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IT'S WHAT'S INSIDE THAT COUNTS: AN ASSESSMENT METHOD TO MEASURE THE RESIDUAL STRENGTH OF ANOBIIDS INFESTED TIMBER USING MICRO-COMPUTED TOMOGRAPHY

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Abstract

The safety assessment of old timber structures is an important issue due to the long-term behavior of wood and the structural complexity found in some older constructions. If the structure is degraded due to the action of wood-boring insects, the complexity of the analysis increases.
The objective of the work reported in this paper is to provide an assessment method to measure the residual strength of pine structural elements degraded by anobiids. Samples of degraded timber were submitted to micro-computed tomography (µ-XCT) to quantify density loss being this parameter of fundamental importance for the assessment of timber structures as it is highly correlated with timber mechanical properties. During the µ-XCT study an empirical correlation between lost material percentage (consumed by beetles) and timber apparent densities (original – before degradation and residual – after degradation) was established.
The results showed an experimental high correlation (r^2=0.66) between original apparent density and lost material percentage and an even higher correlation (r^2=0.87) between residual apparent density and lost material percentage which confirms that µ-XCT can be validly used contributing to the 3D visualization and quantification of timber degraded elements.
After the µ-XCT study, screw withdrawal and shear parallel to grain tests have been made in maritime pine degraded timber. Screw withdrawal force and shear strength values were related with density loss (r^2=0.64 for screw withdrawal; r^2=0.65 for shear strength parallel to grain). A novel assessment method for evaluating the impact of anobiid damage on timber degraded structural elements based in four major steps is proposed enabling a more quantitative assessment of the timber elements residual strength and, therefore, contributing to reduce unnecessary replacement and to provide foundations required to perform experimental modelling tests.

1 INTRODUCTION

Timber is known as one of the oldest and more widespread construction materials. However, this natural material is susceptible to biodeterioration, which is frequently caused by agents like fungi and insects [1]. In Portugal, the insects that cause most problems to timber structures are termites (Blattodea, Termitoidae) or wood boring beetles (Coleoptera) of which several representatives of the anobiid family play a major role in the deterioration problems of older structures. These beetles' attack is normally limited to sapwood [2] and the damage caused is easily recognizable on the outside of timber elements by the size and the shape of emergency holes and the type of frass [3].

A structural assessment is certainly required in cases of insect damage on timber elements and actions must be taken to ensure an adequate safety level. The correct identification of the responsible insects is essential to better set up valid diagnosis and remediation strategies. Nevertheless, due to a diffuse damage create by these insects, the assessment of the structural soundness of the remaining timber becomes more difficult [4]. The damage caused by anobiids is a frequent justification for partial or complete replacement of structures since it is difficult to assess the structural soundness of the "remaining" timber [5]. Furthermore, degraded structural elements are often wrongly assessed as not having any residual strength and thus replaced. It happens that, most of the times, there is no need to remove those elements since the structural safety is still guarantee or can be achieved with appropriate strengthening [6].

When the structure is not replaced, most of times, the effect of anobiids' attack is considered by assuming a significantly reduced cross section or reduced mechanical properties for that cross sections [7]. This approach may although be too conservative, as even the insect damaged-layer can often be able to resist load.

Several studies have been made [6,7,8] with the objective to evaluate the impact of anobiid damage on timber structures. However, the degradation intensity on the structure was mostly inferred from an examination of the surface appearance. This visual approach is not completely representative of the real degradation state as the intensity of the internal holes tends to be much greater than that on the surface [8]. Then, it is important to know the lost material percentage (wood consumed by beetles) as well as the loss of density, in order to conclude on structural safety. Knowledge of timber original and residual apparent density is of fundamental importance to assess timber soundness as these parameters are highly correlated with timbers mechanical properties.

The main objective of the work reported in this paper was to evaluate the impact of anobiid damage on pine timber structures by establishing a valid correlation between lost material percentage (obtained using micro-computed tomography) and original/residual density and by developing an initial approach for a method for an on-site assessment of infested timber structural elements based on a screw withdrawal test.

2 EXPERIMENTAL PROGRAMME

2.1 Sampling

Timber samples used in this study came from a beam of maritime pine (*Pinus pinaster* Aiton) retrieved from a mid-20th century roof structure of a residential building located in Lisbon, Portugal. The beam presented varying degrees of infestation restricted to the sapwood and mainly caused by insects identified as anobiids (Coleoptera, Anobiidae). Furthermore, frass characteristics as well as the size of tunnels and the presence of cocoons inside the wood allowed the identification of *Nicobium castaneum* Olivier has the main species responsible for the degradation, although the presence of other anobiid species cannot be excluded.

The beam was then divided in 4 segments (3 presenting degradation and the heartwood (Fig. 1a) and 17 samples of approximately 40 × 20 × 40 mm^3 were cut (Fig 1b). After that, and because these initial samples cannot be submitted to a procedure like micro-computed tomography due to their relatively large size, samples were cut again in order to obtain 17 “new” paired samples with approximately 40 × 20 × 10 mm^3 (Fig 1c) [4].

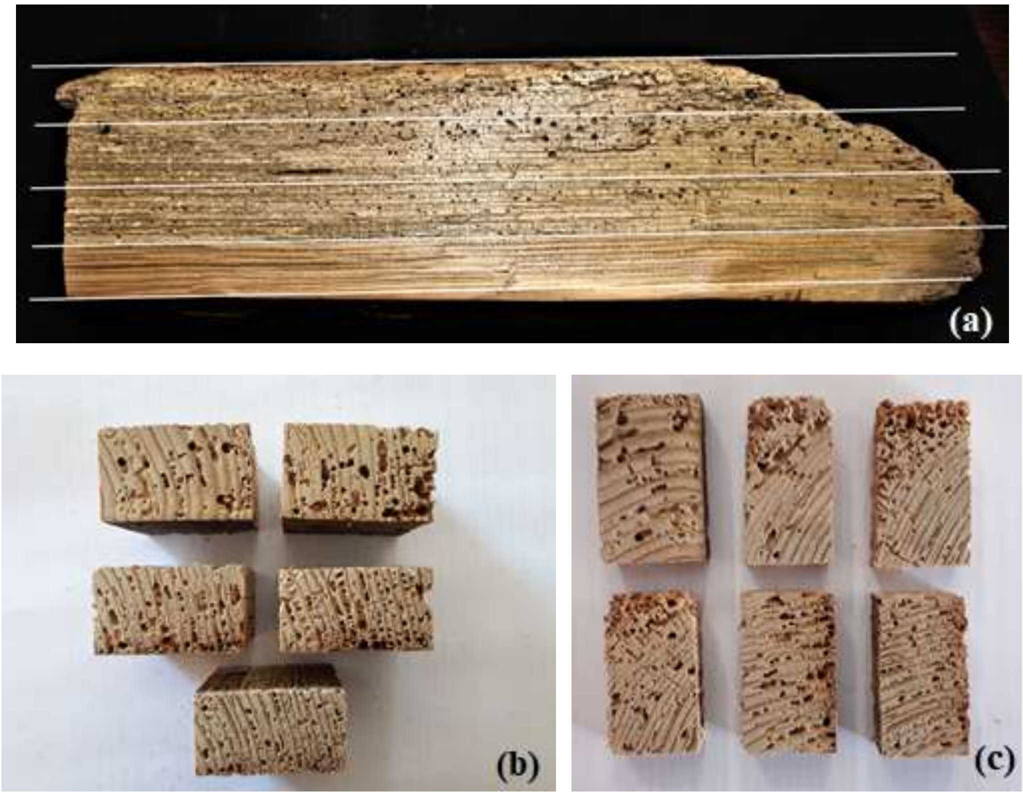

Figure 1: Sampling [4]: (a) timber beam initially divided in 4 segments; (b) some of the 17 samples resulting from the first cut of the beam and (c) some of the 17 “new” paired samples resulting from the second cutting process.

All the samples were conditioned in a climatic room at a temperature of 20±2ºC and a relative humidity (RH) of 65±5% and maintained in this condition until required for mechanical testing of micro-computed tomography scanning procedure [9].

2.2 Micro-computed tomography study

Micro-computed tomography (μ-XCT) was used as a 3D microscope to assess the anobiids’ tunnelling process result (visualizing its spatial distribution and morphology) and calculate void’s volume (lost material) [16] (Fig.2). By knowing this percentage of lost material, the loss of density can be estimated. After that, the loss of density can be correlated with timber mechanical properties via screw withdrawal and shear parallel to the grain tests enabling a valid quantitative assessment of the timber elements residual strength.

The samples were scanned using a compact desktop with micrometric range resolution, μ-XCT Skyscan 1172 microtomograph (Bruker Instruments, Inc., Billerica, Massachustets), using computer-controlled tomography acquisition, processing, reconstruction and analysis software packages (http://bruker-microct.com/products/1172.htm).

The parameters used in the scanning procedure (acquisition) were optimised considering the studied material, the maximum possible resolution (18.09 μm) for the selected samples and the required output parameters (wood – skeleton and voids – empty spaces). Concerning the acquisition process, the best choice of the scanner settings is of fundamental importance since this choice affect substantially image quality. Therefore, these settings must be selected considering the aim of the problem to be studied and the physical, geometrical and operating constraints of the scanner. In this study, the voltage selected for the X-ray source was 60 kV and an aluminium filter with a tick of 0.5 mm was used. The X-ray source was operated at 165 µA and the samples were image through 180 degrees of rotation at 0.7-degree increment' steps. The total acquisition time for each sample was approximately 1.5 h with a total of 288 acquired images. These acquisition parameters were applied to the study of all 17 samples.

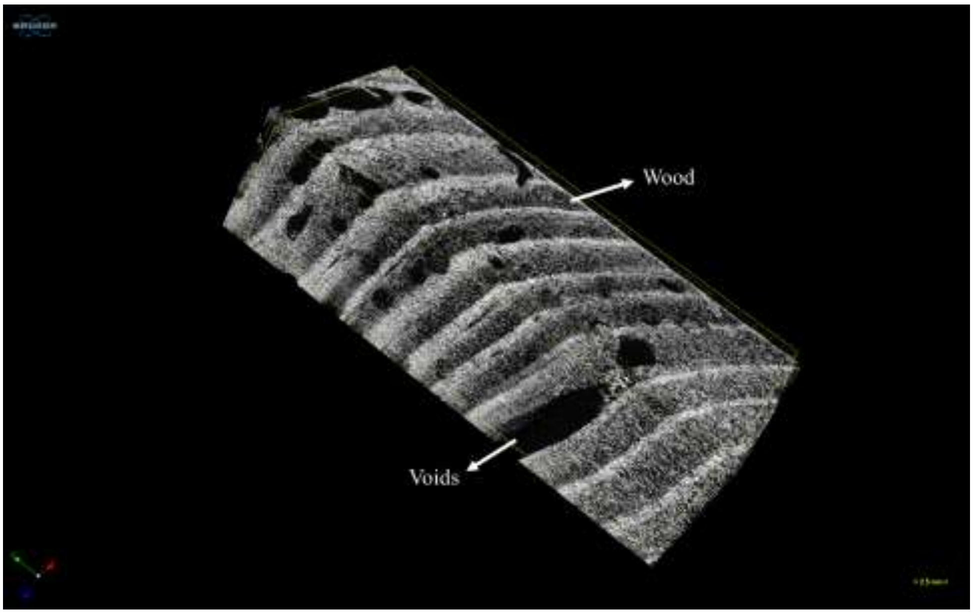

Figure 2: Reconstructed 3D object showing the parameters of interest: wood and voids.

2.3 Data analysis

The output parameters are exported from CTAn software in a form of a *txt* file. In this file, among the various output parameters values that can be estimated, two of them can be highlighted: *total volume*, referring to the volume of the sample (wood and voids) and *wood volume,* relating to the wood itself (skeleton). These parameters correspond to those of interest previously defined, as voids volume will correspond to the difference between *total volume* and *wood volume*. Wood apparent density was assessed at 12% moisture content according to [10]. Original apparent density is obtained by the ratio between the sample weight and *wood volume* whilst residual apparent density is obtained by the ratio between the sample weight and *total volume.*

2.4 Methods

2.4.1. Screw withdrawal perpendicular to grain

Screw withdrawal tests were carried out considering the method specified in [11] and conducted in a universal testing machine (Schimazu AG-250KNIS-MO), capable of measuring the load applied with an accuracy of 1% in the range 1kN to 250 kN. A metal screw with an outer diameter of 6 mm and a length of 60 mm was used. The screw was inserted in the direction perpendicular to the grain and no distinction was made between the radial and tangential directions since the results do not differ significantly [8].

In this study, four screw withdrawal tests were performed at four different places of the beam before the first cutting process. Before measurements, a pre-drilled hole of 4 mm in diameter was made and the penetration length of the screws was 20 mm to enable a comparative profile of strengths at a range of depths. The samples that were submitted to μ-XCT and those that were tested to shear parallel to the grain, due to their relatively small size, cannot be submitted to a semi-destructive test such as is the case of the screw withdrawal test. Therefore, the timber places along the beam where the screw withdrawal test was performed were not used in samples that would be submitted to μ-XCT scanning procedure or shear tests.

2.4.2. Shear parallel to grain

Shear parallel to the grain tests were performed according to [9] and were conducted under deformation-control at a rate of 1 mm min^{-1} in a universal testing machine (Schimadzu), with a load cell of 250 kN. The machine can measure the applied load with an accuracy of 1% in the range of 1 kN to 250 kN. Shear strength parallel to the grain corresponded to the maximum load attained on $40 \times 20 \times 30\ mm^3$ samples. The load was applied at a constant rate so that the maximum load was attained in the interval 300 ± 120 seconds.

The test was performed in nine samples (three samples for each three proposed degradation level). The glue used in these tests was an epoxy glue *Araldite*® with a maximum tension strength of 320 kg/cm^2 in 48 hours.

3 RESULTS AND DISCUSSION

3.1 Micro-computed tomography study

Table 1 presents the results obtained.

Table 1: Output parameters’ values, sample weigh and apparent densities per level of degradation.

Level of degradation	Number of samples	Average values						
		Total volume	Wood volume	Lost material	Weigh	Original apparent density	Residual apparent density	Loss of density
		cm^3	cm^3	%	g	kg/m^3	kg/m^3	kg/m^3
1	5	8.642	7.850	9.12	4.545	582	529	9.2
2	7	7.836	6.648	15.16	3.449	517	439	15.3
3	5	7.427	5.679	23.54	2.720	495	386	21.9

According to the results obtained using micro-computed tomography (parameters of interest), the samples were distributed over three levels of degradation: level 1 (< 10% lost material); level 2 (10 to 20% of lost material); level 3 (>20% lost material). A Shapiro-Wilk test has confirmed the normality of the results (p-value = 0.276).

The obtained results for apparent densities (original and residual) decrease with increasing percentage of lost material, as expected. With regards to the proposed level definition, the highest density loss occurred for level 3, with a loss of 21.9 ± 1.4%. For levels 1 and 2, the loss of density was 9.2 ± 0.64 % and 15.3 ± 3.5 %, respectively. Considering all samples, it was obtained an average loss of density of 80 ± 24 kg/m^3 (15.4 ± 5.5%), an average original theoretical density of 529 ± 53 kg/m^3 and an average residual density of 449 ± 70 kg/m^3.

The obtained results indicate a medium correlation (r^2 = 0.60) between lost material percentage and original timber density, which becomes higher (r^2 = 0.83) when comparing lost material percentage and residual density (Fig.3). The results show that the higher the density, the lower the percentage of lost material, as expected. The obtained results suggest it is very likely that timber density is a determinant of the quality of timber but also supports the claim that μ-XCT methodology was well applied in this research study.

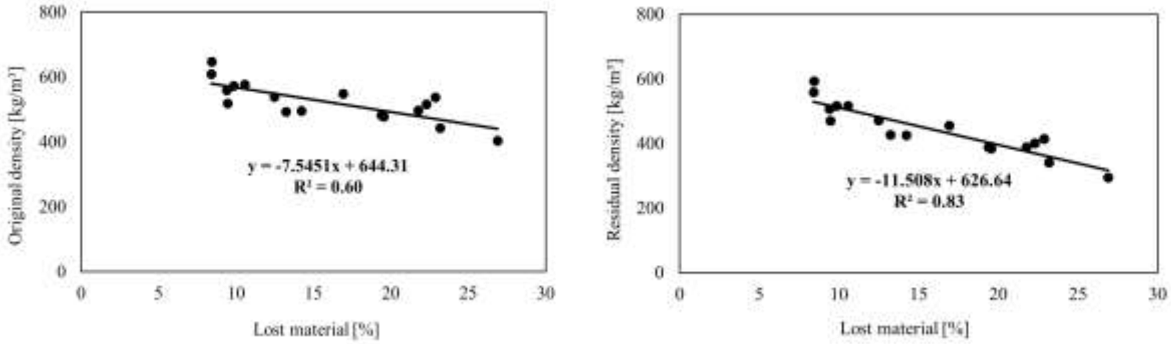

Figure 3: Correlations between original density and lost material percentage (left) and residual density and lost material percentage (right).

3.2 Screw withdrawal perpendicular to grain

The average results obtained for screw withdrawal perpendicular to the grain are lower than those observed in previous studies [6,8]. However, the level of deterioration caused on timber by the beetles seem visually to be much higher. The values of C.V are relatively large which can be explained by the differences found in the level of degradation along the beam. The results are presented in Table 2, where CV is the coefficient of variation.

Table 2: Screw withdrawal test results.

Parameter		Values				
		Average (μ)	Minimum	Maximum	Standard deviation (σ)	C.V (%)
$F_{máx}$	[kN]	0.46	0.28	0.69	0.19	41.7
f	[N/mm²]	6.62	3.99	9.86	2.76	

The Fig. 4 shows the obtained correlations between densities (original and residual) and the screw withdrawal forces. It should be noted that the four places along the beam where the screw withdrawal tests were performed, were not submitted to μ-XCT or shear tests, as previously stated. So, the real density values for that particular test places are still unknown. This, however, is not a substantial problem, since the values used in the correlations of Fig. 4 are those that have been estimated for the samples near the screw withdrawal test site.

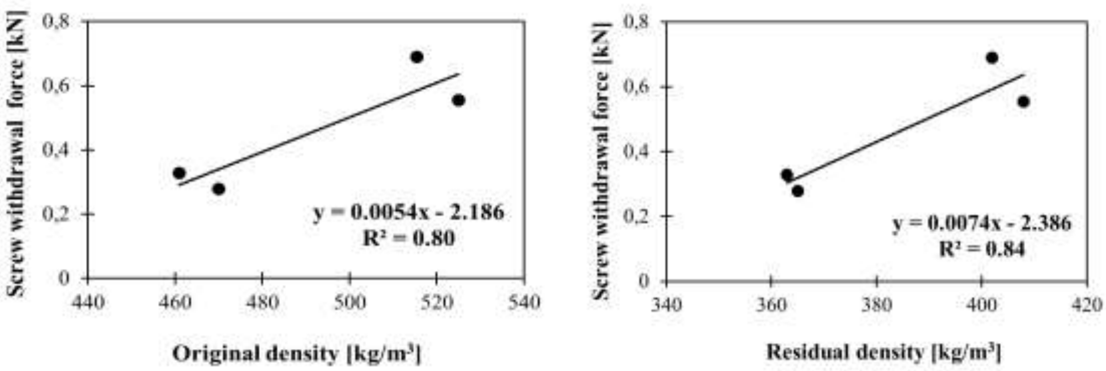

Figure 4: Correlations between screw withdrawal force and original density (left) and screw withdrawal force and residual density (left) [4].

The results show a high correlation ($r^2 = 0.80$) for original density and an even higher correlation ($r^2 = 0.84$) for residual density (Fig. 4). As is to be expected, higher values of density lead to greater values of screw withdrawal forces.

3.3 Shear parallel to grain

The following Table 3 presents the results obtained for shear parallel to the grain tests. Fig. 5 presents the obtained correlations between densities (original and residual) and the shear strength. This figure indicates a medium correlation ($r^2 = 0.75$) for original density and a high correlation ($r^2 = 0.82$) for residual density. These coefficients of determination suggest that the shear parallel to the grain test applied on timber degraded by anobiids can be likely to be quite explanatory of the behaviour of the material at breaking. This is because the tunnels formed by beetles are preferentially formed in the early wood and tend to progress tangent to adjacent late wood [6]. It is in this direction and in zones with greater concentration of tunnels that the material has a greater tendency to break (Fig. 6). The samples crushed easily realising a large amount of bore dust, which indicates the high level of degradation of timber.

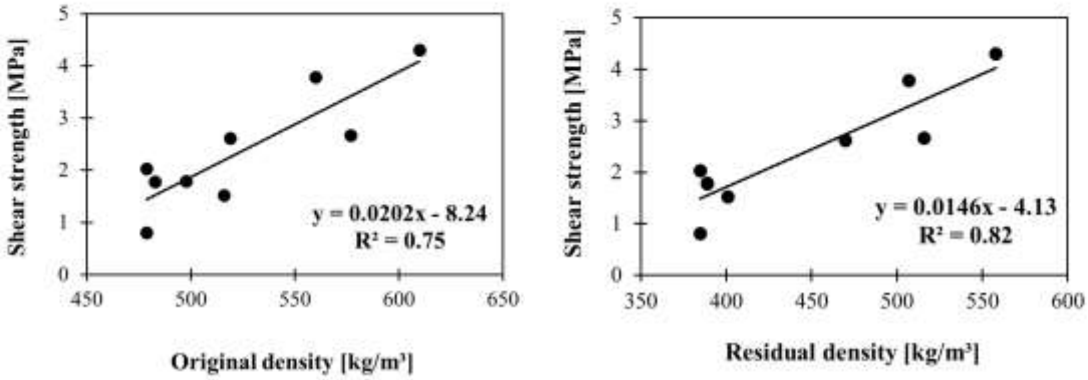

Figure 5: Correlations between shear strength and original density (left) and shear strength and residual density (right) [4].

Figure 6: Rupture of the sample by shear parallel to grain test [4].

3.4 Description of the semi-destructive assessment method proposed

The proposed procedure applies the concept introduced by [8], however with some changes. The method is based on the maximum force required to withdraw a screw which is inserted on the timber' surface in a direction perpendicular to the grain. No distinction was made between the radial and the tangential directions since the results are not expected to differ significantly [8].

In this article, two relationships estimated for deteriorated timber elements are shown. These correlations can be used to estimate density loss of degraded maritime pine elements (Fig. 4) and its associated shear strength parallel to the grain (Fig. 5) via the maximum screw withdrawal force, determined *in situ*.

The procedure, based on laboratory tests, can be briefly summarized in the following steps:

- A preliminary visual inspection of each timber member for identification of the most degraded zones and to identify the presence of defects (knots, fissures, slope of the grain) must be conducted. The *in situ* visual inspections is recognized by several authors as the first step for the assessment of a timber structure [5, 12]. Italian standard UNI 11119 [13] refers to the principles that must be applied during the inspection procedure as well as the necessary conditions for such diagnosis inspection. The screw withdrawal test should not be performed in places where the presence of defects was detected. The results will be affected by the presence of such defects (i.e. when the screw is in or around knots, the provided results will be higher) [14].
- Identification of the screw withdrawal test positions. Screw withdrawal test provide a local parameter, so tests must be applied to multiple locations, and the average result should be used to estimate member properties [15]. However, if the structure has historic interest, this approach can be difficult to perform because the damage to the structure must be kept to a minimum. This fact reinforces the importance of the visual inspection (point 1).
- During the performance of the screw withdrawal test, the type of screw, the outer diameter of that screw, the penetration length, the penetration direction and the predrilling must be checked. The results of the present research are only applied if the setup conditions described in section 2.4.1 are followed. Any change in the application of the technique will lead to the production of anomalous results. Using the correlations of Fig. 4 to estimate density loss (due to the degradation caused by anobiids) as a function of the screw withdrawal force.
- Once the loss of density is obtained can be correlated with shear strength parallel to the grain using correlations of Fig. 5. At the end it can be concluded on the residual resistance and thus contribute to a better quantitative assessment of the structural elements.

4 CONCLUSIONS

A method for evaluating the impact of anobiid damage on timber structures is presented. It is based in four major steps: visual inspection of each deteriorated timber member; semi-destructive prediction of the density loss based on a screw withdrawal test performed *in situ*; using correlations of Fig. 4 to estimate the loss of density; using correlations of Fig. 5 to predict shear strength parallel to the grain and thus to conclude on the residual resistance.

Although good results were obtained for degraded timber elements, the method was developed in laboratory though it is important that the technique can be used *in situ*. For this purpose, the experimental work now needs to be extended using portable devices available to measure screw withdrawal resistance and performing a larger number of measurements. When *in situ*, the screws should be pulled slowly and steadily, according to the methods used on laboratory. This extension is also important to the validation of the proposed method, as well as to estimate and verify valid correlations for other species.

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