Assessment of the Three-dimensional Architecture of Walnut Trees Using Digitising

Hervé Sinoquet, Pierre Rivet and Christophe Godin

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A method for the measurement of the three-dimensional (3D) architecture of trees was applied to describe two 20-year-old walnut trees, one of them is a timber tree while the other is a fruit tree. The method works at the shoot level and simultaneously describes the plant topology, the plant geometry and the shoot morphology. The method uses a 3D digitiser (3SPACE® FASTRAK®, Polhemus Inc.) associated with software DiplAmi designed for digitiser control and data acquisition management. Plant images may be reconstructed from the data set by using the ray tracing software POV-Ray.

Visual comparison between photographs of the walnut trees and images synthesised from digitising was satisfactory. Distribution of basal shoot diameter, as well as leaf area and fruit distributions for both the timber and the fruit tree were non-uniformly distributed in the crown volume. Gradients were likely to be related to the light distribution within the tree. This is in agreement with previous experimental results on several tree species, and also with the predictions of tree architecture models based on light-vegetation interactions.

Keywords tree architecture, topology, geometry, shoot level, digitising, *Juglans regia* L.
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1 Introduction

In both fruit and timber production, the control of the tree architecture is a main determinant of tree growth management. For some years, tree growth models attempt to link tree architecture and physiology in an ecophysiological framework. In these models, tree architecture includes two independent notions: topology, i.e. branching and connection between the plant units (Hallé et al. 1978), and geometry, i.e. the spatial location, orientation, size and shape of the vegetation elements (Ross 1981). Tree geometry generates variability of the environmental factors within the crown (e.g. light, wind speed), while tree topology determines internal relationships between plant units (e.g. hydraulic architecture, assimilate transport and partitioning). Reciprocally tree architecture may be computed as the result of botanical information and complex interactions between the tree structure and its environment (e.g., space competition, Blaise and de Reffye 1994; light competition, Takenaka 1994, Kellomäki and Strandman 1995, Gavrikov and Sekretenko 1996, Mech and Prusinkiewicz 1996). Because dynamics of tree architecture are related to bud fate (i.e. spatial pattern of bud breaking within the crown and morphology of annual shoots), simulation models of tree architecture dynamics deal with growth units which define a shoot level.

Testing simulation models of tree morphology needs measurement methods for the three-dimensional (3D) architecture of the tree. Some methods combining both plant topology and geometry exist (Honda 1971, De Reffye et al. 1988, Prusinkiewicz and Lindenmayer 1990): in that case, topology coding is combined with measurements of branching angle and internode lengths, which allows one to derive the 3D positions of the tips of the branches. More sophisticated methods dealing with the only 3D plant geometry have been proposed, especially 3D digitising (Lang 1973, Sinoquet et al. 1991, Moulia and Sinoquet 1993, Smith and Curtis 1995, Room et al. 1996, Sinoquet and Rivet 1997, Thanisawanyangkura et al. 1997). Three-dimensional digitising allows one to measure the spatial location of every plant entity.

This paper reports measurements of the 3D architecture of two 20-year-old walnut trees, one of them is a fruit tree while the other one is a timber tree. Measurement is made with an electromagnetic digitiser associated with a software designed for the simultaneous acquisition of topology, geometry (3D co-ordinates) and morphology parameters at the shoot level. The data are analysed in order to assess the distribution of basal shoot diameter, leaf area and fruit density within the tree crown.

2 Materials and Methods

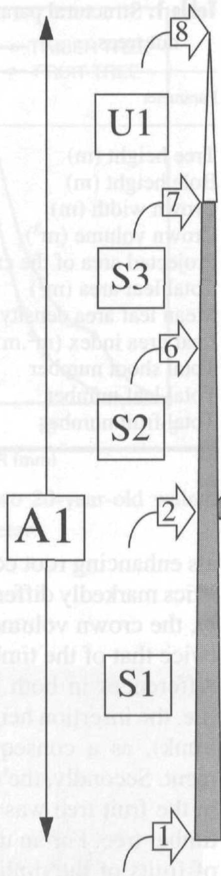
2.1 Measurement of the 3D Architecture of Trees

2.1.1 Description of the Plant Topology

Plant topology is described as proposed by Godin et al. (1997a, b). The plant is described in terms of axis (A), segments (S) and growth units (U). The axis of order 1 is the trunk, axes of order 2 are the branches connected to the trunk, and so on. The trunk and branches set during the previous years are represented as a set of woody elements called segments. Annual shoots are described as one growth unit or several ones in case of polycyclism or sylleptic growth. An axis is then a combination of segments and growth units. This description with these 3 entities disregards the tree history: the age distinction is only made between plant parts developed during the current year and during the former years, i.e. in terms of growth units and segments, respectively. Topological relationships between the tree entities are described by 3 operators (Godin et al. 1997a, b). Operator / accounts for inclusion: an axis A includes a set of segments and growth units. Operator < describes succession: S1 < S2 means that segment S2 is connected to S1 and comes from the same bud as S1. Operator + accounts for branching: S1 + A1 means that axis A1 is connected to S1 and comes from an axillary bud bore by segment S1. Further information about topology coding is given by Godin et al. (1997a) in this issue.

2.1.2 3D-Digitiser for Spatial Co-ordinates Acquisition

The 3D-digitiser (Polhemus® 3Space® Fastrak®, Colchester, V.T., U.S.A.) consists of an electronic unit, a receiver, a single transmitter, and a power supply. The transmitter generates low frequency magnetic fields which induce currents in coils included in the receiver. Values of induced currents depend on the location and orientation of the receiver in the active volume around the magnetic source (Raab et al. 1977). The Carte-



Point	Topology
1	/A1
2	/S1
3	+A2
4	/S1
5	<U1
6	<S2
7	<S3
8	<U1
Branching order:	1 2

Fig. 1. Illustration of topology coding for a simple tree made of the trunk and one branch. Arrows and boxes represent points to be digitised and tree entities, respectively. The table shows the tree topology coding.

sian co-ordinates, i.e., x, y, and z, and Euler orientation angles, i.e., azimuth, elevation, and roll angles, of the receiver are determined with a resolution of 0.0005 cm/cm of range, and 0.025°, respectively. The operation within an active sphere of 4-m-radius is possible with a modified transmitter, the so-called Long Ranger (Polhemus 1993). The main limitation of the digitiser is that other magnetic sources or large metallic objects have to be removed from the active volume because they modify the magnetic fields.

2.1.3 Data Acquisition

Topology coding and digitising process are driven by software DiplAmi, written by P. Rivet in Visual Basic 3.0 for Windows 3.1 (Microsoft Corp.) on PC computers.

To digitise a tree, the first point to be recorded is the base of the trunk, i.e. the axis of order 1. Any axis (order n) may then be decomposed into as many segments as it seems necessary to render curvature and changes in diameter, but it is necessary to record data at the location where branching occurs. At any branching point, the parent axis (order n) is temporarily left in order to describe the branching axis (order n + 1). When the tip of a branch (order n + 1) is reached, the previous branch (order n) is continued. This way of describing each new branch of greater order before the end of the current branch allows not to forget branches. Figure 1 illustrates the procedure for a simple tree made of a trunk and one branch.

All branches and shoots are digitised and topologically described. In the same time, the diameter of each entity is measured with a Vernier caliper. In addition, the number of leaves and fruits on the growth units are recorded in order to provide a bulk description of shoot morphology.

2.2. Tree Visualisation

Tree images are synthetised with the Persistence of Vision (tm) Ray Tracer software, POV-Ray version 3.0 under Windows, which is distributed as a freeware. Segments of branches and shoots are represented as truncated cones, cylinders and spheres to connect the cones, directly from data measured on the trees. DiplAmi converts the data from digitising to the input file format of POV-Ray. The resulting virtual tree can then be looked at from any point of view, after having placed a camera and a light source in the virtual scene.

2.3. The Measured Trees

The 3D architecture was measured on two 20-year-old walnut trees (*Juglans regia* L.) grown near Clermont-Ferrand (45°North, 2°East), France. The first one is a fruit tree trained as open-vase. It was grown in a hedgerow orientated in a north-east / south-west direction. The second one is a timber tree pruned in order to make a bole. It was grown in an orchard of 1.4 ha planted in quincunx. Row and plant spacing were 10 m. The 3D architecture of the fruit tree and timber tree was measured during summer 1995 and September 1996, respectively. Time needed to collect the data was 4 and 2 weeks for the fruit tree and the timber tree, respectively. For each tree, an allometric relationship was established from a set of shoots in order to estimate leaf area from basal diameter at the shoot level.

3 Results

3.1. At the Tree Level.

Structural parameters at the tree level are given in Table 1 for the two walnut trees. Tree height estimated from the height of the highest shoot was about 7.5 m for both trees. A tree height of 7.9 m for a 20-year-old timber tree is small. This might be because the timber tree was grown i) in a windy area and ii) with an understory of cereals enhancing root competition. Other characteristics markedly differed between both trees. Firstly, the crown volume of the fruit tree was about twice that of the timber tree. This was related to differences in both tree radius and bole height (i.e. the insertion height of the first branch on the trunk), as a consequence of the tree management. Secondly, the number of shoots and leaves in the fruit tree was more than twice that of the timber tree. For an unknown reason, the number of fruits of the timber tree was very low. Total leaf area also showed notable differences, since that of the timber tree was about 60 % of the fruit tree leaf area. However, differences in crown volume led to a lower leaf area density in the fruit tree, favourable to light penetration within the crown volume.

Fig. 2 shows the shoot distribution as a function of basal diameter, i.e. disregarding the spatial information. Mean shoot diameter of the fruit and the timber tree was respectively 5.7 and 7.2 mm, and the difference is highly significant ($P < 0.01$). In the case of the timber tree, 13 % of the total shoot number had a small diameter (i.e. < 5 mm), and 12 % had a large diameter (i.e. > 10 mm). The diameter distribution was very different in the case of the fruit tree since 39 % of the shoot number had a small diameter and only 3.5 % had a large diameter.

Table 1. Structural parameters of two 20-year-old walnut trees.

Parameter	Timber tree	Fruit tree
Tree height (m)	7.9	7.1
Bole height (m)	3.0	0.9
Crown width (m)	5.8	8.2
Crown volume (m^3)	95	210
Projected area of the crown (m^2)	27	53
Total leaf area (m^2)	144	238
Mean leaf area density ($m^2.m^{-3}$)	1.5	1.1
Leaf area index ($m^2.m^{-2}$)	5.4	4.5
Total shoot number	1729	4213
Total leaf number	6837	16224
Total fruit number	98	2007

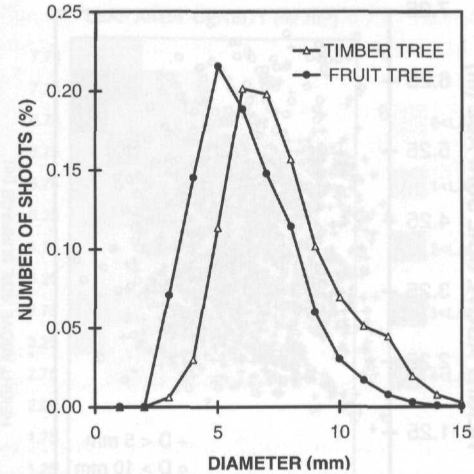


Fig. 2. Shoot distribution of two 20-year-old walnut trees as a function of diameter.

3.2. Spatial Distributions

The quality of the digitising was visually assessed by comparing synthetised views of the virtual trees with photographs of the real trees after leaf fall. Fig. 3 presents views of the timber tree after leaf fall from a south-eastern point of view, with the same sun and camera configurations on both pictures. The visual comparison shows that the digitised tree is very close to the real tree, with branches having very similar locations. This implicitly indicates that the shoot location within the tree is likely to be correctly estimated. Some of the northern branches (on the right on Fig. 3a) are less accurate due to the presence of metallic scaffolding required to complete other previous experiments in the tree during the first two days.

Figs. 4–5 show the spatial distribution of the basal diameter of annual shoots within the crown

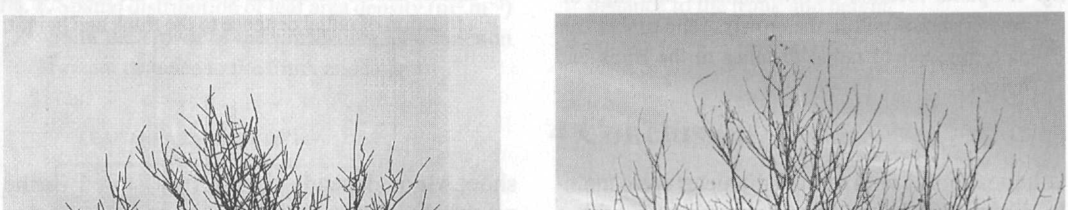


Fig. 3. Comparison between a ray traced image synthesised from digitising (left) and a photograph of the timber tree taken after leaf fall (right). Both pictures are viewed from the south-eastern direction with a 50-mm camera.

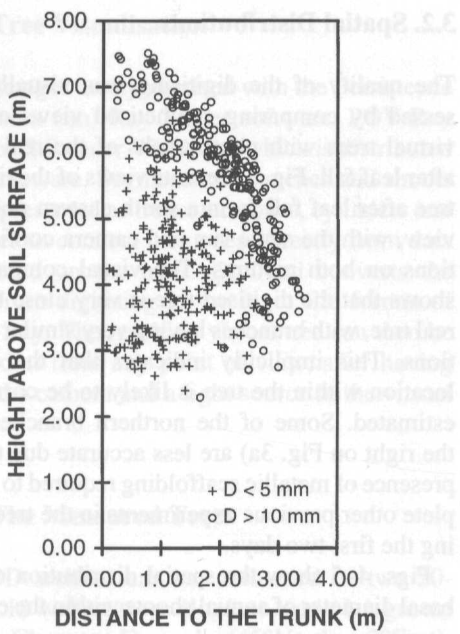


Fig. 4. Spatial location of low-diameter and high-diameter shoots within the crown of the timber tree as a function of radial distance to the trunk and height.

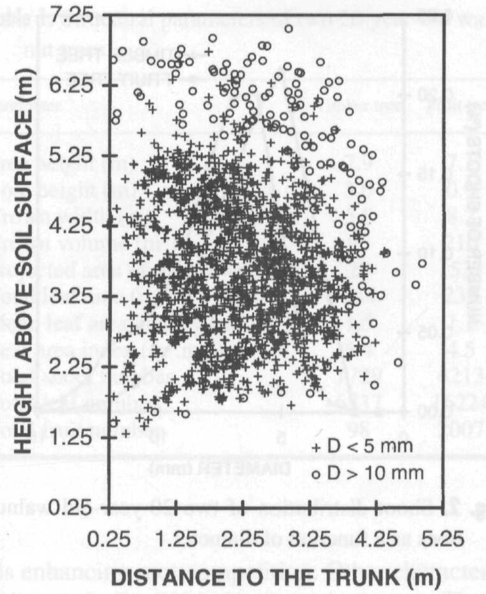


Fig. 5. Spatial location of low-diameter and high-diameter shoots within the crown of the fruit tree as a function of radial distance to the trunk and height.

volume. Shoots with a small diameter were mainly distributed in the inner tree volume with a very small density in the periphery of the crown. On the contrary, shoots with a large diameter were located only in the periphery of the crown. The same behaviour occurred for both the timber tree (Fig. 4) and the fruit tree (Fig. 5). This result agrees with previous reports on the vigour gradient from the outer to the inner part of the tree crown, which is related to light gradient (Hardwick 1986; Sprugel et al. 1991).

Leaf area density as a function of height above the soil surface and radial distance from the trunk showed the same tendencies in both trees (Figs. 6–7). Firstly, leaf area density was larger in the upper part of the tree canopy. Secondly, a gradient of leaf area density existed from the centre to the outer of the crown within the upper hemisphere. These results agree with observed changes in leaf area density within tree crowns, where foliage density generally increases with light availability (e.g. Whitehead et al. 1990; Cohen et al. 1995). The underlying hypothesis is that shoot vigor depends on reserves stored in the parent shoot, thus on parent shoot photosynthesis during the previous year, which is higher in well-lit zones and smaller in shaded areas. Tree architecture models based on this principle (Takenaka 1994; Kellomäki and Strandman 1995) simulate denser foliage density in the periphery of the crown, as the result of enhanced shoot development and self-thinning in sunlit and shaded parts, respectively. Such leaf area distribution also allows the tree to optimise its photosynthetic productivity (Takenaka 1994).

For the fruit tree, fruit density distribution is similar to leaf area distribution (Fig. 8). Therefore, fruit distribution within the canopy volume is also related to light availability, as previously reported (e.g. Klein et al. 1991; Kikuchi et al. 1994). These results show that higher fruit and foliage concentrations are located close to the assimilate sources.

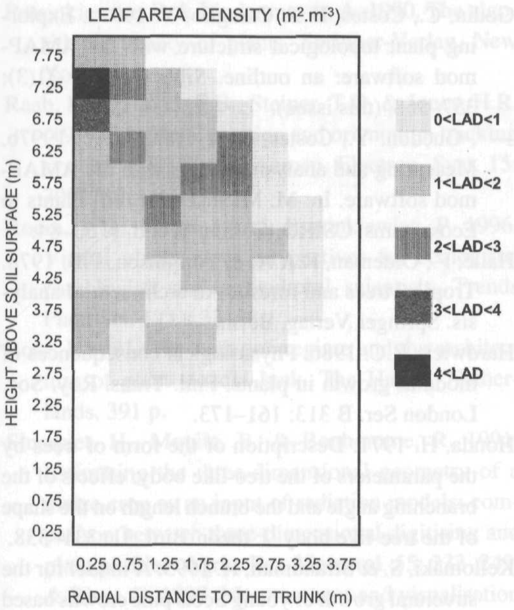


Fig. 6. Spatial distribution of leaf area density ($m^2.m^{-3}$) within the crown of the timber tree as a function of radial distance to the trunk and height.

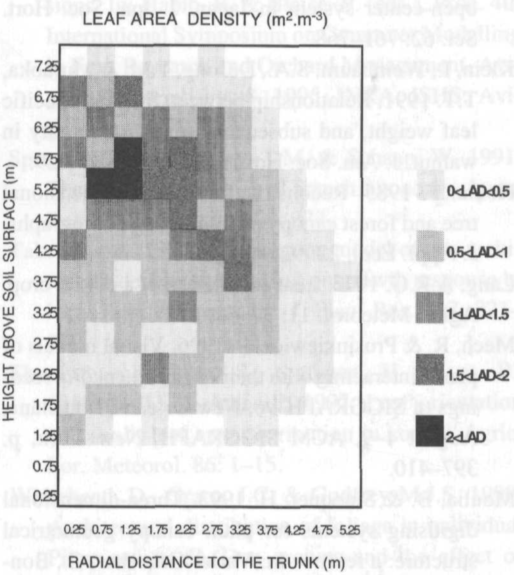


Fig. 7. Spatial distribution of leaf area density ($m^2.m^{-3}$) within the crown of the fruit tree as a function of radial distance to the trunk and height.

photosynthesis and ... within the crown. iii) Data sets which could be obtained on trees measured for several years could be used to test models of tree architecture dynamics. iv) Tree images including ... could be validated from real ... and then used to test ... dealing with light ... The images could also be ... methods of canopy structure ... based on plant photographs ... v) Finally, foliage digitising at the leaf level on small plants or tree branches could help define their light interception properties.

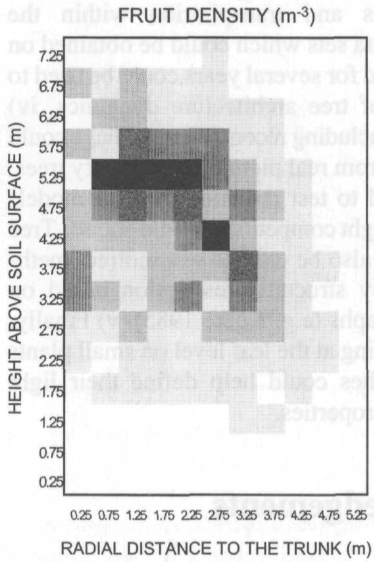


Fig. 8. Spatial distribution of fruit density (m^{-3}) within the crown of the fruit tree as a function of radial distance to the trunk and height.

4 Conclusion

This study shows that shoot diameter, leaf area and fruit are non-uniformly distributed in the crown volume of walnut trees, either grown for fruit or for timber production. Gradients are likely to be related to the light distribution within the tree. This is in agreement with previous experimental results on several tree species, and also with the predictions of tree architecture models based on light-vegetation interactions.

From a methodological point of view, the method used in this study is likely to find a number of applications. i) The data sets could be analysed in order to grasp the variability of shoot properties within the crown. Relationships between shoot morphology and location in both the tree topology and the crown volume could be identified by using adequate software devoted to plant architecture analysis (e.g. AMAPmod, Godin et al. 1997a). ii) The 3D architecture expressed in both shoot and leaf area distributions could be used as an input to 3D models dealing with the distribution of light interception, wind speed, photosynthesis and transpiration within the crown. iii) Data sets which could be obtained on trees measured for several years could be used to test models of tree architecture dynamics. iv) Tree images including reconstructed foliage could be validated from real pictures of the leafy trees, and then used to test radiation transfer models dealing with light competition within shoots. Tree images could also be used to test indirect methods of canopy structure description based on plant photographs (e.g. Koike 1985). v) Finally, foliage digitising at the leaf level on small plants or tree branches could help define their light interception properties.

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