Detection of decay in trees with stress waves and interpretation of acoustic tomograms

F.W.M.R. Schwarze[1,2], C. Rabe[1], D. Ferner[1] & S. Fink[1]

[1]Albert-Ludwigs-Universität-Freiburg, Professur für Forstbotanik, Bertoldstrasse 17, 79085 Freiburg
[2]EMPA Eidgenössische Materialprüfungs- und Forschungsanstalt St. Gallen, Abteilung Holzschutz & Mikrobiologie, Lerchenfeldstrasse 5, CH-9014 St. Gallen

The Picus® acoustic tomograph is a minimally destructive instrument for assessing the internal condition of trees, as an aid for the evaluation of failure resistance (RUST, 2001). A number of sensors, spaced regularly around the stem, measure the transit times of manually produced sound impulses (stress waves). In any substrate, the velocity of sound is governed by two mechanical characteristics: the modulus of elasticity and the gross density, as shown in the following formula:

$$V = \sqrt{\frac{E}{?}} \qquad \begin{cases} V = \text{Velocity of the stress wave} \\ E = \text{Modulus of elasticity} \\ ? = \text{Density} \end{cases}$$

The modulus of elasticity is a property of the material, which can be altered in the early stages of certain kinds of fungal decay, in which the stiffness of the wood is reduced with little corresponding reduction of the gross (fresh) density due to selective delignification (SCHWARZE & FINK, 1994; SCHWARZE et al. 1995). From the above formula, it can be therefore deduced that this form of decay, even at an early stage, causes a measurable reduction in the velocity of sound (SCHWARZE & FINK, 1994). The other main forms of decay in standing trees (i.e. simultaneous white rot and brown rot), which cause a greater loss of density, also have a marked effect on the velocity of sound, albeit for more complex reasons. A long transit time may also be due to the diversion of the pathway around a zone of decay, rather than the slow passage of sound in a straight line through the zone. This can be related due to discontinuities in the cell wall material, even if the E-modulus and the density are both reduced. The major exception is decay caused by the fungus *Kretzschmaria deusta* (*Ustulina deusta*), which causes little change in sound transit times. When transit times across the stems of trees colonised by this fungus were measured with the Metriguard-Impulshammer® (SCHWARZE et al., 1994; SCHWARZE et al., 1995), the values obtained were not reliably different from values stated to be typical of unaffected trees (MATTHECK & BRELOER 1994).

According to the manufacturer's data, the Picus® acoustic tomograph overcomes the difficulty of detecting decay caused by *K. deusta*, as the measurements from all the sensors are calibrated relative to each other, thus providing an overall self-calibration of the measuring system. Although the effects of the decay on transit time may be small, such calibration may obviate any need to compare the measurements with a theoretical absolute value for intact wood. Using the differences in the transit times between each pair of sensors, the Picus® analysis software constructs two-dimensional pictures (acoustic tomograms), which show zones of differing sound transmission properties within the stem (Fig. 1). These zones are colour-coded, so that intact wood is shown as brown, slight degradation as green, moderate degradation as violet and advanced degradation as blue.

The main purpose of the present study was to construct cross-sectional maps of stems affected by fungal decay, showing zones of altered fresh- and dry-matter density, and to compare these with Picus® acoustic tomograms of the same cross-sections. The following questions were, in particular, addressed:

- How much decay-induced reduction in the fresh and dry density of the wood corresponds to each of the colour codes shown in the Picus® acoustic tomograms?
- Do the different colour zones correspond consistently with relative differences in density?
- Does the device detect all density variations in the wood?
- How accurate is the resolution of the acoustic tomograms?
- Can decay caused by *K. deusta* be detected by the Picus® acoustic tomograph?
- To what extent does the moisture content of the wood affect the acoustic tomograms?

2. Material and methods

2.1. Selection of fungally colonised trees

Three trees, one each of beech (*Fagus sylvatica* L.), horse chestnut (*Aesculus hippocastanum* L.) and Norway maple (*Acer platanoides* L.) were assessed. These are listed in Table 1, with the geographic locations and the decay fungi that were present within the cross-sections studied. For identification of the decay fungi, pure cultures were made and examined for morphological characteristics (STALPERS, 1978; ROSE, 1993; FERNER, 2000; FERNER & SCHWARZE, 2002).

Table 1. Origins of fungally colonised trees and the isolated decay fungi

Tree species	Fungal species	Type of decay	Locality
Beech (*Fagus sylvatica*)	*Ganoderma adspersum* (Schulz) Donk	White rot	Bad Schachen
Horse chestnut (*Aesculus hippocastanum*)	*Pleurotus ostreatus* (Jaquin:Fr.) Kumm	White rot	Straßburg
Norway maple (*Acer platanoides*)	*Kretzschmeria deusta* (Hoffm.: P. Martin)	Soft rot	Umkirchen

The acoustic measurements were made either in the main stem or at the base of each tree, with two such measurements being made in the beech tree, two in the horse chestnut and seven in the Norway maple. Subsequently, sample disks were taken from the trees at the heights where the measurements had been made. Thus there were seven such discs removed from the Norway maple at heights from 5 cm to 270 cm above ground, two from the beech at 50 cm and 180 cm and two from the horse chestnut at unrecorded heights. In order to enable the data from the sample discs to be compared with the acoustic tomograms, the northern position was marked on each disc before cutting. The discs shown in the photographs below are orientated with their northern sides uppermost.

2.2. Sub-sampling of the discs into wood blocks

Segments of the beech and horse chestnut sample discs as well as the complete disks of the Norway maple were divided into cubical blocks, each measuring 2.8 x 2.8 x 2.8 cm and thus having a volume of 21.95 cm^3. This was done by first cutting the segments accurately so as to measure 2.8 cm axially and tangentially. After cutting from the segments, the cubes were numbered and photographed with a digital camera.

2.3. Measurement of wet and dry wood density

Immediately after being cut from the sample discs and segments and then numbered, the weights of all the cubical wood blocks were recorded, using a precision balance, so as to calculate their fresh density while fresh. The blocks were dried for 48 hours at 103°C and weighed repeatedly (residual moisture = 0 %), in order to determine their dry density.

The calculations of density were made according to the formula:

$$? = {}^{m}\!/\!{}_{V} \quad \begin{cases} ? = \text{Density} \\ m = \text{Mass} \\ V = \text{Volume} \end{cases}$$

2.4. Alignment of wood block photographs with the tomograms

Beech and horse chestnut

The photographs of the sample segments were overlaid on to their matching positions on the Picus® acoustic tomograms, which had been generated on the same scale (1:1) using the Picus® software. Thus, the visual appearance of each individual wood block within a segment could be compared with its corresponding tomographic colour zone.

Norway maple

Since the sample discs from the Norway maple were completely cut into blocks for density determination, it was necessary to match the photographs of the individual blocks with their exact positions on the 1:1 tomograms (Fig. 8). This was done by aligning the edges of the blocks accurately. After the photographs of the blocks were overlaid on to the outlines of the sample discs, the boundaries of the colour zones were then superimposed on these composite pictures with the aid of a pin. It was thus possible to match the blocks accurately to their colour zones on the tomograms.

2.5. Evaluation and comparison of the tomograms and the sample disks

Beech and horse chestnut

For macroscopic assessment, the photographs of the wood samples and the tomograms were compared on a 1:1 scale. The photographs of the segments that had been removed were included. For each series of samples that were thus found to fall within a particular colour zone, the fresh and dry density values of the individual wood blocks were averaged and represented in a bar chart showing relative percentage values, with 100 per cent represented by the colour zone with the highest density value.

Norway maple

For the Norway maple, density charts were constructed by superimposing the density data on to photographs of the sample discs. As shown in Fig. 8, these data consisted of the outlines of all the individual cubical sample blocks, each being colour-coded so as to represent a density range, either for fresh or dry density. Five such colour codes were selected, so as to correspond with the colours on the Picus® tomograms. This was done by taking one fifth of the difference between the highest and lowest density values, as shown in the example below. Thus the colour blue was assigned to the lowest relative density range (0-20%), then violet (20-40%) followed by green (40-60%), light brown (60-80%) and dark-brown (80-100%).

For clarification, the following example explains the calculation:

- lowest density value: 5
- highest density value: 20
- difference of the values: 15
- division of the difference by 5: = 3

Table 2. Explanation of the allocation of colour codes

Density zone	Percentage density	Density value	Colour code
1	0-20	5-8	Blue
2	20-40	8-11	Violet
3	40-60	11-14	Green
4	60-80	14-17	Light brown
5	80-100	17-20	Dark brown

In addition to the analysis of individual cross-sections of the Norway maple stem, a vertical chart was constructed by integrating the results obtained from the seven Picus® tomograms. This represents the axial pattern of development of decay that had been caused by *K. deusta* (Fig 10). The seven individual tomograms are included in Fig. 10 so as to show their positions in relation to the vertical chart.

3. Results

For each tree species, the following results show a photograph of sample disk, the corresponding Picus® tomogram and the density values. For clarification, the designations used for the view of the illustrations are repeated briefly as follows:

- S_n represents the number of the sample disc, with 'n' representing the sequential position of the disc from ground level (n=0) upwards.
- MPN represents a measuring point on a disc segment, where the value N corresponds to one of the numbered circumferential points where the Picus® probes were inserted.
- The bar charts show the fresh and dry density values which were found to correspond to the different Picus® tomogram colour codes. The standard deviations of the bar values are included.
- For depicting the density values of the Norway maple blocks on the cross-sectional charts, the Picus® colour codes (blue, violet, green, light brown, dark-brown) were used to represent five density ranges. The density chart (Fig. 8) is not therefore located together with the bar charts in Fig. 9.
- In the density charts the relative percentage values are colour-coded as follows: blue = 0-20%; violet = 20-40 %; green = 40-60 %; light brown = 60-80 %; dark-brown = 80-100 %.

3.1. Beech and *Ganoderma adspersum*

The S_0 disc from the beech tree shows the extent of the white rot caused by *G. adspersum* (Fig. 2). The eccentric cavity occupies approx. 30 % of the sampled cross-sectional area. The bleached zone surrounding the cavity, mainly on the upper side of the picture (north), consists of selectively delignified wood. There is still a zone of intact wood on the eastern side, where the reaction zone of the tree had not yet been breached. There is also an intact zone on the north-west, corresponding to measuring points 2, 3 and 4. In the accompanying tomogram, the dark-brown colour zone represents the highest density; this applies both to the fresh and dry density (Fig. 3). It is remarkable that, for the fresh density values in Fig. 3, there is rather a slight gradation of values from the dark-brown to the blue categories. Even the blue-coded wood retained a fresh relative density of 64.9 %. The difference between the dark brown and green categories was only 6.4 %, although the following difference between green and violet is substantially greater at 25.5 %. The remaining difference of 3.2 % between violet and blue is, however, again very small. The variation, as shown by the standard deviation, is greatest in the violet category (39 %) and smallest in the dark-brown category.

The dry density values show a difference between the dark-brown and green categories (21 %), which is about 15 % greater than the difference in fresh density. The residual dry density of the blue category (12 %) is smaller by about 52 % than the corresponding fresh density value (Fig. 3). The actual dry density value for the dark-brown category (0.62 g cm^{-3}) is somewhat less than the average value of 0.68 g cm^{-3} stated by WAGENFÜHR (1996).

3.2 Horse chestnut and *Pleurotus ostreatus*

The S_1 sample disc shows an extensive brownish discoloration (Fig. 4). The most strongly decayed zone, where there is dysfunctional tissue at the bark surface, is on the northern side between measuring points 1 and 2. This appears to be accurately represented in the Picus® tomogram. A high proportion of the remaining wood, with its brownish discoloration, falls within the green and light brown colour categories in the tomogram. The excised segments clearly show the typical netlike pattern of decay caused by *P. ostreatus*.

The percentage density values are approximately the same for fresh and dry wood (Fig. 5). The greatest difference between successive colour categories is approx. 30 % between light brown and green, whereas there is a difference of only approx. 10 % between the light brown and dark-brown categories (Fig. 5). The blue category represents a density loss of 70 %. The variation within this category, as shown by the standard deviation, is almost twice as great for fresh density (35 %) as for dry density. The dark-brown colour category shows the smallest standard deviation (11.63 % for fresh density and 9.47 % for dry density. The actual dry density value is 0.46 g/cm^{-3}, which lies within the lower part of the range stated by WAGENFÜHR, 1996).

3.3. Norway maple and *Kretzschmaria deusta*

The photograph of sample disc S_0 from the Norway maple shows a large pale zone of wood decay caused by *K. deusta*, which extends well into the sapwood near measuring point No. 4. This decay involves the preferential degradation of cellulose, leading to a brittle consistency. The zone lines typical of this fungus can be clearly recognized (Fig. 6). Between the decayed zone and the outer band of intact wood, the dark-brown boundary, up to eight centimetres wide in places, is the reaction zone, characterized by an increased moisture content (SCHWARZE, 1995; SCHWARZE & GÜLPEN, 1995). Another dark brown zone lies within the innermost part of the disc. The advanced state of the decay on the western side of the disc is represented very faithfully by the acoustic tomogram.

In the fresh density chart, the high density of the dark zone at the centre of the disc is clearly evident in the form of brown-coded sample blocks. On the same basis, the circular reaction zone is well represented. In the Picus® tomogram, however, neither of these high-density zones are represented. The low-density areas are much better represented within the tomogram, especially near measuring point No. 4, where a blue colour zone corresponds with a region of advanced decay. The functional sapwood exhibits a lower fresh density than the reaction zone, and is therefore represented by sample blocks with a light-brown colour coding (Fig. 6). The tomogram shows some green areas within the northern part of the image, indicating a reduced density, but this is not borne out by the density chart.

The dry density of the brown-discoloured central part of the cross section is very low (i.e. much lower than its fresh density), and this is shown both on the tomogram and the dry density chart (Fig. 7). Large areas that fell into the violet colour category in the fresh density chart are green according to the dry density chart. The zone of advanced decay on the left-hand side of the image (MP4) has the lowest density on both charts, as shown by the blue colour coding.

The fresh and dry density loss represented by the blue category is approx. 40 % (Fig. 7). Within this category, the standard deviation is 13.3 % greater for fresh density than for dry density. The difference between the green and violet categories is 15 to 20 % and there is a further difference of 10 % between the violet and blue categories. The actual value of dry density of the healthy wood was 0.57g cm^{-3} on average (WAGENFÜHR, 1996).

3.4. Spatial extent of wood decay caused by *Kretzschmaria deusta* in Norway maple

Figure 8 clearly shows the vertical boundaries of the extent of colonisation by *K. deusta* in the stem of the Norway maple. This colonisation presumably follows the vascular trace of a damaged major root on the western side of the stem. The eccentric decay column at the stem base and the fungal fruit bodies on the western side of the tree support this interpretation.

The zone of advanced decay (blue colour coding) occupies a large proportion of the stem cross-section up to a height of 110 cm and then tapers abruptly. At a height of 270 cm, no loss of density due to decay by *K. deusta* could be detected.

4. Discussion

4.1. Beech and *Ganoderma adspersum*

The acoustic tomogram of the S_0 disc sample does not show the major cavity completely. The zone of selective delignification on the northern side is, however, well represented. If the blue and violet zones are added together and then compared with the actual extent of decay, it is apparent that the acoustic tomograph represent with reasonable accuracy the proportion of the cross-section affected by the decay. It seems, however, that the diagnostic system is less good at locating the exact position of the decayed zones. This difficulty is probably related to the complexity of the shape of the cross-section. The more strongly the shape deviates from a circle, the greater the inaccuracy even if the positions of the measuring points are recorded as accurately as possible. In the case of the beech tree, the major buttress on the north of the stem contributed substantially to the asymmetry of the sample disc. Further evidence that the Picus® acoustic tomograph is accurate in showing the cross-sectional area of decay zones, but not necessarily their exact location, is provided by the designer of the equipment (RUST 2003, personal communication).

A further reason why the cavity in the beech stem was not represented very accurately by the tomogram is that the zone of decay extends to the surface on the north of the stem, and that there is also a strongly delignified zone within the sapwood near measuring point No. 5. Thus the sensors 2, 3 and 4 were inserted into an intact zone of outer wood, but they were surrounded by strongly decayed wood. The same applies to the sensors inserted at measuring points No. 6 and 7 and likewise Nos. 9 and 10. As a result, there was a marked increase in the sound transit times, not only between sensors on opposite sides of the stem, but also between adjacent ones. An exact delineation of the decayed zone is difficult for this reason.

During the determination of wood density, a considerable amount of moisture was lost from the strongly delignified wood, as shown by the marked difference (well over 50%) between the fresh and dry density values in the blue category and over 30% in the blue category (Fig. 3). The wood delignified by *G. adspersum* is obviously able to absorb large quantities of moisture (FERNER, 2000; SCHWARZE et al., 1999). With less advanced decay, there is progressively less difference between the fresh and dry density. The fact that the Picus® acoustic tomograph showed a blue colour coding for the zone in which advanced decay was combined with high fresh density shows that its accuracy is not much affected by a high moisture content in decayed wood.

The large standard deviation of the dry density values in the wood blocks that came from areas showing violet on the tomogram can be explained by the fact that these violet areas extended both across zones of advanced decay and of intact wood. These intact zones were overlapped by the violet coding in places where inaccuracies coincided with sharp transitions between decayed and intact wood. Such transitions were in many places related to the reaction zone, which is characterised by a density value higher than that of the intact wood.

4.2. Horse chestnut and *Pleurotus ostreatus*

The tomographic representation of the dysfunctional area on the surface of the sample disc appears to be smaller than the true area. There is, however, an interesting agreement between the pattern of wood decay caused by *Pleurotus ostreatus* and the colours on the tomogram. A high portion of the discoloured wood within the zone of relatively advanced decay shows as green and light brown on the tomogram. The light brown colour category corresponds to the rather high density loss of 10%. Unlike *G. adspersum* decay in the wood of beech, *P. ostreatus* decay induces the loss of fresh and dry density at similar rates in horse chestnut wood. As the decay is a simultaneous white rot, all cell wall components of the wood are degraded, leading a marked decomposition of cellulose and thus a less moisture-retentive consistency.

4.3. Norway maple and *Kretzschmaria deusta*

Past investigations have failed to detect wood decay caused by *K. deusta* by means of acoustic measurements, even when strength loss is advanced. It has been assumed that the modulus of elasticity and the gross density are reduced at a similar rate, so that the velocity of sound is only insignificantly changed. The results of the present study show, however, that *K. deusta* decay can be detected even at an early stage by the Picus® acoustic tomograph. This conclusion is based on the presence of areas of green colour-coding within the S_0 sample disc. These represent less advanced decay than is generally present within the extensively decayed zone, in which the dry density is reduced to about 60 % of normal. Thus, the tomogram shows accurately the abrupt boundaries between intact wood and zones of either slightly or advanced decay. As in the case of the beech stem, the extent of the decayed zone but not its precise location is recognized.

The tomogram of the Norway maple disc sample (Fig. 6) shows slight inaccuracies within the green-coded zone, which extends into the functional sapwood. Both the density charts (Figs. 7) show clearly that *K. deusta* strongly had degraded the wood adjacent to the reaction zone but without breaching this zone. The blue-coded zone represents a relative density range of 60-70% in all the sample discs and the corresponding ranges for violet, green and brown are 70-80%, 80-90% and 90-100% respectively.

The results from the Norway maple show only a slight effect of wood moisture on the accuracy of the device. The high moisture content of the discoloured zone in the centre of the sample disc shown in Fig. 6 is represented by a high value for fresh density, yet the tomogram shows a blue colour coding, which represents the actual wood condition. This is clearly decayed, as shown by the dry density chart (Fig. 7) which shows low values, in contrast to the fresh density chart (Fig. 7).

Although the reaction zone has a high value for fresh density; up to 30 % above that of the functional sapwood, it is not revealed in the tomogram. This may be because the Picus® software is unable to resolve features as narrow as the reaction zone, which is only three to four centimetres wide on average, even though this resolution should be achievable with the hardware. As is evident from Fig. 1, the intersections of the acoustic pathways are the points with the highest accuracy. Sound waves travelling between these intersections contribute less information about density patterns within the wood. This means that the accuracy of the acoustic tomograms decreases with increasing distance from the intersections. It is probable that several intersecting pathways would have to fall on a reaction zone in order to show the associated density patterns accurately. An intact reaction zone is an important boundary both for assessing the extent of decay and for providing the tree with a natural defence against the extension of the decay and hence against an increasing probability of fracture, often over a long period. It should be noted that the hazard potential is always dependent partly on the particular combination of host and fungal species and this is essential information for any prognosis. It would therefore be desirable for the software to be able to represent such host-dependent defence reactions.

Finally it must be emphasised that, due to the small number of sample master discs, it has not been possible to assign exact density ranges to the Picus® colour categories. This may in any case be possible only with difficulty, due to the relative sound velocities used by the measuring system. For this reason, it might be impracticable to investigate further the physical properties of wood, as demarcated by the colour categories.

5. Conclusions

The following statements can be made on the basis of the investigations of acoustic tomography:

- No statement can be made about the density values that relate to certain colour categories.

- Within a sample cross-section, a zone of decay can be determined accurately for its size and moderately accurately for its position.

- Reaction zones cannot yet be represented, despite their high density.

- The shape of the sample cross section influences the accuracy of the acoustic tomograms. The greater the deviation from a circular outline, the poorer the accuracy. Likewise, the number of sensors naturally affects the accuracy.

- The resolution of the tomograms is still worthy of improvement.

- Wood decay caused by *K. deusta* can be detected by the Picus® acoustic tomograph.

- High moisture contents, unlike frost, appear to affect the acoustic measurements only slightly.

h) Although capable of improvement in some respects, the Picus® acoustic tomograph currently offers a very good diagnostic support for evaluating the condition of trees and hence their resistance to fracture.

6. References

FERNER, D. (2000). Histologische Studien zur Aggressivität von *Ganoderma spp*. an Platane. Diplomarbeit Inst. f. Forstbotanik u. Baumphysiologie, Albert-Ludwigs Universität Freiburg.

FERNER, D. & SCHWARZE, F.M.W.R. (2002), Lackporlinge an Bäumen. Differenzierung und Aggressivität verschiedener Arten. Neue Landschaft 46, 50-55.

MATTHECK, C. & BRELOER, H. (1994). Handbuch der Schadenskunde von Bäumen. 2. Aufl., Rombach, Freiburg.

ROSE, D.R. (1993). Rotters; an expert key for the identification of wood-rotting fungi in culture. Binary 5, 43-46.

RUST, S. (2001). Baumdiagnose ohne Bohren. AFZ - Der Wald 18, 924-925.

RUST, S. (2003) Mündliche Mitteilung, Institut für Gehölze und Landschaft Dr. Gustke GmbH, Unter den Eichen, D 16259 Neu Gersdorf.

SCHWARZE, F.W.M.R., MATTHECK, C. & BRELOER, H. (1993). Der spröde Baumbruch -verursacht durch den Brandkrustenpiiz. Neue Landschaft 38, 737-747.

SCHWARZE, F.W.M.R. & FINK, S. (1994). Ermittlung der Holzzersetzung am lebenden Baum: Möglichkeiten und Grenzen verschiedener Diagnoseverfahren zur Erfassung von Holzzersetzungsmustern. Neue Landschaft 39, 182-193.

SCHWARZE, F. W. M. R. (1995). Entwicklung und biomechanische Auswirkungen von holzzersetzenden Pilzen in lebenden Bäumen und in vitro. Diss. Univ. Freiburg, svk- Verlag, Erndtebrück.

SCHWARZE, F. W. M. R. & GÜLPEN, M. (1995). Computertomographische Untersuchungen an Spitzahorn, zur Ermittlung des Ausmaßes einer Holzzersetzung durch den Ascomyceten *Ustulina deusta*. In: Habermehl, A. (Hrsg.) Die ComputerTomographie als diagnostische Methode bei der Untersuchung von Bäumen. BZM-Verlag, Minden, 127-131.

SCHWARZE, F.W.M.R., LONSDALE, D. & MATTHECK, C. (1995). Detectability of wood decay caused by *Ustulina deusta* in comparison with other tree-decay fungi. European Journal of Forest Pathology 25, 327-341.

SCHWARZE, F.W.M.R., ENGELS, J. & MATTHECK, C. (1999). Holzzersetzende Pilze in Bäumen – Strategien der Holzzersetzung. Rombach Verlag, Freiburg 245 pp.

STALPERS. J.A. (1978). Identification of wood inhabiting Aphyllophorales in pure culture. Centraalbureau voor Schimmelcultures, Baarn, Studies in Mycology 16, 1-248.

WAGENFÜHR, R. (1996). Holzatlas. Leipzig : Fachbuchverlag 688 pp.

Legends to Figures

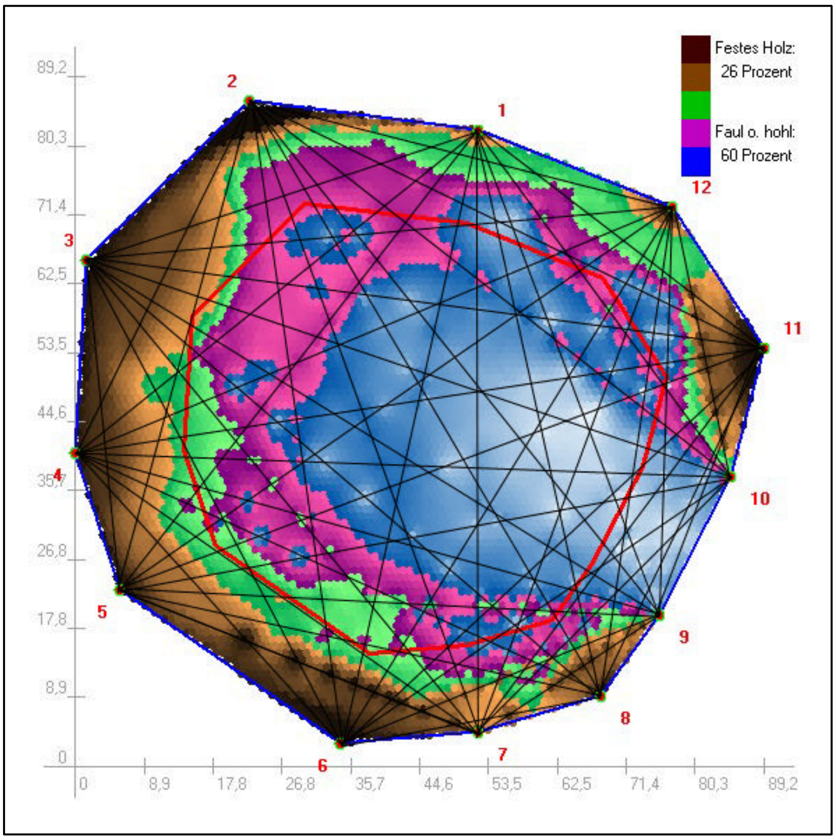

Fig. 1. By tapping each sensor in turn, a close network of acoustic measurements develops. The accuracy of the acoustic data is highest at the points where the propagation pathways of the acoustic waves intersect. With increasing distance of these intersections the accuracy of the measurement decreases. The red line on the tomogram marks the failure criterion T/R = 0.3 after Mattheck & Breloer (1994).

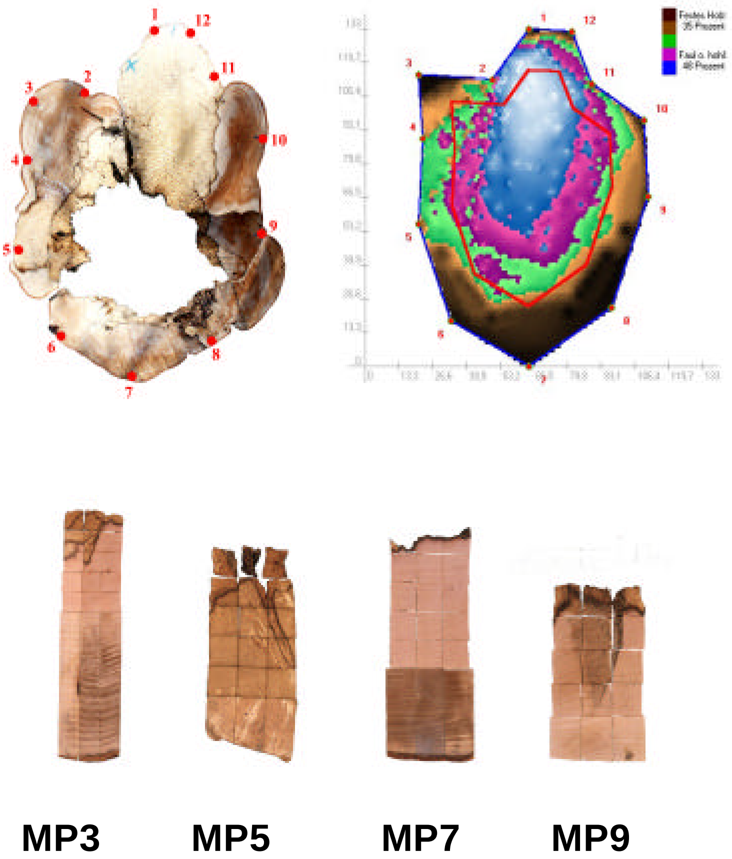

Fig. 2. *Ganoderma adspersum* in beech (Fagus sylvatica) at 50 cm above ground. Top left: photo of the sample disk (diameter 116 cm). Top right: acoustic tomogram, showing the cavity represented partly blue, violet and partly in green. A zone of advanced decay (blue), extending towards the upper edge (north), corresponds well with the photograph. The segments illustrated below were excised at the indicated measuring points (MP).

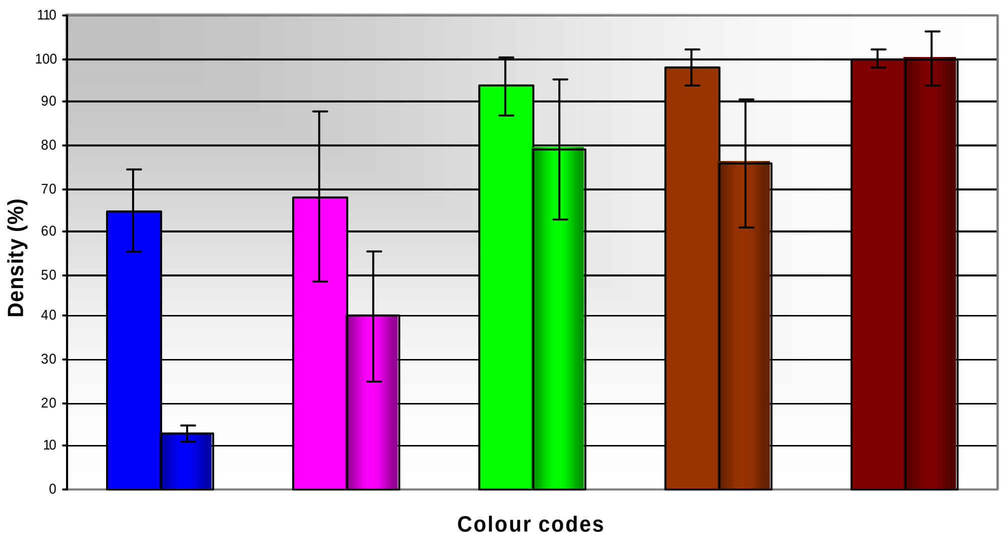

Fig. 3. Relationship between gross density (left), dry density (right) and the colour categories in the delignified wood of the S_0 beech sample disc.

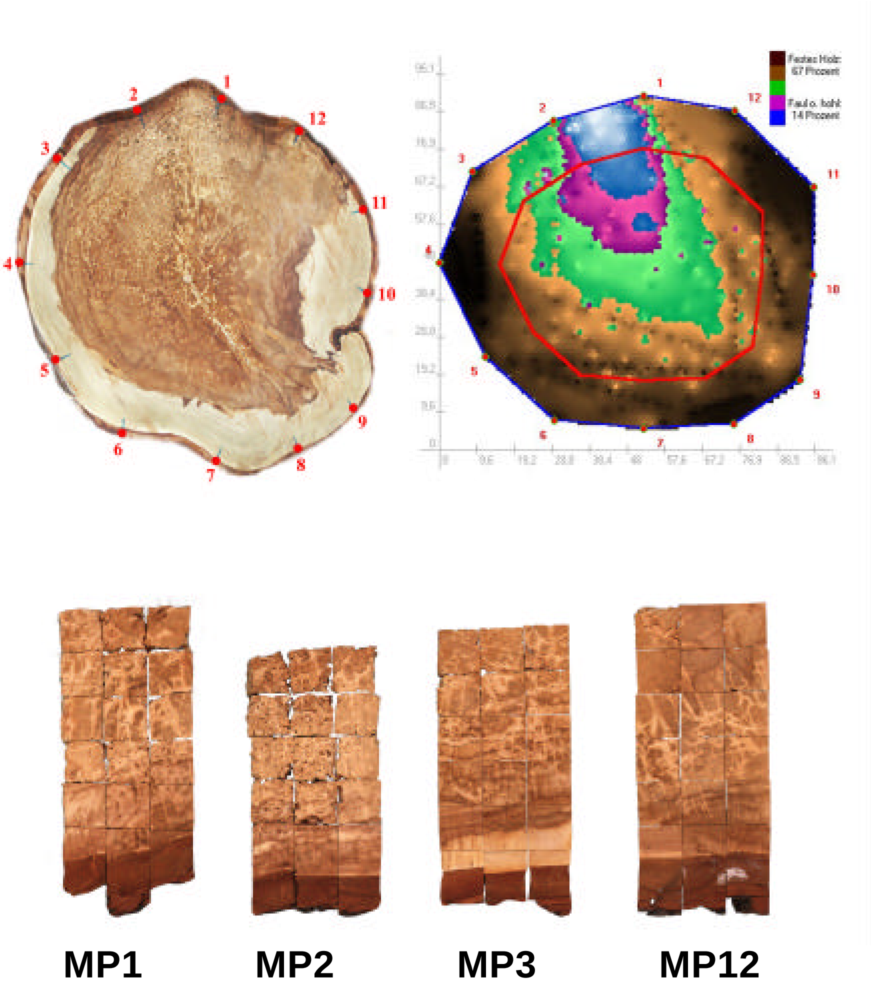

Fig. 4. *Pleurotus ostreatus* in the S_1 Horse chestnut sample disc. Top left: photograph of the disc (diameter: 96 cm). Top right: the corresponding Picus® acoustic tomogram. Below: the four segments excised from the sample disc.

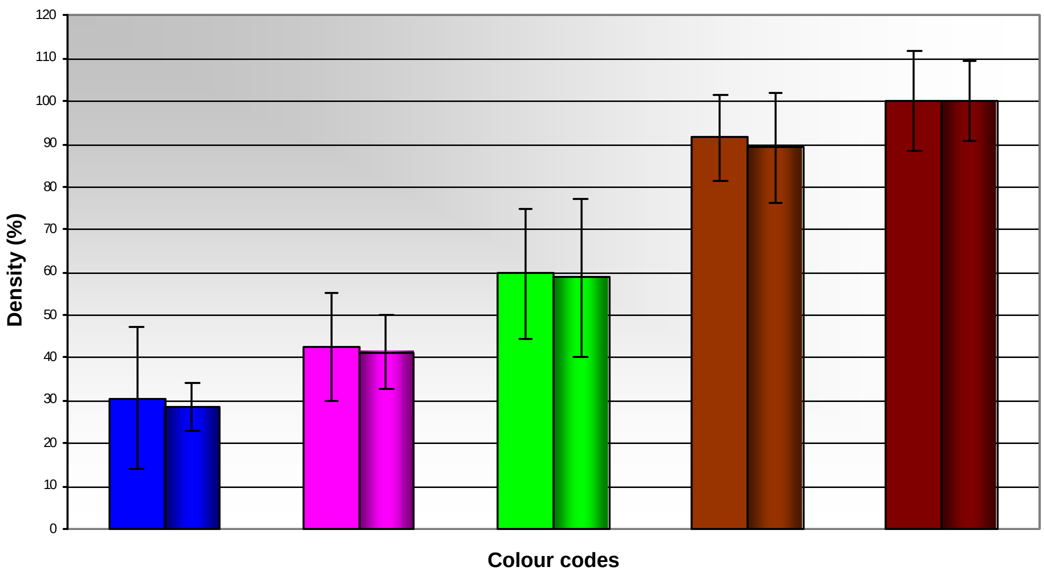

Fig. 5. Relationship between gross density (left), dry density (right) and colour categories in the white-rotted wood of the S_1 horse chestnut sample disc.

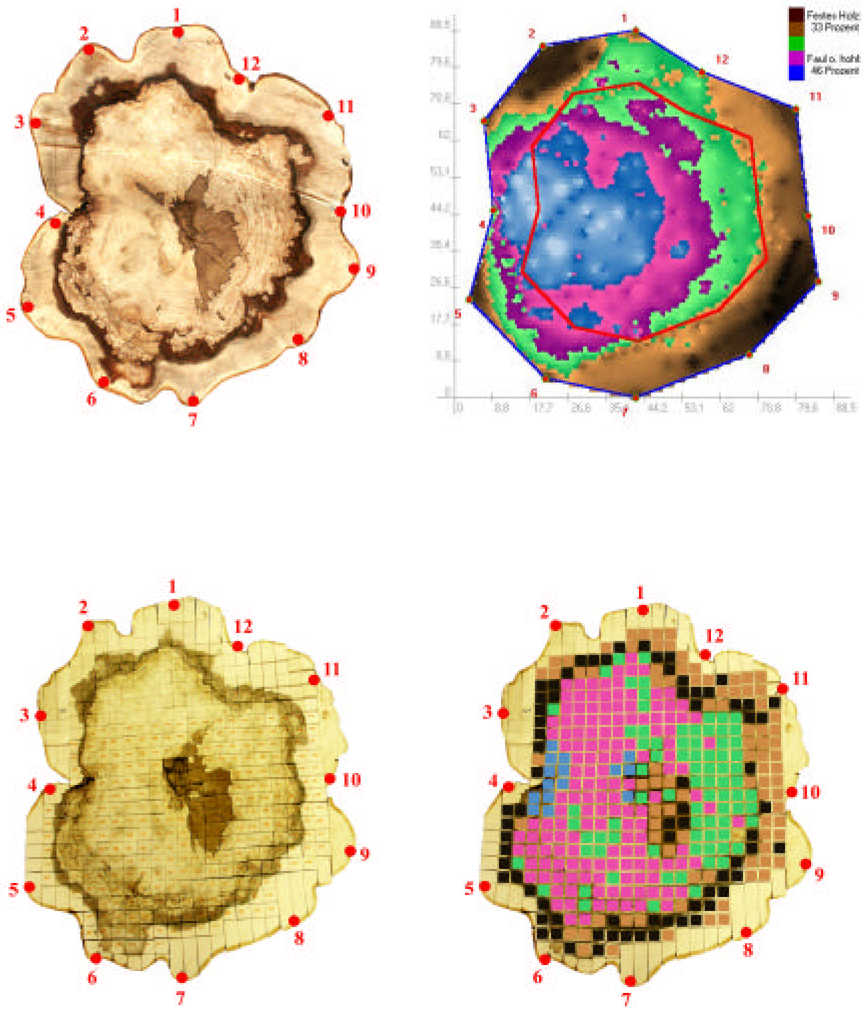

Fig. 6. *Kretzschmaria deusta* in the Norway maple S_0 sample disc. Top left: photograph of the disc (diameter: 90 cm), taken from 5 cm above ground. Top right: the corresponding acoustic tomogram. Below left: the S_0 sample discs divided in numbered cubical blocks. Below right: the corresponding density chart with the colours assigned to the fresh density value-ranges.

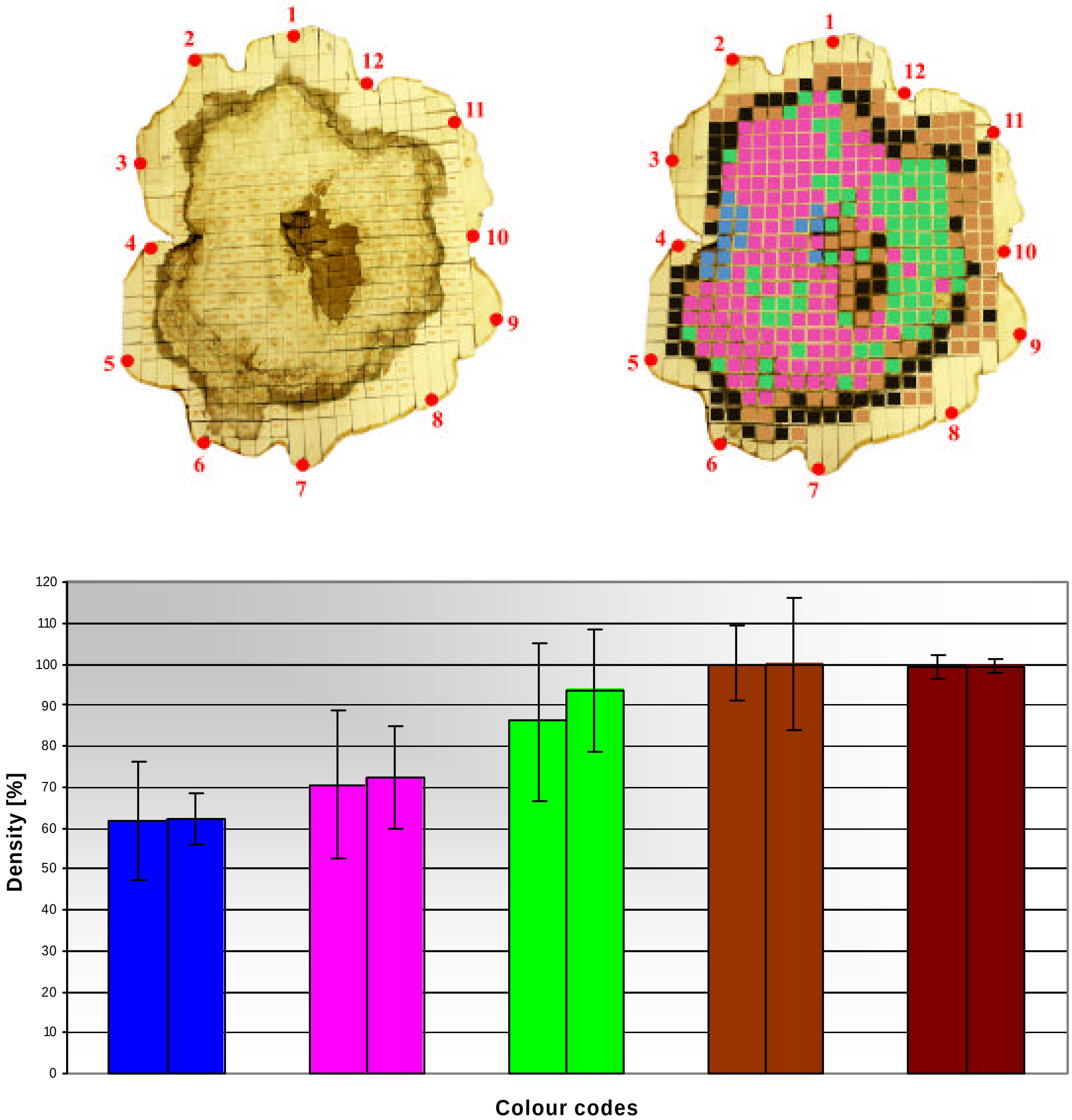

Fig. 7. Top left: Photograph of the Norway maple S_0 sample disc, overlaid with the outlines of the numbered cubical blocks into which it was divided for determination of density. Top right: the same picture, with the dry density value of each cubical block shown by colour coding. Below: Relationship between gross density (left), dry density (right) and colour categories in the Norway maple decayed by *Kretzschmaria deusta*.

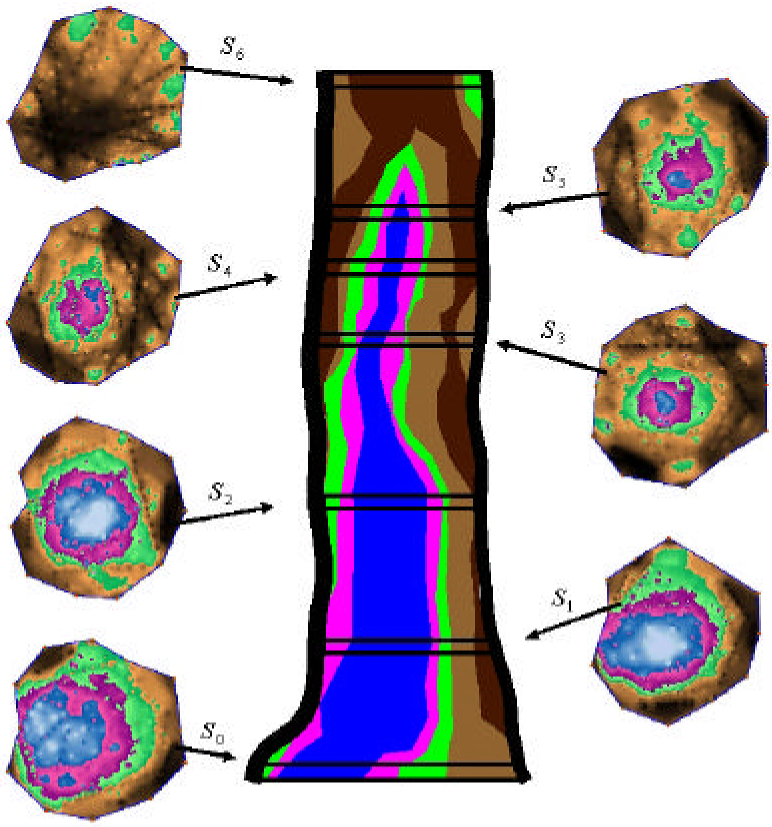

Fig. 8 Spatial extent of the wood decay caused by *Kretzschmaria deusta* in the Norway maple stem. The seven numbered sample discs from which this image was generated are shown to the left and right. The discs were cut from the following heights above ground: S_0 = 5 cm; S_1 = 50 cm; S_2 = 110 cm; S_3 = 170 cm; S_4 =200 cm; S_5 = 220 cm; S_6 = 270 cm.