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Accuracy of the Rotfinder instrument in detecting decay on Norway spruce (*Picea abies*) trees

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ABSTRACT

Rotfinder is a non-destructive decay-sensing apparatus based on resistance measurements in standing trees. The accuracy of Rotfinder in detecting decay was evaluated in 500 standing trees in three Norway spruce (*Picea abies*) plots. Trees were measured at three heights, 0.30, 0.66 and 1.30 m. Sections were later inspected for the presence of decay and reaction zones. Inspected trees were mostly infected by *Heterobasidion annosum* and showed a large variation in the amount of decay present, ranging from 0.1% to 88.0% of the section. Correctly and incorrectly classified trees were compared in terms of ion and element concentration, density and moisture. Measurements at stump level (0.30 m) were more accurate than measurements at breast height (1.30 m) where the reaction zone and decay columns showed lower moisture content. The accuracy of Rotfinder increased when trees with small decay columns were regarded as 'non-decayed'. When only trees with more than 15% of the section decayed were regarded as 'decayed', Rotfinder had an accuracy of 0.86 when performing assessments at stump level. False negatives, as opposed to true positives, corresponded to trees with smaller and drier decay columns, drier reaction zones and lower K^+ (potassium) concentration in the decay column. False positives corresponded to trees with large sapwood and high sodium content in the sapwood. Rotfinder represents an alternative to the standard method of using increment core observations to assess decay in living trees.

1. Introduction

In arboriculture and forestry, assessments have to be made about the presence of decay in standing trees. At present, root and butt rot fungi are considered the most destructive pathogens in forests ecosystems (Garbelotto, 2004). Indeed, in regions such as Scandinavia, the average decay incidence in mature Norway spruces (*Picea abies* (L.) H. Karst) is as high as 16% (Thor et al., 2006b). Decay in Norway spruce is mostly caused by the basidiomycete fungus *Heterobasidion annosum* s.l. (Fr.) Bref, although other decay fungi such as *Armillaria* spp. and *Stereum sanguinolentum* (Alb. & Schwein.) Fr. can also cause significant damage at the local level (Bendz-Hellgren et al., 1998). The presence of *H. annosum* has probably been exacerbated by cutting activities, which have steadily created substrates for infection (wounds and stumps) (Redfern and Stenlid, 1998). The fungus spreads between trees via root-to-root contacts creating extensive decay damage in the stand, with decay columns reaching up to 11 m in the stem (Swedjemark and Stenlid, 1993), and is often associated with growth losses (Bendz-Hellgren and Stenlid, 1997; Oliva et al., 2010). Because the fungus can survive in the stumps after the final cutting, the inoculum is carried over into the next rotation (Stenlid and Redfern, 1998). Decay damage needs to be monitored and quantified based upon direct measurements because it is difficult to classify infected trees based on external symptoms (Vollbrecht and Agestam, 1995).

In Sweden, the incidence of decay is currently sampled by means of an increment borer. However, only 58% of decay present at stump height is detected using this method (Stenlid and Wästerlund, 1986), and therefore, a non-invasive method that is able to indicate the presence of decay more accurately may be preferable. Non-destructive decay-detection techniques in standing trees can be sorted into two main types based on the signal used for detection (Ouis, 2003): vibro-accoustical methods, such as tomography (Axmon et al., 2004; Deflorio et al., 2008), or electromagnetic radiation methods, such as infrared thermography (Catena, 2003). Accurate measurements can be achieved with some of these techniques: for example, a decay column 4–5 cm in diameter can be detected in 60-cm diameter trees (Martinis et al., 2004). Unfortunately, most of these techniques are not well suited for routine use under forest conditions owing to low time efficiency and cumbersome equipment needs (Ouis, 2003). For example, tomography techniques require installing sensors along the trunk circumference, which can take from 5 min (Axmon et al., 2004) to 45 min per tree (Martinis et al., 2004). Other destructive

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methods are available, such as the Shigometer, the Resistograph, the Densitomat, the Fractometer and the Pilodyn, but like the increment core assessments they involve different levels of invasiveness that make them undesirable in forestry (Ouis, 2003).

Rotfinder is a fast and non-invasive device based on electrical conductivity (Larsson et al., 2004). The measurements are taken by attaching four sensors (3 cm long × 3–4 mm width) to the bark, which penetrate approximately 1 cm into the sapwood producing minimum damage to the wood. It offers an alternative to the decay assessments based on increment cores, but the accuracy of the device has not been quantified yet. The method is based on the smaller effective resistivity of decayed trees, which, as defined by the authors, corresponds to "the resistance of a stem section, when a constant current is passed vertically through the stem and the voltage is measured at two points on the stem surface". Decay columns often show differences in terms of wood moisture and ion concentration that may affect the accuracy of the measurements. For example, ion concentration is higher in more advanced decay columns and it tends to decrease with the height of the column (Rennerfelt and Tamm, 1962; Nilsson et al., 2002). The influence of the height of the measurement and of the size and stage of the decay column need to be considered when studying the accuracy of Rotfinder. However, not only may decay affect the electrical conductivity but also differences in the wood moisture and ion concentration in the healthy tissues of the stem may influence the measurements (Lin, 1967; Lindberg and Johansson, 1989). In particular, consideration should be given to the effect that the reaction zone may have on the accuracy of Rotfinder. The reaction zone develops in the tree when the decay column contacts the sapwood, and it is characterized by having a higher amount of ions than healthy wood (Shain, 1971).

The objectives of our research were to: (i) study the accuracy of Rotfinder in detecting the decay in standing Norway spruce trees, (ii) develop predictive equations about the presence and the size of the decay based on Rotfinder values that can be used for inventory purposes, and (iii) understand the factors limiting decay detection with Rotfinder.

2. Material and methods

2.1. Description of Rotfinder

The instrument is based on the relative-impedance *in situ* examination (RISE) four points method. The current is passed through the object by means of two electrodes and the voltage difference is measured by another pair of electrodes (Larsson et al., 2004). Decay has lower resistivity to the electric current than healthy tissue and, therefore, healthy trees cause a higher voltage difference. The measurement procedure can take less than 2 min when performed by a trained operator. The user may decide at which height they want to perform the measurement, then they first measure the diameter of the section, and then they attach the measurement unit with two nails that penetrate the bark. After setting the diameter in the measurement unit, the user attaches two electrodes, one below and one above the measurement unit. The Rotfinder instrument has a scale from 0 to 10, where 0 indicates a healthy tree and 1 to 10 indicates the increasing probability of decay presence. The device is commercialized by Rotfinder AB in Malmö, Sweden, and more information can be found on the Rotfinder website: http://www.websitefolder.net/rotfinder/Start_page.asp.

2.2. Field experiment and sample selection

Measurements were performed in three mixed Norway spruce–Scots pine (*Pinus sylvestris* L.) stands located in Central Sweden (Table 1). Five hundred trees were measured with Rotfinder in June 2009 at three heights (0.30, 0.66 and 1.30 m.). The diameter of every measured section was determined, and the point of measurement was permanently marked. Trees were felled 2–3 weeks after Rotfinder assessments and every measured section was inspected for the presence of decay. Four zones were differentiated in the section according to observations made with the naked eye: sapwood, heartwood, decay and reaction zone. Every section was sprayed with a pH indicator: 2,6-dichlorophenolindophenol, revealing the presence of areas with a high pH. If the high-pH area did not match with the reaction zone identified by the naked eye, it was included as a fifth category called the incipient reaction zone. According to Rotfinder measurements and section observations, trees were sorted into four categories: (i) true positives – Rotfinder value higher than 0 and decay present; (ii) true negatives – Rotfinder value of 0 and no decay; (iii) false positives – Rotfinder value higher than 0 but no decay; and (iv) false negatives – Rotfinder values of 0 and decay present. A qualitative measurement of the decay was performed and three classes of decay were distinguished based on subclasses I, II and III in Axmon et al. (2004): (i) incipient decay – light discoloration and wood still hard; (ii) intermediate decay – dark-coloured decay with minor changes in wood texture and hardness; (iii) advanced decay – dark-coloured decay and soft texture of the wood. Every section was photographed before and after staining with the pH indicator dye, and the relative area of each zone in the section was calculated from pixel counts. Pictures were manually classified in Adobe Photoshop CS3 Extended (version 10.0.1) and a pixel count of every zone was performed in ImageJ (version 1.42q). The image analysis was performed for a total of 427 sections corresponding to 114 decayed trees and 50 healthy trees. In two locations (Enåker and Härsbo), the pictures at breast height were not analysed for those trees that were only decayed at stump level, i.e. they were measured up to the first section with sound wood.

2.3. Measurement of the physical properties of the wood

Decayed trees and a sub-sample of healthy trees were measured for moisture content (64 decayed versus 13 healthy) and density (79 decayed versus 13 healthy) (Table 1). In each section, a wood sample (average 4.4 cm^3) was cut from each region and kept in a hermetic plastic bottle. Moisture content was measured in 228

Table 1
Characteristics of the studied stands.

Location	Municipality	Coordinates (WGS 84)		Age (years)	Average diameter (cm), (min–max)	Decay incidence (% of trees)[a]	% *H. annosum* incidence	Number of trees sampled		
		X	*Y*					Rotfinder	Wood moisture	Density
Ingbo	Heby	N 60° 6.666′	E 16° 46.904′′	83	23.9 (12–40)	26.8	73.7	300	32	47
Enåker	Heby	N 60° 4.435′	E 16° 45.840′	88	17.4 (9–38)	20.2	72.2	100	27	27
Harsbo	Tierp	N 60° 23.445′	E 17° 22.272′	72	18 (8–31)	14.0	38.5	100	18	18

[a] Represents the proportion of inspected trees with decay.

sections from sapwood, 162 from heartwood, 128 from reaction zone, 150 from decay and 95 from incipient reaction zone samples. Density measurements were taken for 273 samples from sapwood, 187 from heartwood, 159 from reaction zone, 182 from decay and 102 from incipient reaction zone samples. The different number of samples in each category is because not all trees had all five types of tissue present, for example, some trees with decay did not have heartwood left. Wood samples were dried in an oven at 105 °C for 24 h (heartwood and incipient reaction zone samples) or for 48 h (sapwood, decay and reaction zone samples). Sample moisture content was calculated as the percentage of water with respect to the dry weight. Volume was calculated by first soaking the samples in water and then introducing the samples into a graduated cylinder with known water content to calculate the volume difference. Density was calculated by dividing the dry weight by the volume of the sample.

2.4. Measurement of the chemical properties of the wood

The content of C, N, Mg^{2+}, Ca^{2+}, K^{+}, Na^{+} and Mn^{2+} was measured in 24 sections. These sections belonged to twelve randomly chosen trees with true positive measurements, corresponding to five trees with the highest Rotfinder values and seven trees with low-intermediate Rotfinder values (average of 3). The other samples belonged to five false negative measurements, two false positives and five true negatives. A sample of every region in the section (i.e. sapwood, heartwood, reaction zone, decay and incipient reaction zone) was extracted, stored and dried as for moisture measurements. Samples were ground for 15 min and the nitrogen and carbon analyses were performed in a dry combustion instrument (Leco, CNS-2000, St. Joseph, MI, USA) and the analyses of the rest of the elements were performed with a ICP–OES (Perkin Elmer Optima 3000 DV, Perkin Elmer Life and Analytical Sciences, Boston, MA, USA). Altogether, these analyses included 12 samples of sapwood, 10 of heartwood, 15 of reaction zone, 17 of decay and 6 of the incipient reaction zone.

2.5. Fungal isolation

Given that *Heterobasidion* and *Armillaria* are the most common decay fungi, we attempted to assess their incidence in the sampled trees. One slice of every decayed tree was kept in a plastic bag and incubated in the dark. After two weeks, the slices were observed under the dissecting microscopic. Trees were considered to be decayed by fungi of the genus *Heterobasidion* when conidiophores of this fungus were observed, or to be decayed by *Armillaria* sp. if sclerotic mycelia appeared. All trees were included in the accuracy analyses regardless of whether *H. annosum* or *Armillaria* sp. could be identified on them.

2.6. Accuracy measurements

We compared differences in the performance of Rotfinder at the three heights of measurement by comparing the area under the curve (AUC) of the receiver operating curve (ROC) (Bradley, 1997), constructed with MedCalc v. 11.2.1.0. The standard error of the AUC was calculated following Delong methodology, and the curves were compared with a *z*-test implemented using the same software. For every curve, we searched for the Rotfinder value that showed the greatest accuracy. In each case, the sensitivity and specificity values and their confidence limits were identified. We considered sensitivity the proportion of decayed trees correctly classified. Specificity was considered as the proportion of healthy trees correctly classified. We searched for the minimum value of percentage of decay in a section for considering a tree decayed that would give the highest AUC. It was obtained by comparing the AUC between heights of measurement and between decay sizes from 0% to 100%, by 5% threshold increments. We used the following rule of thumb for AUC: 0.50–0.60 = fail, 0.60–0.70 = poor, 0.70–0.80 = fair, 0.80–0.90 = good and 0.90–1.0 = excellent. Note that AUC = 0.50 represents the same classification that would be obtained by sorting the numbers at random.

2.7. Statistical analyses

As a result of the hierarchical sampling, data were analysed considering different levels: area, tree within area and section within tree with the MIXED procedure implemented in the statistical software SAS/STAT version 9.1 following Schabenberger and Pierce (2002). The likelihood ratio test was used to examine which parameters increased the fit of the model. Multiple mean comparisons were protected by the Tukey–Kramer method. Degrees of freedom were calculated according to the Welch–Satterthwaite correction. For linear models, including random effects, the likelihood ratio R-square (R^2_{LR}) was used. Linear regression analyses, including more than one linear variable were tested for the severity of multicollinearity, calculating the variance inflation factor (VIF) amongst independent variables with the REG procedure. VIF values above 10 are generally considered indicative of multicollinearity whereas values close to one indicate no correlation. Significant interactions were partitioned by the "slice" instruction and *F*-tests were performed across combinations of different treatment levels. Principal component analyses were performed with JMP statistical software (version 8.0.1, SAS Institute Inc.).

Two generalized mixed models were constructed for predicting both the presence and the size of the decay (percentage of the section with decay) based upon Rotfinder values. The presence of decay and size of the decay where converted into *logit* values, and a binomial distribution of the errors was supposed. We attempted the inclusion of the areas and the particular tree within the area as a random factor to the intercept, to the slope, or to both parameters. We tested the increase of the fit due to their inclusion with the *z*-test based on the quotient of the variance component and its standard error (Schabenberger and Pierce, 2002). The most parsimonious model was selected in every case. Generalized mixed models were adjusted with the GLINMIX procedure. We did not have an independent sample for validating the predictive models. Instead, we used an *n*-way cross validation technique in which the observations of every tree were predicted with a model fitted excluding that particular tree. We adjusted a linear regression between the values predicted by cross-calibration and values predicted with the original model (Piñeiro et al., 2008) and we performed a simultaneous *F*-test on the intercept (Ho = 0) and on the slope (Ho = 1) (Yang et al., 2004). We used the root mean squared error as an additional validation measure.

3. Results

3.1. Predictive models

Rotfinder values can be used for predicting the average size of decay (proportion of the section) and the probability of the presence of decay in the tree ($p < 0.0001$) (Table 2 and Fig. 1). The inclusion of the variation within trees significantly increased the fit of the predictive model for decay presence and decay size ($p < 0.0001$). The inclusion of the variation between plots did not increase the fit of the models ($p = 0.24$ and $p = 0.19$, respectively, for decay size and decay presence). Predictive models supported a particular intercept and slope parameter for measurements at different heights, and, hence, we adjusted the models using a different equation for measurements taken at 0.30, 0.66 and 1.30 m

Table 2
Parameter estimates for predictive models of the size of the decay (proportion of the section) and the presence of decay in the stem of *P. abies* trees depending on Rotfinder values. Models were adjusted separately for Rotfinder measurements at 0.30, 0.66 and at 1.30 m. Model equation: *Logit* (p) = $a + bx$, where p is equal to the probability of presence or to the proportion of the section with decay. RMSE stands for root mean square error.

	Height of measurement	*a*	*b*	R^2_{LR}	Cross-validation	
					RMSE	Simultaneous *F* test: intercept = 0, slope = 1
Size of the decay	0.30	−4.0390 (−4.4221 to −3.6540)	0.4688 (0.3981–0.5394)	0.34	0.0018	0.13
	0.66	−3.8228 (−4.1803 to −3.4654)	0.5064 (0.4216–0.5912)	0.31	0.0024	<0.0001
	1.30	−3.6257 (−3.9841 to −3.2673)	0.5106 (0.3881–0.6330)	0.17	0.0030	<0.0001
Presence of decay	0.30	−1.8315 (−2.105 to −1.5581)	0.6229 (0.4656–0.7802)	0.32	0.0026	0.56
	0.66	−2.0765 (−2.3693 to −1.7837)	0.7388 (0.523–0.9546)	0.28	0.0028	0.0057
	1.30	−2.2002 (−2.5034 to −1.897)	0.6272 (0.4133–0.8412)	0.17	0.0028	<0.0001

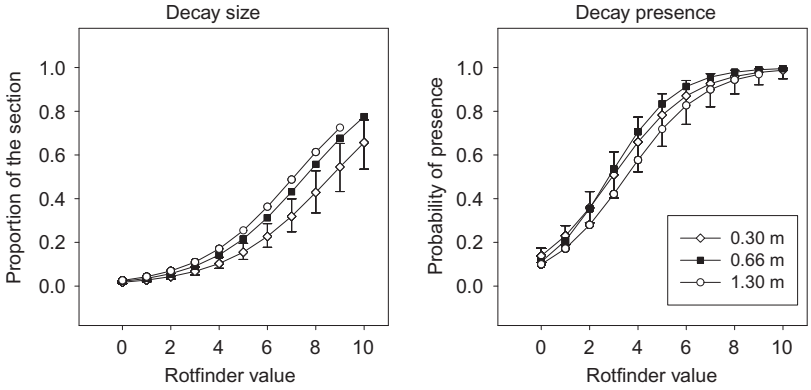

Fig. 1. Predicted decay size (proportion of the section) and decay presence in *P. abies* trees based upon Rotfinder measurements at 0.30, 0.66 and 1.30 m. Model equation is shown in Table 2. Bars representing confidence intervals at 95% are only indicated for measurements at 0.30 m.

(Table 2 and Fig. 1). Predictions from cross-validation were mostly similar to predictions from the original models; however, only in the case of predictions based on measurements at 0.30 m, was there no significant deviation from a 1:1 line detected (Table 2).

3.2. Accuracy analysis

A higher AUC was observed at 0.30 m and at 0.66 m than at 1.30 m (Table S1, Supplementary material). We studied trees whose decay size ranged from 0.1% to 88.0% of the section. The AUC significantly increased when only trees with a certain amount of decay were considered to be 'decayed' (Fig. 2a and c). Increasing the minimum size of decay for classifying a tree as 'decayed' increased the sensitivity of Rotfinder while the specificity remained constant (Fig. 2b). Rotfinder AUC at stump level significantly increased when sections with less than 15% decay were considered to be 'healthy' (sensitivity of 75.5% and specificity of 90.9%). At 0.30 m, a higher sensitivity was obtained when trees with a Rotfinder value of 1 were considered to be 'non-decayed'. Under these conditions, Rotfinder accuracy could be considered to be 'good' (>0.80). At 0.66 m, a significant AUC increase occurred when trees with less than 10% decay were considered to be 'non-decayed' (sensitivity of 65.2% and specificity of 92.3%). At 1.30 m, a significant increase was not reached until trees with less than 30% decay were considered to be 'non-decayed' (sensitivity of 58.0% and specificity of 90.1%). No significant AUC differences were detected between these

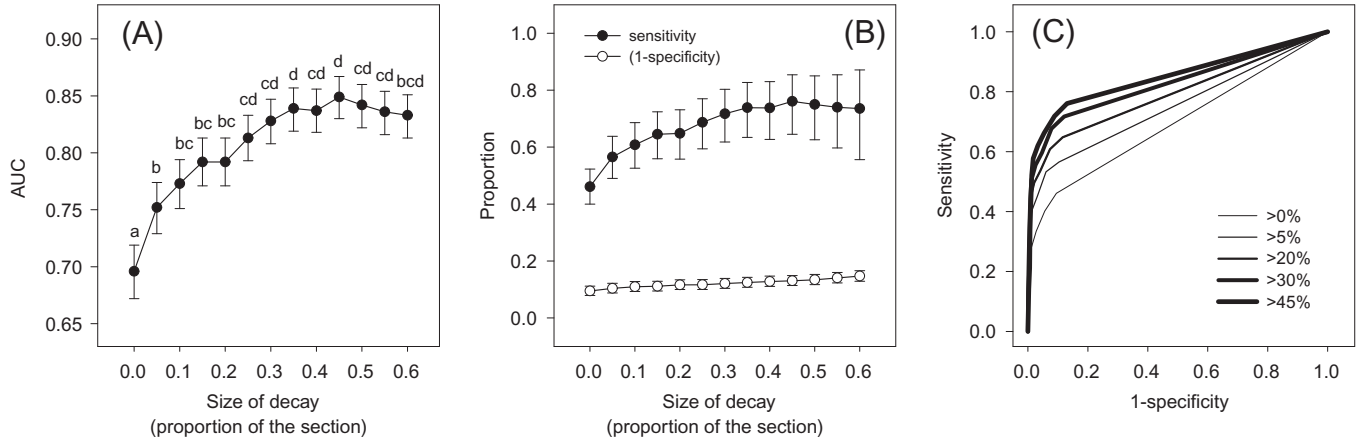

Fig. 2. Evolution of accuracy (A), sensitivity and specificity (B) and ROC curves (C) as the minimum size of decay (proportion of the section) for considering a tree as decayed increases. Same letters indicate non-significant differences at $p < 0.05$. Bars indicate confidence limits at 95%.

three setups (0.30 m versus 0.66 m, $p = 0.26$, 0.30 m versus 1.30 m, $p = 0.096$, and 0.66 versus 1.30 m, $p = 0.49$).

When only those trees with advanced decay were considered to be 'decayed' (i.e. intermediate and incipient decayed trees were considered to be healthy), this resulted in a significant AUC increase (0.69 versus 0.82, $p = 0.0001$). In this case, no accuracy differences were observed between measurements at 0.30, 0.66 and 1.30 m, or when decayed trees with small decay columns were considered to be 'non-decayed'. When considering both trees with advanced and intermediate decay as decayed (i.e. only trees with incipient decay were considered to be 'healthy'), the increase was no longer significant (0.69 versus 0.74, $p = 0.07$). The accuracy of detecting trees with a reaction zone was similar to the accuracy of detecting decayed trees (0.69 versus 0.72, $p = 0.18$).

3.3. Physical and chemical properties of decayed wood sections

The different regions of a decayed section (i.e. sapwood, heartwood, incipient reaction zone, reaction zone and decay) showed significant differences in terms of moisture content ($p < 0.0001$), density ($p < 0.0001$), N ($p = 0.019$), Ca^{2+} ($p = 0.0006$), K^+ ($p = 0.0001$), Mg^{2+} ($p < 0.0001$), Mn^{2+} ($p < 0.0001$) and Na^+ ($p = 0.015$) (Table 3). The sapwood showed the highest moisture content, and the decay and the reaction zone showed a higher moisture content than the heartwood ($p < 0.0001$). The highest density was registered in the reaction zone. The decay region had the highest content of N, K^+, Ca^{2+}, Mg^{2+} and Na^+. No differences between reaction zone and decay could be detected in the case of N, Ca^{2+} and Mn^{2+}.

No size or moisture differences were detected amongst advanced, intermediate and incipient decay columns ($p = 0.22$ and 0.28). Size and moisture differences between these three decay stages were solely explained by differences between the height of measurement ($p < 0.0001$). The density of wood in areas of advanced decay was lower than that for wood with intermediate and incipient decay, but such differences were no longer significant (i.e. from $p = 0.0025$ to $p = 0.08$) when the size of the decay was included in the analysis as a confounding factor ($p = 0.008$).

Decay represented an average of 24.2% (CI: 18.7–29.7) of the area of the section. The density of the decay correlated with the percentage of the section decayed ($R^2_{LR} = 0.62$, $p < 0.0001$). On average, decayed parts had lost 11.9% in terms of density compared with sound wood (sapwood and heartwood) when weighted by the size of the decay. A similar value was obtained when density losses were weighted by decay volume per tree (−11.7%) or when only trees whose decay had reached breast height were considered (−12.4%). Signs of *Heterobasidion* sp. and *Armillaria* sp. were observed in 93 trees and 36 trees, respectively. No density loss or decay area differences were observed between *H. annosum*- and *Armillaria* sp.-decayed trees ($p = 0.78$ and 0.57, respectively). The decay agent in 53 trees could not be identified as either *Heterobasidion* or *Armillaria* sp. Trees whose decaying agent could not be identified had significantly ($p = 0.02$) larger decay areas at 0.30, 0.66 and 1.30 m (21%, 16% and 36%, respectively) and showed higher density losses ($p = 0.07$) than decayed trees in which *H. annosum* and *Armillaria* were isolated at 0.30, 0.66 and 1.30 m (−5%, −7% and −26%, respectively).

We observed significant differences in moisture ($p < 0.0001$) and density ($p < 0.0001$) between the different zones of the section at different heights. The decay and the reaction zone had lower levels of moisture at 1.30 m than at 0.66 m or at 0.30 m (Fig. 3). The density of the reaction zone varied between the three heights of measurement ($p = 0.0024$); it was higher at 0.30 and 0.66 m than at 1.30 m. The reaction zone had a higher density than the sapwood at 0.30 and at 0.66 ($p < 0.0001$) whereas no differences could be detected at 1.30 m ($p = 0.55$). We inspected possible associations between the size of the different regions of the section and the moisture content and we found none: moisture content did not correlate with the size of the sapwood ($p = 0.28$), heartwood ($p = 0.11$), incipient reaction zone ($p = 0.32$), reaction zone ($p = 0.21$), or decay ($p = 0.28$).

3.4. Characteristics of correctly and incorrectly classified trees

False negatives, corresponding to undetected decayed trees (Rotfinder value = 0), had smaller decay and reaction zones than true positives (decayed sections correctly classified). False negatives had a lower density and lower moisture content in the reaction zone, and lower moisture content in the decay column than true positives. The Ca^{2+} content in the reaction zone and the K^+ content in the decay were lower in false negatives than in true positives.

False positives, corresponding to healthy sections incorrectly classified as decayed (Rotfinder value > 0), were associated with a larger sapwood, a less dense heartwood, a less dense incipient reaction zone, and a higher content of Na^+ in the sapwood than true negatives (healthy sections correctly classified) (Table 4). The sapwood moisture content of false positives was similar to the sapwood moisture content of false negatives and true positives. A significant interaction between the correctness of measurement, the height of the measurement and the size of the sapwood was found (Table 4). Sapwood of false positives was larger than sapwood of true negatives at 0.30 m (63.6% versus 52.8%, $p < 0.0001$) and at 0.66 m (59.0% versus 51.4%, $p = 0.017$), but not at 1.30 m (56.9% versus 51.0%, $p = 0.058$). Within false positives, the area of sapwood at 0.30 m was bigger than at 1.30 ($p = 0.0004$), while no differences were observed between 0.66 and 1.30 or 0.30 ($p = 0.95$ and $p = 0.10$, respectively). No such sapwood size differences were observed in the case of true negatives ($p = 0.13$).

Table 3
Average physical and chemical properties of the measured wood sections. Same letter indicates non-significant differences at $p < 0.05$ (according to Tukey's range test method) between means. Comparisons are within the same row. Only significant comparisons are shown. Confidence intervals (95%) are shown in brackets.

Region	Sapwood	Heartwood	Incipient reaction zone	Reaction zone	Decay
Moisture (%)[a]	120.4 (114.8–126)a	36 (29.5–42.5)d	39.6 (31.9– 47.2)d	72.2 (65.2–79.3)b	56.5 (50.0–63.1)c
Density (kg dm^{-3})	0.42 (0.41–0.44)b	0.41 (0.39–0.42)cd	0.42 (0.4–0.43)bc	0.47 (0.46–0.48)a	0.39 (0.38–0.4)d
Nitrogen (%)	4.22 (3.27–5.17)ab	3.65 (2.62–4.67)b	4.51 (3.3–5.72)ab	5 (4.13–5.87)ab	5.78 (4.91–6.65)a
Carbon (%)	50.2 (49.7–50.7)	50.1 (49.5–50.6)	50.1 (49.4–50.8)	50.3 (49.9–50.8)	49.5 (49.1–50)
Ca^{2+} (mg kg^{-1})	667 (175–1159)c	971 (434–1508)c	949 (268–1630)bc	1948 (1507–2390)ab	1952 (1510–2394)ab
K^+ (mg kg^{-1})	594 (−944–2132)b	669 (−749–2087)b	1763 (−102–3627)b	2208 (920–3496)b	4844 (3556–6132)a
Mg^{2+} (mg kg^{-1})	64 (−32–159)c	94 (−10–198)bc	186 (59–313)bc	255 (169–342)b	491 (405–578)a
Mn^{2+} (mg·kg^{-1})	39.8 (−7.0–86.6)c	88.2 (38.2–138.3)bc	65.6 (8.6–122.7)c	150 (106–193)ab	176 (133–219)a
Na^+ (mg kg^{-1})	8.5 (0.4–16.7)ab	4.1 (−4.7–13)b	14 (3.6–24.4)ab	8.2 (0.7–15.6)b	20 (12.5–27.5)a

[a] Moisture content refers to the percentage of water (g) compared with the dry weight of wood (g).

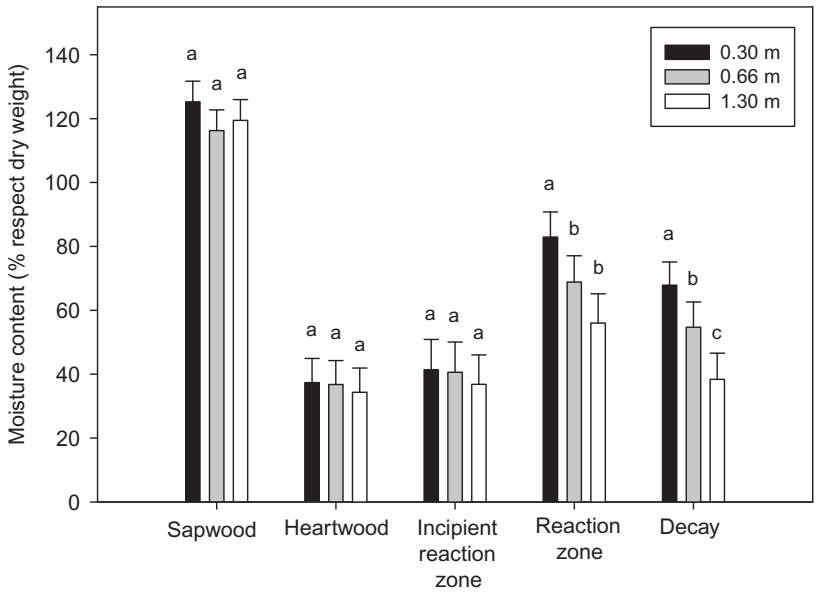

Fig. 3. Moisture content of sapwood, heartwood, incipient reaction zone, reaction zone and decay at different heights: 0.30, 0.66 and 1.30 m. Differences in reaction zone and decay were significant at $p < 0.0001$ and at $p < 0.0001$. Same letters indicate non-significant differences at $p < 0.05$, according to Tukey's range test method.

Table 4
Significant differences between the physical and chemical properties of trees correctly and incorrectly classified as decayed by the Rotfinder instrument. The wood section was divided into sapwood, heartwood, incipient reaction zone, reaction zone and decay. The influence of the height of the measurement (0.30, 0.66 and 1.30 m) on the differences between the different types of measurements (i.e. true and false negatives and positives) is shown. Comparisons are within the same row. Same letter indicates no-significant differences at $p < 0.05$ (according to Tukey's range test method) between means. Means corresponding to the group with a higher value are shown in bold. Moisture content refers to the percentage of water (g) compared with the dry weight of wood (g).

	Region of the section	Type III test of effects ($p > F$)			Healthy trees		Decayed trees	
					Rotfinder value = 0	Rotfinder value > 0	Rotfinder value > 0	Rotfinder value = 0
		Type	Height	Height × type	True negatives	False positives	True positives	False negative
Size (Proportion of the section)								
	Sapwood	<0.0001	0.003	<0.0001	51.7 (49.2–54.3)b	**59.8 (56.5–63.2)a**	49.6 (47.1–52.1)bc	49.7 (47.3–52.1)c
	Heartwood	<0.0001	0.003	0.46	**31.7 (28.7–34.8)a**	**27.9 (23.7–32.2)ab**	22.0 (19.0–24.9)b	**27.7 (24.9–30.5)a**
	Incipient reaction zone	0.007	0.96	<0.0001	2.73 (1.31–4.16)b	0.68 (−1.42–2.78)b	**6.46 (5.09–7.84)a**	**4.99 (3.79–6.18)a**
	Reaction zone	<0.0001	0.98	<0.0001	5.84 (0.41–11.27)bc	5.13 (2.82–7.44)c	**13.13 (11.4–14.86)a**	8.92 (7.36–10.49)b
	Decay	0.0006	<0.0001	0.59	–	–	**29.1 (23.3–34.9)a**	15.2 (10.1–20.4)b
Density (kg dm^{-3})								
	Heartwood	0.018	0.43	0.14	**0.43 (0.41–0.44)a**	0.39 (0.36–0.42)b	**0.42 (0.40–0.44)ab**	**0.40 (0.38–0.41)ab**
	Incipient reaction zone	0.009	0.26	0.29	**0.43 (0.40– 0.47)a**	0.36 (0.31–0.40)b	**0.44 (0.42–0.45)a**	**0.42 (0.40–0.44)ab**
	Reaction zone	0.0004	–[a]	–[a]	0.46 (0.44–0.48)b	–	**0.50 (0.48–0.51)a**	0.45 (0.41–0.49)b
Moisture content (%)								
	Sapwood	0.017	0.031	0.032	108 (97.2–118.8)b	**118.7 (101.4–136.1)ab**	**125.9 (117–134.9)a**	**122.8 (114.1–131.4)a**
	Heartwood	0.020	0.002	0.52	**36.3 (33.7–38.9)ab**	**41.6 (37.4–45.8)a**	34.3 (30.8–37.8)b	34.6 (32.2–36.9)b
	Reaction zone	<0.0001	–[a]	–[a]	28.8 (7.1–50.6)c	–	**80.3 (73.3–87.3)a**	64.0 (56.1–72.0)b
	Decay	0.027	0.0004	0.015	–	–	**59.2 (48.5–69.9)a**	44.8 (34.2–55.4)b
Ions (mg kg^{-1})								
Sodium	Sapwood	0.005	–[a]	–[a]	3.7 (0.6–6.8)b	**15.1 (10.2–19.9)a**	7.6 (4.5–10.7)b	–
Manganese	Incipient reaction zone	0.031	–[a]	–[a]	–	–	60.9 (31.1–90.7)b	**122.4 (80.2–164.6)a**
Potassium	Decay[b]	0.033	–[a]	–[a]	–	–	**6324 (4176–9576)a**	2234 (832–5996)b
Calcium	Reaction zone	0.018	–[a]	–[a]	–	–	**2451 (1738–3163)b**	898 (−110–1906)a

[a] Not enough data for the analyses.
[b] Back-transformed from natural logarithm.

3.5. Rotfinder values and physical and chemical properties of wood

Rotfinder values correlated with a larger decay column and a larger reaction zone, with a higher moisture content in the reaction zone and in the decay, with a higher density in the reaction zone and with a lower density in the decay (Table 5). The model with best fit to Rotfinder values ($R^2_{LR} = 0.63$) included as variables: the size of the reaction zone (F-value = 53.53, $p < 0.0001$), the moisture of the decay (F-value = 28.45, $p < 0.0001$) and the size of the decay (F-value = 12.88, $p < 0.0001$). No multicollinearity was detected

Table 5
Statistical significance of the correlation between Rotfinder values, and the physical and chemical properties of the different regions of the tree section. Significant associations are highlighted in bold. Negative association is indicated by "(−)" only for significant ($p < 0.05$) associations.

	Sapwood	Heartwood	Incipient reaction zone	Reaction zone	Decay
Surface	**<0.0001**	**<0.0001**	0.08	**<0.0001**	**<0.0001**
Moisture	0.63	0.30	0.96	**0.0003**	**<0.0001**
Density	0.32	0.68	0.85	**<0.0001**	**0.025 (−)**
Density loss	–	–	–	–	**<0.0001**
N	0.11	0.85	0.39	**0.040**	**0.019**
C	0.63	0.55	0.68	0.41	0.59
Ca^{2+}	0.20	0.15	0.48	**0.028**	0.91
K^{+}	0.94	0.056	0.32	**0.023**	**<0.0001**
Mg^{2+}	0.67	0.69	0.65	0.056	**0.016**
Mn^{2+}	0.08	**0.040**	0.40	**0.025**	0.37
Na^{+}	0.18	0.72	0.55	**0.0018**	**0.0007**

amongst these three variables (VIF values from 1.32 to 1.07), whose corresponding variance components were of 24%, 12% and 3%. A model with only reaction zone size and decay moisture explained the variation amongst Rotfinder values better than a model with the size of the decay and the decay moisture $R^2_{LR} = 0.43$ versus 0.27. However, the Rotfinder values showed a better correlation with the size of the reaction zone than with the size of the decay (Fig. S1, Supplementary Material).

Rotfinder values correlated with a higher N, Ca^{2+}, K^{+}, Mn^{2+} and Na^{+} concentration in the reaction zone and with a higher N, K^{+}, Mg^{2+} and Na^{+} in the decay area (Table 5). PCA analysis of chemical and physical properties of the wood correlating with Rotfinder values explained 55.8% of the variability in two components (32.1% and 23.7%, respectively) (Fig. 4). The first component separated the observations along a decay gradient. In the second component, three groups of variables were identified: (i) Ca^{2+} in the decay and the reaction zone, Mn^{2+} in the reaction zone and Mg^{2+} in the decay, and higher moisture content in the decay, (ii) K^{+} in the decay, Rotfinder values and a larger reaction zone and decay, and (iii) Na^{+} concentration in the decay and the reaction zone. Along with decay size, K^{+} correlated well with Rotfinder values (Fig. 5).

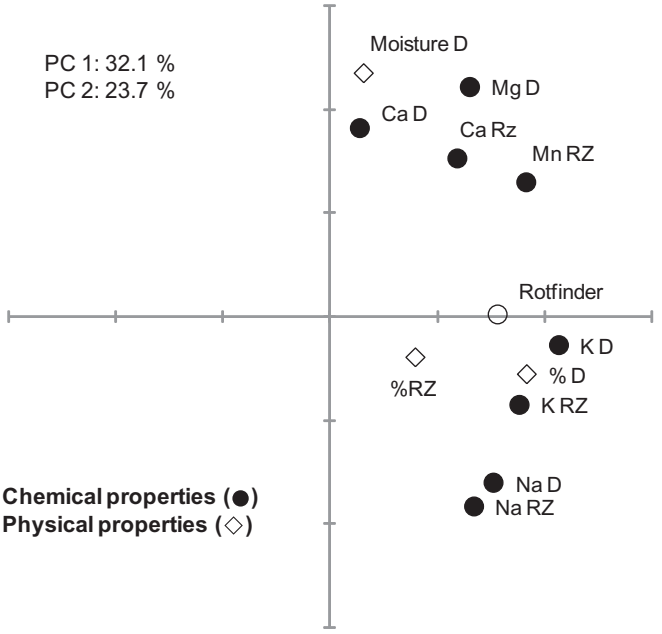

Fig. 4. Loadings from principal component analysis (PCA) of chemical and physical properties of reaction zone (RZ), decayed wood (D) and Rotfinder values (represented by a white filled circle). % indicates the percentage of the section.

4. Discussion

The Rotfinder instrument can be used for detecting the presence of decay in standing trees. The possibility of predicting the size of the decay column and the non-invasiveness of the test may represent an advantage when compared with increment borer assessments, which is the standard practice for assessing decay in standing trees. In our experiment, Rotfinder had an accuracy of 0.70 (CI: 0.67–0.72), which could be regarded as "fair". Failures of Rotfinder are frequently caused by its low sensitivity (46%); it is slightly less sensitive at detecting decay than an increment borer (Stenlid and Wästerlund, 1986). The sensitivity of increment borer assessments could in theory be increased by performing a greater number of drillings per tree. This would not be the case for Rotfinder, whose measurement outcome can be regarded as independent of the position of the decay column (Larsson et al., 2004). Although specificity of Rotfinder was high (0.91), it may still be considered disadvantageous with respect to the increment borer technique for which no false positive judgments would be expected.

Rotfinder accuracy can be improved if measurements are carried at 0.30 and 0.66 m rather than at breast height (1.30 m). Accuracy differences are due to the greater sensitivity found at lower heights. In general, no significant differences were observed between 0.30 and 0.66 m, nonetheless at 0.30 m, Rotfinder values of 1 may be regarded as false positives (i.e. the optimum discrimination threshold between decay and healthy trees at 0.30 m was with values greater than 1 (instead of above 0). The fact that false positives occurred more frequently at stump level may relate to the presence of larger areas of sapwood and higher concentrations of Na^{+}. Na^{+} is believed to be a highly movable element (Foster and Lang, 1982) that can contribute to the electrical conductivity of the stem (Tattar et al., 1972). In line with our results, Na^{+} variation within tree stems seemed to be associated with a higher share of sapwood in the section (Ovington and Madgwick, 1958; Rothpfeffer and Karltun, 2007). A large sapwood typically associates with a higher growth rate (Sellin, 1996), which might result in a greater quantity of ions being pumped from the soil. In these cases, one would expect that a higher moisture content would dilute the effect of the ions (Tattar et al., 1972); however, this did not seem to be the case in our samples because no differences between sapwood moisture content in false positives and true negatives were observed.

Rotfinder sensitivity drastically dropped when only a small decay column was present. Consequently, the accuracy of the instrument increased when trees with small decay columns were considered to be 'healthy' trees. When only considering trees with more than 5% of the section area affected by decay as 'decayed', the sensitivity increased by 10% and 14% at 0.30 and 0.66 m, respectively. Interestingly, no further increase in sensitivity was observed when the decay threshold for discriminating between healthy and decayed trees was increased. At 0.30 and at 0.60 m, Rotfinder can be considered a 'good' test if we accept that trees with small decay columns (<10% or <15%) will probably be classified as healthy. This setup may be appropriate for regular forestry measurements in which, for example, the user is aiming to discriminate between premium spruce pulpwood and normal (sulphate) pulpwood with minimum quality requirements of 10% and 50% of decay in the section, respectively (Thor et al., 2006a). If the aim of the test is to detect incipient decay, then other techniques may be more suitable. However, it is important to note that incipient decay is also difficult to detect even with more precise devices such as Picus or ultrasonic tomography (Nicolotti et al., 2003; Deflorio et al.,

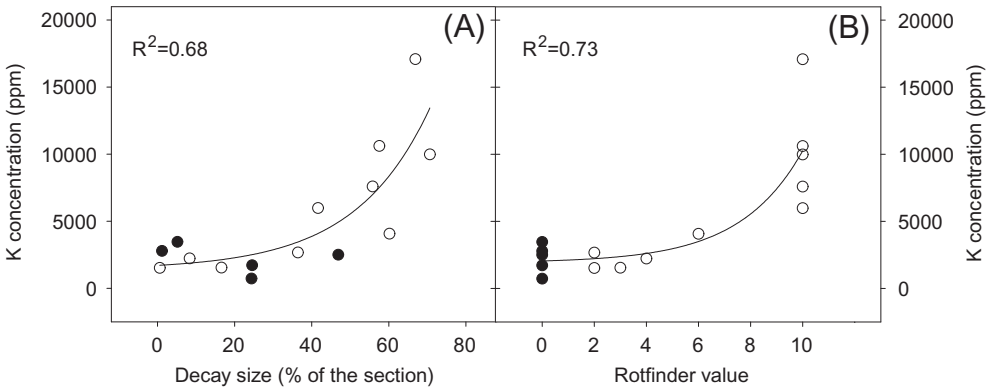

Fig. 5. Association between potassium concentration in the decay column, decay size (A) and Rotfinder values (B). Filled circles represent false negative measurements (i.e. wood sections with decay and with a Rotfinder value of 0). In both cases an exponential growth function has been adjusted which is represented by a full line (R-square shown in the left-upper corner).

2008). For example, Martinis et al. (2004) have claimed to have obtained the best resolution using a tomography technique detecting a decay column of 4–5 cm from a 60 cm diameter section (0.6% of the section).

We observed a lower sensitivity at 1.30 m than at lower heights, which was not associated with the size of the decay or with the size of the reaction zone. The lower moisture of the decay and the reaction zone and a lower concentration of mobile ions at 1.30 m than at lower heights may explain this observation. Ideally, above 30% moisture content (fibre saturation) the conductivity would only depend on the quantity of ions (Tattar and Blanchard, 1976); however, some authors have observed that electrical resistance correlated with wood moisture above 30% (Lindberg and Johansson, 1989). Indeed, we observed a drop in moisture from 1.30 m in both decay and reaction zone. Rotfinder values correlated well with higher K^+ concentrations. We did not have information about the ion distribution at different heights, but other studies have shown that ions tend to be more abundant in lower parts of the stem (Rennerfelt and Tamm, 1962; Nilsson et al., 2002), thus giving a possible explanation for the observed trend.

Rotfinder values correlated with the size of the decay, the decay moisture and the potassium content in the decay column. Our results seem to confirm that larger decay columns generally correspond to a lower electrical resistivity (Shortle and Smith, 1987), and that potassium is the main ion associated with an increase in the conductivity of decayed wood (Tattar et al., 1972). In our study, most of the observed decay was produced by the white rot fungi *H. annosum* and *Armillaria*. Several white rot species such as *Armillaria* are well known for accumulating potassium over time (Ostrofsky et al., 1997), which corresponds well with the increase of potassium that we observed in larger decay columns. The size of the reaction zone and the potassium content in the reaction zone seemed to have a role regardless of the other factors. The reaction zone had a higher moisture content than the decay regions and a high ion content, which probably contributed to reduce the resistivity of the section. Rennerfelt and Tamm (1962) suggested that K^+ accumulation in decayed wood had an origin in the transpiration stream. If we assume that a reaction zone occurs when the decay comes in to contact with the sapwood, it could be hypothesized that the high ion concentrations of the decay column at a certain height originate in the reaction zone. We observed that K^+ concentration exponentially increased when decay represented more than 40% of the section (Fig. 5a), which would correspond to the time when the fungus has completely colonized the heartwood and is completely in contact with the sapwood. Between the decay column and the sapwood the tree creates a reaction zone [cf. Shain (1971)]. The reaction zone has a high ion content, so it seems likely that the transfer of soluble ions from the reaction zone to the decay column is the highest at that point.

High concentrations of Ca^{2+}, Mg^{2+} and Mn^{2+} in the reaction zone tended to cluster together with decay moisture. The ion Ca^{2+} is mobile and can contribute to the electrical resistance of the stem (Tattar et al., 1972), but in our study Ca^{2+} concentration did not correlate with decay or with Rotfinder values. As observed in early studies, Ca^{2+}, Na^+ and Mg^{2+} showed a different pattern to that of K^+ in decayed sections (Safford et al., 1974). The ions Ca^{2+} and Mg^{2+} are typically increased over time in decayed wood by several white rot fungi (Ostrofsky et al., 1997). Fungi use oxalate that chelates with calcium in order to detoxify their growth media (Evans et al., 1994) and, for that reason, depending on the species, calcium may be less mobile than potassium (Ostrofsky et al., 1997). Although following the same pattern as Ca^{2+}, the ions Mg^{2+} and Mn^+ probably do not contribute much to the overall electrical conductivity of the section (Tattar et al., 1972).

Rotfinder can give good predictions about the presence of decay and it can non-destructively give us quantitative information about the size of the decay. Rotfinder may be appropriate in cases when missing small decay columns (<10%) is not problematic. Measurements may be carried out at 0.30 m where the reported models can give better predictions. Measurements at 0.66 m may be recommended if false positives are specifically unwanted.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2011.06.033.

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