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Method for evaluation of coarse cork oak root system by means of digital imaging

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Abstract Digital imaging is becoming a powerful tool for data storage and information retrieval. Image comparison and similarity evaluation has become part of the information market and it is today a common part of, for example, web search engines. The cork oak tree (*Quercus suber* L.), the dominant species of the 'montado' woodland system is, due to its cultural and socio-economic value, protected by law that prevents extensive destructive studies on an essential part of the tree—the root. Especially in the Mediterranean zone, where the water is the limiting growth factor, the root development studies are of significant interest. In this work we present a method of using digital images for cork oak coarse root systems-evaluation by means of digital imaging. Acquired images of structural roots are processed automatically to prevent subjective decisions by the human observer. The performance of the method, its potential for semantic retrieval and similarity assessment is demonstrated, having as example eight young cork oak root systems, and critical issues for evaluation and conclusion-making, are discussed.

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Introduction

Cork oak (*Quercus suber* L.) is an important species in the agro-silvo-pastoral systems of southern Portugal, and its product, cork, represents significant income for the farmers. In the Mediterranean ecosystem where there is sometimes no precipitation for 6 months, the water is the limiting growth factor and roots represent the most important organ for its acquisition. Apart from this function, roots are vitally important for nutrient acquisition and tree stability, and they play an important role in sink and storage functions, and deposition and excretion of biochemical compounds (Pagès, 2002 in Danjon and Reubens 2008).

The root systems of cork oak are, however, rarely studied. This is mostly due to the fact that the cork oak is protected by law and only in occasional situations can it be felled and its root system excavated. It is nearly impossible that sufficiently large statistical samples would be excavated in diverse site conditions. On the other hand, construction works, (road cuts, road construction, accidental landslides, etc.) can represent unique opportunities for assessment of root profiles (as demonstrated in Moreno et al. 2005 or Nadezhdina et al. 2008), which can later represent excellent opportunities for similarity studies, if precise geometric images could be acquired. To the best knowledge of the authors, no articles about coarse root structure of cork oak, apart from preliminary results from this research published in Surovy et al. (2007) were found, although some information can be found in Nadezhdina et al. (2008). A research study was conducted on the root structure of a species similar to cork oak—the holm oak (Quercus ilex L.) in Moreno et al. (2005) (including coarse roots), and López et al. (2001) (focused on fine roots). The works done in cork oak were mostly oriented to cork oak adaptability to soil (Ferreira and Gonçalves 2001). Correia 1998; Goes, 1991 and Martins 1989 (in Ferreira and Gonçalves 2001) suggested that cork oak growth is restrained in soils with lack of drainage or excessively humidity. The same group of authors found growth restraints in soils with excess clay and calcium.

Image similarity has, in the last years, become a challenging issue and new retrieval systems in public domains appeared in the market (Google Image Search, Yahoo! Image Search). The demand for image similarity and retrieval is also well documented in science (Csillaghy et al. 2000; Schröder et al. 2000; Wang 2003; Zhang and Chang 2004). The presence of reliable tags with pictures is necessary for text-based image retrieval; however, visual features can also be used for image similarity assessment (Datta et al. 2008).

In this work we aim to present a modification of the methodology of van Noordwijk et al. (2005), using digital imaging as a tool to compare different vertically-exposed root structures. We demonstrate the capabilities of this method on the structural roots of young cork oaks (age 7 and 8 years), which were grown either from seeds or in plantations.

Materials and methods

Profile wall technique

The methodology of root observation through profile walls in trenches excavated close to the plant, described in van Noordwijk et al. (2000), describes a method to assess root distribution in the soil. We introduce some changes due to precise image acquisition and image-processing facilitation.

Choosing observation plane

The planes may be horizontal or vertical (van Noordwijk et al. 2000). However, if structural roots are to be studied it is important to install the plane close to the stem where one is supposed to find the taproot. In the case of road cuts or excavations, the vertical plane position and orientation should be measured towards the tree stem.

Preparing access

In the case of cork oak, the trench should be at least 1 metre deep to expose most of the taproot and the width might depend on the excavation status. When working with trees higher than 1.5 m, the aerial part should be fixed, to be firm during windy periods.

Smoothing the profile wall

Smoothing can be performed with the use of a knife a shovel. If the tool disperses small pieces of soil, these can be washed away with a gentle water current.

Painting and washing

The woody roots of cork oak do not have a very clear contrast with the soil because of their dark brown colouring, which is very similar to the dark horizons of the soil profile. Water-resistant tint can be used to spray over the smoothed wall in areas where roots are visible, or over the entire plane. After drying of the tint, washing is used to remove the painted soil. If the water current is gentle enough, the tint remains on the roots and only the soil is washed away. If necessary, this step can be repeated to ensure that all the roots are coloured.

Taking the picture

This step represents the most difficult part of the method. While the positioning of a plastic layer over the profile wall is relatively easy, the correct positioning of the camera in such a way that it does not create any geometrical error requires some skills. The camera must be positioned on a tripod. There are three possible distortion movements of the camera: 1—rotation of the objective down and up, in computer science usually referred to as ‘pitch’; 2—rotation of the objective to the left and to the right, in computer science referred to as ‘yaw’ and 3—rotation of the objective in clockwise or counter-clockwise direction, in computer science referred to as ‘roll’. All of these rotations must be avoided, because any one of them can cause distortion of the image geometry, which would require additional image-processing steps (such procedure is beyond the scope of this article).

Pitch and roll The camera must be horizontally levelled. The horizontal bubble level, with two directions levelling, can be mounted on top of the camera. It is important to verify whether the mounting of level is correct by taking a picture of the horizontal and the vertical scale with a levelled camera. If the level is mounted correctly, the pixel number in one unit (e.g. centimetre) would be the same among the images. If the mounting is incorrect, the number of pixels per one distance unit will be different on the left and right parts of the image (top and bottom respectively).

Yaw The plane of CCD sensor in the camera should be parallel to the plane of trench wall being photographed. This means that the axis of the objective should point perpendicularly to the wall. There are two possibilities to assure this. First, is to position the camera at the point where distances to both edges of the wall are equal, and direct the objective to half of the trench wall. The second possibility is to measure the azimuth of the wall and then orientate the objective axis perpendicularly. (For example, if the profile wall has orientation North–South, the objective should be in direction East–West.) The campus can be mounted on the camera together with the horizontal level.

Distance between the wall and camera—spatial resolution of pixel

The distance between the wall and the camera is a key factor when determining the minimum detail which can be obtained from the photography, and also for determining the trench size. The spatial resolution of individual pixels is defined by: 1—distance of the camera from the profile wall; 2—focal depth of the objective and 3—the resolution (in pixels) of the CCD sensor of the camera. Following the Shannon sampling theorem, anything bigger than twice the size of the sampling unit can be reconstructed from the sample (Surovy 2006), e.g. in our case, any root with diameter bigger than twice the spatial resolution of pixel can be measured. Some authors however, suggest that three pixels instead of two are recommended for fine roots' images (Genis et al. 2006). SIGMA SD14 with CCD resolution (2640 × 1760 pixels) and objective 17–70 mm f/2.8–4.5 DC Macro/HSM with focal length 17 mm (Angle of View = 72.4°) are displayed in Table 1. (Before taking images for analysis, the scale should be photographed to verify the actual values.)

From Table 1 it can be seen that the distance of 2 m from the profile wall is not sufficient to quantify the measure of the coarse roots with 2 mm diameter. In the case of larger profile walls, more images can be taken in sequence and joined.

Image-processing

The images can be segmented (divided) into root area and background by thresholding (Gonzalez and Woods 1992). This segmentation type requires grey level images as input. The colour images can be transformed into grey level scale by splitting into R, G and B-channel, and choosing one of the channels as grey level, or by transforming of the image into another colour system. The use of colour transformation, instead of splitting RGB into individual channels, is proposed. In the case of splitting the RGB, the blue channel for example, has maximal value in case of blue colour, but also in case of white. (White objects can appear in the image because of stones.) Transformation to Lab colour space, and then use of the B-channel for segmentation, is recommended. This was decided

Table 1 Minimal detectable root diameter (and spatial resolution of pixel) in relation to distance from profile wall for SIGMA SD14 CCD sensor and 17 mm focal depth objective

Distance from profile (m)	Width of profile wall covered (cm)	Spatial resolution of pixel (mm)	Min detectable root diameter by Shannon (mm)	Min detectable root diameter by Genis et al. (mm)
0.5	73.19	0.28	0.56	0.84
1	146.38	0.55	1.10	1.65
2	292.76	1.11	2.22	3.33

mostly due to the fact that the blue ink used had caused the best bimodality in the histogram of the aforementioned B-channel, and in such a way as to support the thresholding. It is possible to automatically define the threshold in B-channel using the histogram; however it is advisable to use human-supervised thresholding. After this step, the image is transformed into a binary image where segments of the root are black and the background is white.

Dendrometics, tree size and competition estimators

Tree dendrometric data are collected in a monitoring system based on permanent plots established in 1995 (Ribeiro et al. 2003). The monitoring system is spatially explicit and it is centred on the trees, where a set of simple and transformed variables are collected, in order to characterise precisely the tree dimensions and management (Fig. 1).

This simple set of variables is used to process the transformed set of tree parameters such as:

HD2 Hegyi spatial competition index (Ribeiro et al. 2006):

$H = \sum_{j=1}^{n} \frac{d_j}{d_i} * \frac{1}{\mathrm{dist}_{ij}}$, where i: target tree, j: competitor, d: diameter at 1.3 m, dist_{ij}: target tree, i: competitor, j: distance, n.

Competitor number according to rule D2:

$\mathrm{dist}_{ij} \langle 0.33 * d_j.$

For crown surface (cs, m^2) and volume (cv, m^2) calculations using the following models were used (Ribeiro et al. 2006):

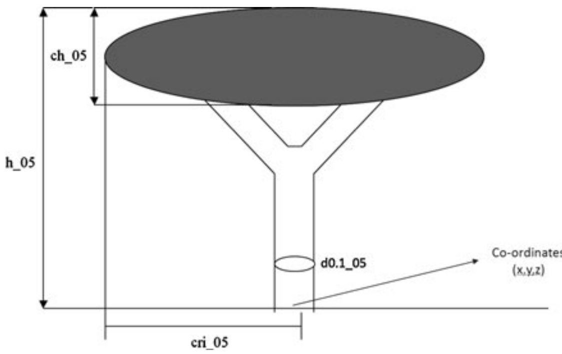

Fig. 1 Set of simple dendrometric variables collected at tree level: *h_05* total height, *ch_05* crown depth, *d0.1_05* diameter in 10 cm height, *cri_05* ith cross crown projection radius

$$cs = 2\pi \int_0^b f(x)\sqrt{1 + [f'(x)]^2}dx;$$

$$cv = \pi \int_0^b [f(x)]^2 dx$$

where $f(x) = r_i\left[1 - \left(\frac{cw_{up,down} - y}{c_{wup,down}}\right)^{E_{up,down}}\right]^{\frac{1}{E_{up,down}}}$, $cw_{up,down}$—Crown depth of upper and down part, $E_{up,down}$—Ellipsoid parameters (Ribeiro et al. 2006): $\left(\frac{x}{ri}\right)^{2.2791} + \left(\frac{y}{cw_{up}}\right)^{2.2791} = 1$, upper E parameter; $\left(\frac{x}{ri}\right)^{1.8284} + \left(\frac{y}{cw_{down}}\right)^{1.8284} = 1$, down E parameter.

Results and discussion

In this chapter we want to demonstrate the capabilities of this methodology to retrieve the data and, at the same time, discuss the interpretation of the results which, in some cases, may be crucial for retrieval of the semantics of the images and, finally, for image similarity assessment. The profiles from eight different young trees are shown in Fig. 2. There are two groups of trees: trees grown from seeds (marked with stars) and trees grown from seedlings.

The image similarity concept can be understood as a method that helps organise images by their visual contents. The technology is often described in literature as content-based image retrieval (CBIR) Datta et al. (2008). Following Datta et al. (2008) the image similarity assessment can be divided into two steps—1: mathematical description of the images and 2: assessment of similarity based on their mathematical description. Mathematical description can be understood as an extraction of the semantics from the images or, in other words, a construction of the image signature. In recent years a remarkable increase in diversity of image signatures has been noticed (Datta et al. 2008). Among others, derivation of new features like shape, and construction of signature based on these features, are becoming more pronounced.

Root area

Root area in the profile wall represents root surface measured by summing the pixels defined as root

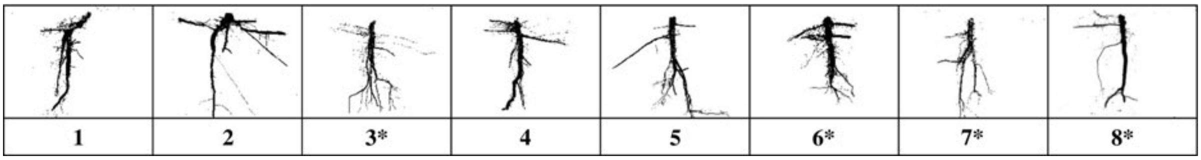

Fig. 2 Images of structural roots of eight young cork oak trees (adapted from Surovy et al. 2007)

pixels in the image. Simple comparison of areas can indicate the similarity among groups, or indicate concordance with some grouping variables (size of trunk, etc.). We performed tests for significance of difference between root areas in the groups planted with seeded trees. The difference was found significant, with $P = 0.023$ proving that the area of planted trees is larger than the one from trees originating from seeds.

Another comparison can be done using the distribution of root area at individual depths. The results are presented in Fig. 3. We checked these two patterns for differences in individual depths, but no significant differences were found.

The shape of distribution appears to indicate that the first depth class (0–10 cm) is smaller than the second one (10–20 cm), e.g. in both classes the structural root is less established in the first 10 cm of soil than in depth 10–20 cm. Another possible way to search for image similarity is to search for similarity between variables from images, and variables from tree measurements.

Figure 4 shows regression between the following values (h05—total height of tree, d0.1_05—diameter in 10 cm height, HD2—index of competition (Ribeiro et al. 2006), rarea-area of roots measured from

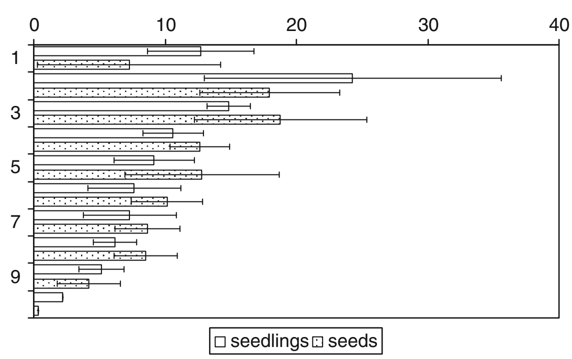

Fig. 3 Non-cumulative percentage of root area at individual depths

digital image, total crown height (TRCh), crown surface (cs), crown volume (cv)). It is possible to observe correlation, epecially between root area and diameter of trunk, indicating an allometric relationship between above-ground dimensions and root system dimensions.

Root length, root tips amount, root forks amount

These variables are obtained from digital images, and by contrast with root area (surface), which is influenced only by the position of the profile wall itself. Root length, amount of tips and forks may be influenced by image analysis and processing techniques. Therefore, it is important to use the same processing technique for the comparisons. Root length is estimated as the length of roots in the profile wall without considering the thickness (or surface) of individual roots. The variables can be calculated by using software for root analysis like WinRHIZO, or free software ImageJ. The similarity of images can be assessed by comparing the results in individual groups, or cluster analysis. In data from Surovy et al. (2006) we would find slightly higher root length in images from seeded trees, contrary to their smaller area. This would suggest that it is possible to find similarity within groups; however, indicating that trees with larger area have shorter length, or in other words, the difference in area, is mostly caused by the diameter of roots.

Root shape

A method using adapted Gaussian kernel for smoothing (filtering) the image is used in some image analysis techniques for similarity evaluation (Greenspan et al. 2001). According to this method, a density of signal inside the image is recalculated and only one principal blob remains in the image. The peak of this node and its shape can be used as a standard for

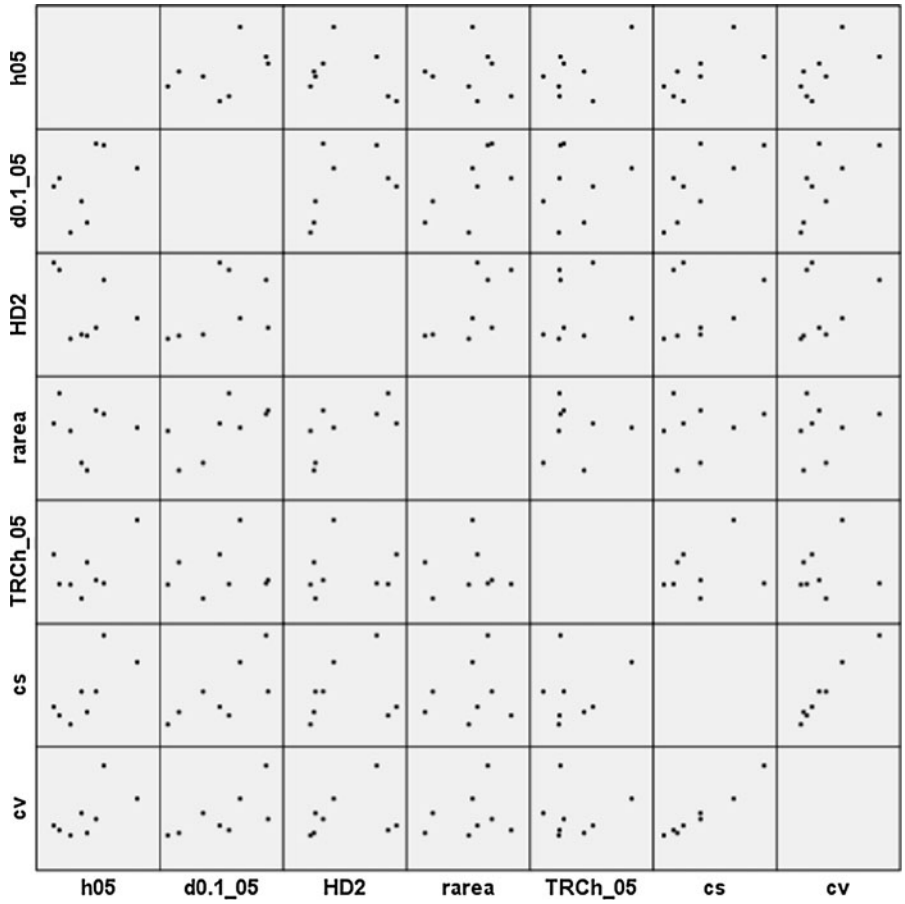

Fig. 4 Correlation of root area (rarea) with dendrometical tree variables : *h05* total height, *d0.1_05* diameter in 10 cm height, *HD2* index of competition, *TRCh* total crown height, *cs* crown surface, *cv* crown volume

evaluation of the shape. A similar approach has already been used for root study. Coelho and Or (1999) proposed semi-lognormal bivariate-Gaussian distribution to be used for evaluation of patterns in two-dimensional root profiles. This method was proposed for profiles dug from the plant centre out, e.g. the plant is placed on one of the sides of the trench (left or right). It is obvious that lognormal distribution should be used because of the asymmetrical shape of root area in this case. In our case, asymmetry is not to be expected, as we evaluate the whole profile and the plant is at its centre. Therefore we use normal bivariate-Gaussian distribution for the creation of the pattern.

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}.$$

For Gaussian kernel, the value of sigma and kernel size used has to be known. (Sometimes only one of these factors is mentioned and the other is calculated correspondingly.) We defined desired kernel size as equivalent to the height of the trench wall and sigma was calculated respectively.

The shape of the node could be visually interpreted (Fig. 5), but there are also procedures for doing this task more objectively. One of the possibilities is to calculate the circularity of the node. Circularity is defined as compactness of the shape and it can be calculated following the formula:

$$M = 4\pi(\text{area}) / (\text{perimeter})^2$$

The similarity can be evaluated either by calculation of the average inside groups or, in smaller samples, by ordering the samples by value of circularity and observing the queue for grouping of some variables. As shown in Table 2, most trees from seeds (marked with stars) are in the right part of the table, so they have more circular shape than the planted trees. This can also be confirmed when using

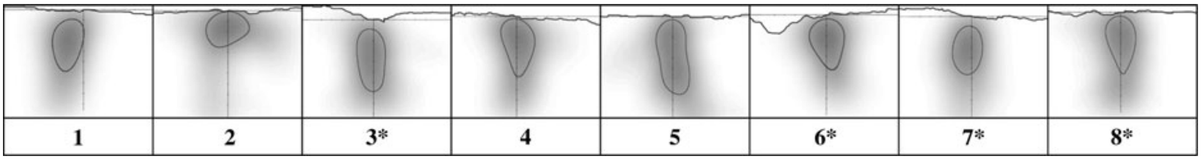

Fig. 5 Root shape blob created by Gaussian transformation; trees from seeds are marked with stars (adapted from Surovy et al. 2007)

Table 2 Circularity values for individual trees ordered by circularity value from left; trees from seeds are marked with stars

Sample	8*	4	5	1	2	3*	6*	7*
Circularity	0.652	0.707	0.727	0.732	0.735	0.765	0.798	0.811

averages in the group. Similarities between other factors can be found this way.

Another way of estimation of image similarity is to measure similarity between Gaussian nodes (Greenspan et al. 2001; Goldberger et al. 2003; Surovy 2006). Greenspan et al. (2001) suggest the use of Kullback–Leibler distance (or relative entropy) to measure the distance between two distributions (image descriptors). Here we present a simpler method using statistical distance for two probability measures:

$$\delta(P,Q) = \frac{1}{n}\sum_{1}^{n} |P(x) - Q(x)|.$$

The results are presented in Table 3.

In Table 3 first minima were marked in each row; next in each column, and if more than one minimum exists in the column, the smallest was chosen. These minima represent the 'best' matching for the trees in rows. In other words, tree number 1 has the best match with tree number 4. The interpretation of these results however, is not unimportant and should be done with caution. For example, trees 6 and 5 results are similar, though the coefficient is ?, so this matching can be interpreted as that tree 6 is the most similar to tree 5, but this similarity is globally not very high. The overall similarity of certain trees can be calculated as average-similarity coefficient for this tree with other trees (row labelled: total). It can be noted that trees 2 and 6 have the highest coefficient average (so a lower similarity) and can be considered the most distinct trees from this group.

Figure 6 shows the spatial distribution of sampled trees from Surovy et al. 2007 over water-accumulation model.

The water-accumulation model was constructed by ArcGIS software by function Flow Accumulation, which calculates the amount of water available in each cell of the surface grid. This grid was constructed using the existing 3D terrain model for the

Table 3 Similarity calculation between individual images from profile walls

	1	2	3	4	5	6	7	8
1		7.307	5.765	*3.517*	6.976	9.653	5.22	6.353
2	7.307		8.649	7.051	9.574	8.402	8.067	7.666
3	5.765	8.649		3.31	2.946	7.711	*2.199*	3.537
4	3.517	7.051	3.31		5.118	8.221	4.014	5.104
5	6.976	9.574	2.946	5.118		*7.08*	3.468	4.213
6	9.653	8.402	7.711	8.221	7.08		8.085	7.921
7	5.22	8.067	*2.199*	4.014	3.468	8.085		2.497
8	6.353	7.666	3.537	5.104	4.213	7.921	2.497	
Total	6.399	8.102	4.874	5.191	5.625	8.153	4.793	5.327

The italicized values represent the best similarity matches between the trees

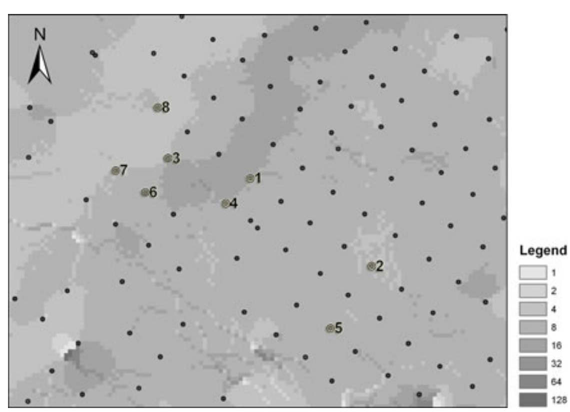

Fig. 6 Spatial distribution of sampled trees over water-accumulation model

study plot. It shows area of water-accumulation with darker colours. The grid validity was confirmed by observations during various field walks in winter, when water-accumulation is visible due to heavy rain and bad drainage of the soil.

The intention here is to verify similarity among trees growing in similar water conditions which would lead to conclusions similar to those of Correia 1998; Goes 1991 and Martins 1989 in Ferreira and Gonçalves (2001). Some indications, for example similarities between trees 1 and 4, or 3 and 7, which grow in similar water conditions, can be found, although at this time, it is difficult to conclude anything, and further research and more data would be needed to confirm this hypothesis. This case can serve as an example of how image similarity could be used to evaluate similarity between plants.

Impact of method on plants' survival

Despite the fact that the method of profile walls is considered destructive, we can conclude that in the present year (2010), 8 years after the experiment, no visible signs of declination of trees were found. None of the trees died, and no significant differences between height or diameter increment were noted. It would be difficult to extrapolate this conclusion for other soil types, or other tree species. This survival was also probably due to the fact that the trees were relatively young (at the time of the study, 7 and 8 years old) and so resistant to root damage. However, it should not be forgotten that exactly half of the root system was completely removed, exposed to the air, and the trenches were left uncovered for more than 6 months. The experiment was carried out in the months of July and August, at the peak of the dry season.

Conclusions

We present in this paper, a method for the evaluation of root systems by means of digital imaging. It is based on original methodology of profile walls (van Noordwijk et al. 2000). We propose contrast enhancement of the root by painting with contrasting colour, and we describe the steps necessary to correctly take the pictures without introducing any geometric distortion.

The question of what is possible to measure in terms of spatial resolution was demonstrated in the previous chapter. The minimum detectable root diameter depends mostly on the focal depth of objective, camera CCD resolution and distance from profile wall. Then, the Shannon sampling theorem, which suggests that the minimal detectable object corresponds to twice the sampling size, can be used. Some authors (Genis et al. 2006) recommend using at least three pixels per minimum diameter.

The image acquisition using this method has, as its principal objective, the calculation of the similarity between roots from various origins (different treatments, soil conditions, climate, etc.). Image similarity is not an easy task, but results obtained to date are encouraging (Greenspan et al. 2001; Goldberger et al. 2003). New trends in computer science show that image similarity and retrieval is an important issue which is going to progress, especially with regard to the development of new, cheap sensing machines, or the development of professional high-level equipment.

The performance of the described method is evaluated on the root systems of eight young cork oak trees. The root systems of this species have seldom been studied, and it is thus difficult to compare our results with other works. Due to the sample amount, no significant conclusions can be drawn, though it is possible to demonstrate the possibilities of similarity evaluation and critical issues when comparing the images.

The main advantage of digital imaging is that it is easier, compared with painting of the roots over plastic sheets; it is quicker and allows observation or evaluation of any spatial component (which could have been omitted during painting on plastic) afterwards, on a computer. The aforementioned problem arose when merging data from different measurements for global conclusions in Schenk and Jackson (2002), and some numerical data were missing information concerning the presence of rocks or gravel. Regarding the problems with destructive sampling of the cork oak species, and documented appearances of profile walls, due to construction or accidental flooding (Moreno et al. 2005; Nadezhdina et al. 2008) we believe that this methodology can bring new knowledge to root systems studies.

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