree, this number of absent rings was then added to the number of visible rings recorded in the partial core.

The first method (A) stems from previous studies that showed that when the arcs of the inner rings were not visible, an extrapolation of the 5–20 innermost rings provided less error than an extrapolation of the 50 innermost rings or more, as it reduced any bias caused by a change in growth rate (Rozas, 2003; Ranius et al., 2009; Altman et al., 2016). In many cases, it turned out that the fewer extrapolated rings the better the estimate. Since we are focusing on old Scots pine with very narrow rings, we decided to use the 20 innermost rings to have a sufficiently consistent growth rate value. Consequently, method A is a linear extrapolation of the radial growth of the 20 innermost visible rings of the incomplete tree

Table 2
Equations to estimate the number of absent rings (AR) for the five methods compared in this study, where "r" is the length of absent radius (cm), "g_{tot}" is the growth rate of the total number of visible tree rings of the incomplete tree core (cm/year), "g_{20}" is the growth rate of the 20 innermost visible tree rings of the incomplete tree core (cm/year), "L" is the total length of the incomplete tree core (cm), "L_{20}" is the length of the 20 innermost visible tree rings of the incomplete tree core (cm).

Method	Equation
A	$AR = 20\ r / L_{20}$
B	*when* 50 % *or less of sample is visible:* $AR = (20\ r / L20) * 0{,}787$ *when more than* 50 % *of sample is visible:* $AR = (20\ r / L20) * 0{,}894$
C	$AR = r / (k * g_{20})$ *with* $k = 1{,}3139$ *for all sites*
D	$AR = (r * \text{number of years last 2 cm}) / 2$
E	*when* < 1/3 *of sample visible, for all sites:* $AR = [(1/3\ r - L) * 1/0{,}76 * gtot] + (1/3\ r * 1/1{,}15 * gtot) + (1/3\ r * 1/1{,}8 * gtot)$ *when* > 1/3 *of sample visible, for all sites:* $AR = [(2/3\ r - L) * 1/1{,}15 * gtot] + (1/3\ r * 1/1{,}8 * gtot)$

core.

The second method (B) uses part of an age-estimation method for large trees presented by Altman et al. (2016). They found that the best estimates were obtained by combining a method using the mean radial growth (MRG) of the innermost visible rings (such as method A) with a method using the basal area increment (BAI) of the tree. This association provided good results for pedunculate oak, since using either only MRG-based methods or BAI-based methods led respectively to over- and underestimation. According to Altman et al. (2016), these results are also applicable to other light-demanding species. Old Scots pines, however, usually produce very narrow tree rings, which would make the use of BAI imprecise and time-consuming. Using an MRG method alone, Altman et al. (2016) obtained overestimates of the total age, thus we decided for our study to use these overestimation rates and subtract this percentage as a correction factor. Method B thus comprises a linear extrapolation of the 20 innermost visible tree rings of the incomplete tree core, with a reduction by 21.3 % when half of the core or more is missing (scenarios 1 and 2), and by 10.6 % when only one third is missing (scenario 3), based on the error rates published by Altman et al. (2016).

The third method (C) has been used successfully by Ranius et al. (2009) to estimate absent rings of rotten hollow oak trees. In this method, the growth rate is not considered linear and the total tree age (a) is estimated using the formula:

$$a = C + r / (k*g)$$

where C is the number of visible rings of the incomplete tree core, r is the missing radius (cm), g is the growth rate (cm/year) of the innermost tree rings (unspecified number of rings), and k is the quotient between the growth rate of the absent tree rings from the missing part of the trunk and the growth rate of the innermost rings visible in the remaining tree core. The k coefficient is thus a correction to adjust growth rates between visible and absent tree rings. For our study, we estimated k using the calibration set of 40 healthy tree cores (20 from each study site) that were of a similar size to the rotten ones recorded in the field, as described by Ranius et al. (2009). Further, to estimate the proportion of tree rings that should be used to measure the absent rings' growth rate, we used the average proportion of rotten radius of our set of hollow pines from the Tjeggelvas sampling site ($n = 28$). We applied this proportion (63.26 %) to the calibration set and measured the simulated absent rings' growth rate. We established one k coefficient that was then used for both sites and for all three scenarios. According to Ranius et al. (2009), the number of innermost rings used in the growth rate calculation doesn't have a significant effect on the result. We decided to use the 20 innermost visible tree rings, as we did for methods A and B.

The fourth method (D) is an extrapolation of the number of rings contained within the sample's innermost visible 2 cm. It is known that trees can have a very slow growth rate when they get older, therefore extrapolating a number of tree rings (as in methods A, B and C) can represent a source of errors when the rings are very narrow, as they often are in old trees. Our idea here is to avoid the inter-variability bias by not using a number of rings but a given length.

Finally, the fifth method (E) is an attempt to use another non-linear model for the growth rate, dividing the core into three parts. In order to measure the gradual change in growth rate for the trees used in the calibration set ($n = 40$), we divided each tree core into three equal parts, corresponding to three different stages in the growth rate (outer, middle, inner). For each of these sub-growth rates, we used a linear function to evaluate their relationship with the sample mean total growth rate (Fig. 3). We found that all sub-growth rates had an acceptable r^2 except for the inner one, for which there was a lot of inter-tree variability. Using our calibration set, we calculated the mean ratio between the total growth rate and each sub-growth rate in order to obtain proportional coefficient. These coefficients were used to derive the number of absent rings (see Table 2), so that one can use the mean growth rate on a partial core as a proxy to estimate how many rings are lacking.

Methods A, B and D only use the innermost part of the incomplete core. This is based on the supposition that the innermost rings, and thus nearest to the rot section, have the same width and growth rate as the absent rings, and thus avoid a bias caused by a changing growth rate throughout the whole sample. It is widely established that trees have a changing growth rate throughout their lifetime, with a fast juvenile growth rate culminating at a certain age and then slowly approaching a slow constant rate at a mature age (e.g. Fritts, 1976; Zahner et al., 1989; Ryan et al., 1997; Smith and Long, 2001; Young et al., 2011). Methods C and E are an attempt to take this growth function into consideration and evaluate the precision that could be gained from this.

2.5. Statistical analysis

We used a Wilcoxon test (Wilcoxon, 1945) with an adjusted significance level (Holm, 1979) in order to evaluate whether the estimates

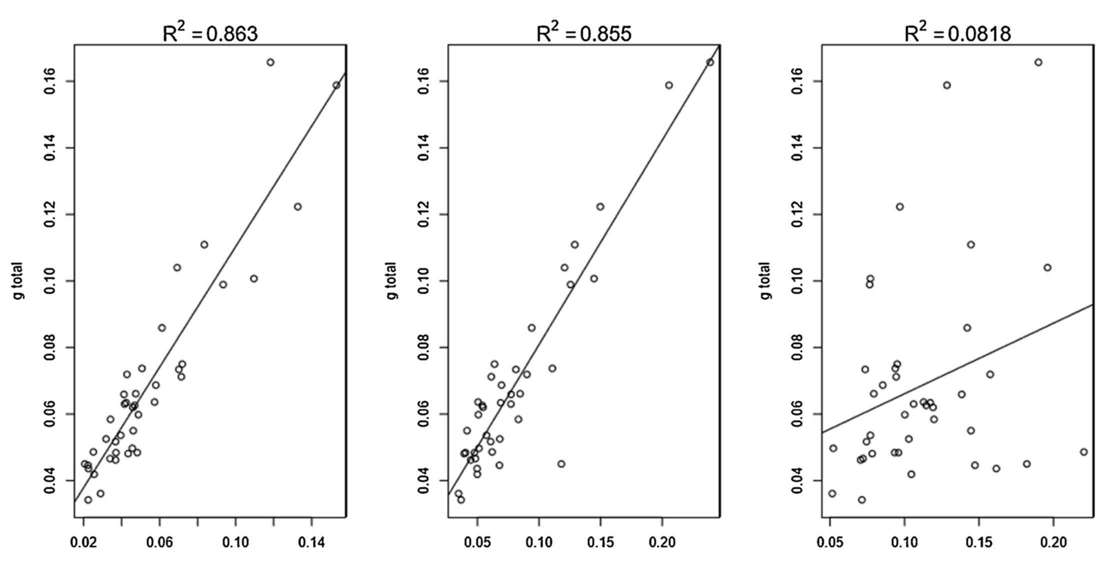

Fig. 3. Linear relationship between the total growth rate (g total) and the three sub-growth rates for the outermost part of the tree (g outer), the middle part (g middle), and the innermost part (g inner). All growth rates are expressed in cm/year.

differed from the known age. We repeated this test for each method and each scenario. Secondly, we estimated the statistical error rate for each method, for all sites and for all rot scenarios. We then performed repeated ANOVA type II tests to assess whether the quality of methods differed from each other, and if tree age as a covariate had an effect on the method efficiency. For the multiple comparisons test, we used an adjusted p-value (Hommel, 1988) to avoid false discovery mistake. All statistical analysis was conducted using R (R Core Team, 2016), with R packages "ggpubr", "stats" and "rstatix".

3. Results

3.1. Age estimation and error rates

The estimates provided by the methods were generally larger than the real number of tree rings of the cores. Methods A and D led to a large overestimates, with sometimes up to three times the number of actual absent rings for method D. Method E was the only one to have a statistical median below the reference, i.e. more than half of its estimates were lower than the actual value (Fig. 4).

When compared to each other, the tendencies of the methods were the same for all three scenarios, yet there was a clear reduction in the amplitude of the errors when a larger section of the core was available. Therefore all methods performed best in scenario 3 and worst in scenario 1.

When using the methods as a tool to evaluate the total age of the tree, the error rates varied between 5.0 % (C3) and 27.3 % (A1 and D1) (see Table 3). For all scenarios taken together, the lowest error rates for total age estimation were with methods B, C and E (all under 17 %). Overall mean error rates and methods could be ranked as follows: C (10.6 %), E (11.1 %), B (11.5 %), A (17.7 %) and D (18.37 %). All in all, methods taking into consideration the growth rate evolution (C and E) gave better results than methods based on mean radial growth (A, B, and D).

3.2. Influence of amount of rot

The three experimental scenarios we created showed that the proportion of rot clearly had an impact on the accuracy of the estimates for all methods (see Table 3). No method could provide an age approximation with an error rate of less than 15 % in scenario 1, whereas in scenario 3, all methods had an error rate less than 10 % (down to under 7% for methods B, C and E).

The Wilcoxon tests showed that when a small part of the sample was available (scenario 1), methods B, C and E provided estimates that were not significantly different to the reference within the 95 % confidence interval (annex 1 in supplementary material). The same result was found under the rot scenario where half of the radius was missing (scenario 2). Finally, when most of the sample was available (scenario 3), only methods C and E produced estimates similar to the reference. The figures generated by methods A and D diverged significantly from the reference in every experimental situation. When all scenarios were analysed together, the Wilcoxon tests showed that only method E provided estimates not significantly different from the reference ($p =$ 0.087).

Among the methods that gave estimates statistically close to the reference, we identified different behaviours indicating that some methods were more efficient in different scenarios. When comparing the methods with the best performances, E was the most accurate (smallest mean error rate) under rot scenarios 1 and 2, whereas C was the most accurate under scenario 3 (Table 4). Both methods have a similar standard deviation in scenario 3, although the mean difference is lower for method C (Table 4).

3.3. Influence of tree age

The known reference age of each sample was found to have an impact on the performance of the methods. We found that the absolute error rate of each method (except for method E) increased with the age of the cored tree (Fig. 5). Method E was the only one displaying a stable yet slightly decreasing absolute error rate as the age of the sampled tree increased. For trees under 200 years old, methods B and C were the ones with the lowest absolute error rate whereas for trees older than 200 years, it was method E (Fig. 5).

Method E was the only method to display a negative median value (Fig. 4), meaning that it mostly produced underestimates. By comparing the mean error rate with the reference age of the sampled tree (to allow an analysis of the direction of this error), we observed that for younger trees (<200 years old at breast height), the mean error rate of method E was positive (overestimation) but for older trees (>200 years old at breast height) it was negative (underestimation), moving away from the reference as the age increased (annex 2 in supplementary material).

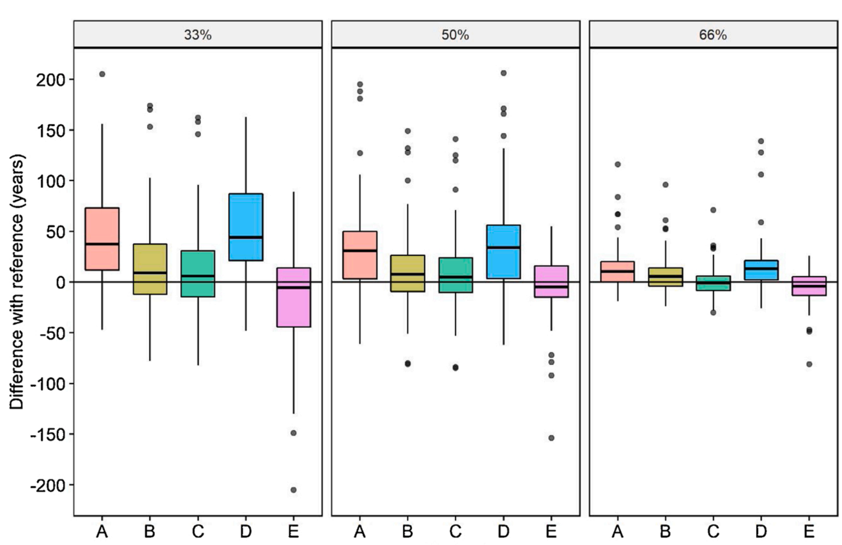

Fig. 4. Offset with reference for each method, all sites mixed. The three graphs correspond to the three rot scenarios, named by the percentage of remaining radius on the core sample (33 % for scenario 1, 50 % for scenario 2, 66 % for scenario 3) The boxes in colour show the 25 %-75 % interval, and the median in bold.

Table 3
Mean absolute difference between the estimates and the reference (n = 60 trees of the validation set) and error rates for both absent rings and age estimation, with standard deviation (Stdev) and standard error (SE). Each experimental situation was given a name combining the method (capital letter) and the rot scenario (number).

Method and rot scenario	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3
Mean absolute diff. estimate-reference	**69.0**	**46.0**	**19.0**	**41.0**	**30.0**	**15.0**	**38.0**	**29.0**	**12.0**	**65.8**	**50.0**	**20.3**	**38.1**	**24.4**	**13.4**
Mean absolute error missing rings (%)	**56.8**	**60.1**	**39.5**	**33.6**	**38.1**	**31.1**	**31.7**	**35.9**	**24.2**	**57.1**	**64.8**	**45.3**	**31.4**	**30.7**	**27.6**
Stdev	0.54	0.57	0.37	0.37	0.38	0.30	0.35	0.36	0.22	0.49	0.61	0.53	0.29	0.26	0.24
SE	0.38	0.41	0.26	0.26	0.27	0.21	0.25	0.26	0.15	0.34	0.43	0.38	0.21	0.18	0.17
Mean absolute error total age (%)	**27.3**	**18.3**	**7.4**	**16.4**	**12.1**	**5.9**	**15.5**	**11.5**	**5.0**	**27.3**	**19.6**	**8.1**	**16.4**	**10.9**	**6.0**
Stdev	0.23	0.15	0.06	0.15	0.10	0.05	0.15	0.09	0.04	0.20	0.16	0.07	0.15	0.10	0.05
SE	0.16	0.10	0.04	0.11	0.07	0.03	0.10	0.07	0.03	0.14	0.11	0.05	0.11	0.07	0.04

Table 4
Descriptive statistics for the difference between the estimates and the reference (n = 60 trees of the validation set), for the three best-performing methods (B, C and E) and for each rot scenario. The table displays the minimum and maximum values for the difference, the median value, the mean of the 60 observations, and the standard deviation.

	B	C	E
Scenario1	*Min: -78.00*	*Min: -82.00*	*Min: -205.00*
	Median: -9.00	*Median: 6.00*	*Median: -5.50*
	Mean: 24.07	*Mean: 19.32*	*Mean: -14.13*
	Max: 315.00	*Max: 298.00*	*Max: 89.00*
	St dev: 62.73	*St dev: 60.37*	*St dev: 52.61*
Scenario2	*Min: -81.00*	*Min: -85.00*	*Min: -154.00*
	Median: 7.50	*Median: 5.00*	*Median: -5.00*
	Mean: 13.12	*Mean: 10.07*	*Mean: -5.00*
	Max: 149.00	*Max: 141.00*	*Max: 55.00*
	St dev: 43.51	*St dev: 42.26*	*St dev: 34.83*
Scenario3	*Min: -24.00*	*Min: -30.00*	*Min: -81.00*
	Median: 5.50	*Median: -1.00*	*Median: -4.00*
	Mean: 8.70	*Mean: 0.33*	*Mean: -5.43*
	Max: 96.00	*Max: 71.00*	*Max: 26.00*
	St dev: 20.96	*St dev: 17.41*	*St dev: 18.48*

4. Discussion

4.1. Accuracy in estimation

This study shows interesting variations in the methods' performance. Furthermore, the ranges of error that we obtained for total age estimates are fairly similar to those reported in other studies of different tree species (e.g. Rozas, 2003; Ranius et al., 2009; Altman et al., 2016). When using linear methods, we obtained an average overall error rate of 15.8 %, which is comparable to that reported by Sedmák et al. (2014) for Norway spruce (mean error rate of 20 % using similar methods).

Methods assuming a constant growth rate (A and D) produced very poor estimates, and their error rate increased when the length of the partial core decreased. The same result was found for different tree species, for example deciduous species such as beech and oak, and also conifers including Norway spruce in several similar studies (e.g. Rozas, 2003; Sedmák et al., 2014; Altman et al., 2016). Such methods should be avoided in dendroecological studies involving Scots pine. When the extrapolation of radial growth rate is corrected by a reduction coefficient (B), the results are slightly better and the estimates are sufficiently reliable only when most of the radius is rotten. Method B produced a low error rate under scenario 3, but the statistical tests rejected it being close to the reference. This method comes with an issue though: it is not clear how large the reduction should be, here we based our reduction percentage on overestimation rates from oak (Altman et al., 2016). To improve this method by making it more specific to Scots pines, we also tested a variation using the error rates we obtained on our own data when trying out method A. The overestimation rates were respectively of 25 %, 16 % and 6% for scenario 1 to 3. We used these rates as correction factors in a variation of method B that we named B'. This gave similar results compared to the ones we initially obtained using figures from Altman et al. (2016). The absolute error rate is similar between B and B', although we observed that using our own error rates led more often to an underestimation (annex 3 in supplementary material). Although the estimates provided by method B were found to be statistically different from the age reference under scenario 3 (pv = 0,034), they were statistically consistent when using B' (pv = 1). This leaves room to investigate more closely how big the reduction should be, but we can argue that an average reduction by 20 % for short cores (< half of radius) and by 6% for longer cores should give acceptable results.

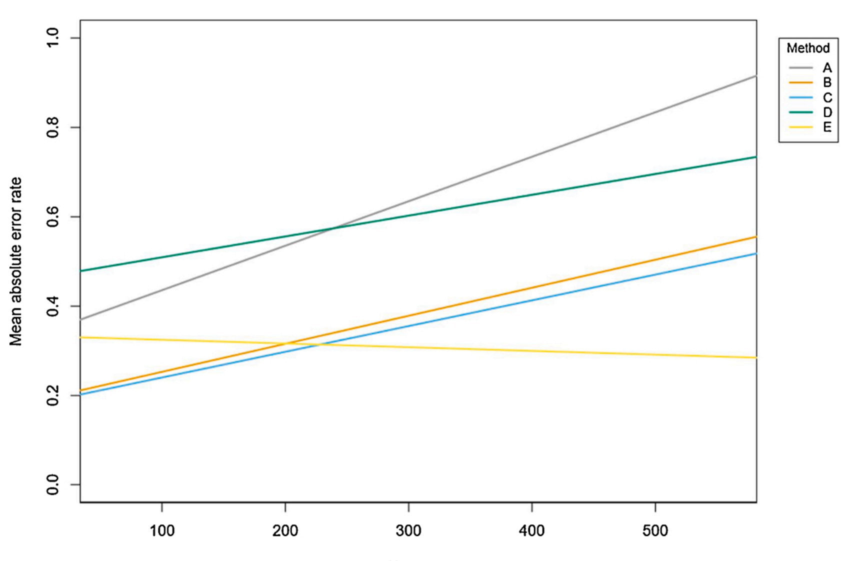

Fig. 5. Absolute error rate for each of the five methods as a function of the tree reference age (n = 60 trees of the validation set).

Methods using a non-linear radial growth model (i.e. models assuming a varying growth rate) for Scots pines gave satisfactory results. Methods C and E turned out to be the best performing in the current study and the most homogeneous with respect to their accuracy: 10.0 % of the estimates produced by method C have an absolute error rate less than 5% (9.4 % for method E), and for both methods 11 % of the estimates have an absolute error rate over 60 %. Based on the growth pattern of healthy trees, method C works well on samples with small radius and young trees. Although the multiple linear model that we used in method E performed well, there is a need to refine it as the correlation coefficient for the inner rings was very poor ($r^2 = 0.08$). This might explain the loss in accuracy for cores with a large part of the radius missing. One potential solution is the use of alternative growth models used on other conifer species, such as an exponential function (Stephenson and Demetry, 1995) or an inverse differential form of non-linear growth function (Sedmák et al., 2014).

In this study, we found that when only a small portion of the core was available, the error rates were high. This conclusion is supported by other studies which simulated several increment core lengths (e.g. Norton et al., 1987; Sedmák et al., 2014; Altman et al., 2016). In the case of a tree with heart-rot, our interpretation is that methods used on a tree in the early stage of rot give better results than for a tree with advanced rot. This means that linear methods do not function well for trees in an advanced stage of rot. It has been suggested that whole-wood white rot significantly reduces the growth rate of infested Norway spruce, both in pristine and managed conditions (Hellgren and Stenlid, 1995; Lännenpää et al., 2008). Although it is not clear whether this is generally the case (Lännenpää et al., 2008), it seems worth exploring the extent to which inner rot affects Scots pine growth.

Other studies have also established that the older the tree, the more difficult it is to estimate its precise age from a partial core (e.g: Sedmák et al., 2014). Our results were no different, although we did find that the age class of the tree changed the accuracy of method E. There was an interesting change in cores with at least 200 year rings at breast height; these corresponded to trees around 240 years old once the years required to reach breast height had been taken into account, according to our reference for the Tjeggelvas site (Josefsson et al., 2010). The method showed good performance for trees around that age but with a small tendency to overestimate. Although no physiological changes have been documented for trees that old, studies on Scots pine senescence classified a tree as being old once it exceeded 200 years (Martínez-Vilalta et al., 2007; Fish et al., 2010).

4.2. Applicability of the methods

There are some important considerations to take into account before choosing which method to use. First, the choice of method will be affected by the proportion of rot damaging the core. This means that it is important to know how much of the core is missing, and thus have a precise idea of the pith location. Possibilities for improvement that we did not test here but that have been used in other studies include subtracting the bark width from the diameter (Ranius et al., 2009; Sedmák et al., 2014; Altman et al., 2016) and using a graphical method to localize the pith position (Duncan, 1989; Villalba and Veblen, 1997; Rozas, 2003). It has been shown that the chronological centre of partial cores of Norway spruce is often closer to the increment core than the geometrical centre of the tree (Sedmák et al., 2014), therefore getting a better indication of the location of the chronological centre of the tree might be a solution to reduce the common overestimates produced by the methods considered. Secondly, one must take into account the age class of the tree when selecting a method. Defining age groups or cohorts has been suggested in other studies (Rozas, 2003; Ranius et al., 2009; Sedmák et al., 2014) and it seems in our case that the threshold for Scots pine is around 200 years old. It is possible to estimate the age of the tree on the basis of its general characteristics (height, shape of crown) and diameter. According to the sample age class and rot ratio, methods E or C are to be preferred (Table 5).

In some cases, it is safe to remove the trees affected by rot from the sampled population, when they are only a few individuals and when it is possible to use nearby healthy trees to infer on the age of rotten ones. However this is not sufficient in the case of a multi storied old-growth Scots pine forest with no management, where trees have a wide range of ages, and not necessarily in cohorts. The narrow year rings that they produce result in a surprisingly small diameter for trees with an advanced age, making it impossible to use the diameter repartition to gauge the age. Moreover, if one deals with a unique tree of particular interest (e.g. a culturally modified tree that is affect by rot) or when it is important to include all trees when sampling an area, method B (based on linear growth rate with a reduction) seems to be acceptable on cores with more than 33 % of the radius rotten. This method offers the opportunity to assess the age of a hollow pine tree quite rapidly, and without the use of a calibration data set. It is particularly adapted to work on a single sample, or to scientific studies with practical requirements. Nevertheless, if time is not a limiting factor and if it is possible to gather a calibration data set of healthy trees from the same area, it is best to select the method according to the suggestions in Table 5.

Once the number of absent rings has been estimated from a partial core, an important step to estimate the total age is to pay attention to anomalous rings (e.g. false rings), and to add supplementary years corresponding to the mean number of years between germination point and breast height (1.3 m) (Norton et al., 1987; Duncan, 1989; Rozas, 2003).

In this paper we selected our methods with hollow Scots pines in mind (i.e. cores that do not display the arcs of the inner rings, often short remaining cores). Other conifer species such as spruce (*P. sitchensis, P. engelmannii*), fir (*A. lasiocarpa, A. balsamea*), or European larch (*Larix decidua*) are more likely to be infected by decay and rot fungi (e.g: Whitney, 1995; Vollbrecht et al., 1995; Asiegbu et al., 2005). It would therefore be worth exploring how applicable our findings for Scots pine with heart-rot are to other conifer species.

4.3. Field recommendations

The presence of inner rot in pine trees is very hard to predict and can often only be determined when pulling out the core sample. As discussed above, more accurately determining the pith location and assessing how much of the radius is missing are of paramount importance for age estimation analysis. This can be improved when collecting samples in the field, with specific recommendations for when the core taken has a large proportion of rot (>50 % of tree radius), and when the scientific protocol does not allow sampling another tree.

The first strategy would be to take a second core from the tree, perpendicular or at an obtuse angle to the first core. By doing this, there is a chance of obtaining a longer sample with a larger number of visible rings, to increase the precision of pith location and thus to improve the accuracy of age estimation. This strategy has been recommended in similar studies (Stephenson and Demetry, 1995; Rozas, 2003; Ranius et al., 2009; Sedmák et al., 2014) because of eccentric tree growth and asymmetry in the rot pattern, depending on cardinal direction (Ranius et al., 2009).

The second recommendation that would improve age estimations for Scots pine trees considerably, would be to have a coring strategy that allows the arcs of the innermost rings to be seen. The inner rings and

Table 5
Decision table showing which method to use based on the percentage of remaining radius on the core sample and the predicted age of the tree.

% of remaining sample	33 %	50 %	66 %
< 200 years old	C,E	C, E	C
> 200 years old	E	E	C,E

their arcs can be a useful tool to help locate the chronological centre of the tree, when combined with a graphical estimation method (Duncan, 1989; Villalba and Veblen, 1997; Rozas, 2003). This allows better estimation of how much of the radius is missing, and can be a stand-alone method to assess the number of absent rings. In the case of a tree with heart-rot, the inner part of the sample is messy and the inner arcs are lacking. Therefore, a solution could be to have an innovative coring technique not aiming at the tree centre but aiming sideways, bypassing the inner rotten rings and getting the arcs of the middle rings. There is clearly space for future investigations to explore this topic in more depth and examine alternative coring methods when a pine tree happens to be rotten.

5. Conclusion

In this study we adopted a problem-solving approach to find quick and reliable ways to estimate the number of absent rings of incomplete pine cores, where the arc of the inner rings is not visible. We argue that the underlying issue is to find a mathematical function that can be used to predict the tree radial growth rate. Although such estimations are sensitive, it is possible to obtain a reliable result thanks to either a linear method associated with a reduction coefficient (such as method B in this study), or to a non-linear method (such as methods C and E in this study). The first has the advantage of being rapid and not requiring the collection of a calibration data set, whereas the latter is empirical and can provide reliable results even from poor quality samples. Assessing the number of absent rings is a first step, and once added to the number of visible rings, an important second step is to adjust this estimated total age on the basis of other factors (for instance year rings invisible from coring high above the germination point, anomalous rings revealed by cross-dating, climatic variation).

The most important aspects to take into account when deciding which method to use are 1) the age class of the core and 2) whether the rot stage is advanced or not. The findings in this study seem very likely to be relevant to other conifer species. Heart-rot is not uncommon in species such as fir and spruce, and the similarities between these trees and Scots pine in terms of tree characteristics, growth rate and ecological range, make this question worth exploring more widely.

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Declaration of Competing Interest

The authors reported no declarations of interest.

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Appendix A. Supplementary data

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