Probabilistic Reconstruction of a Peach Tree Canopy and Simulation of Its Photosynthetic Activity

R. Giuliani and E. Muzzi
Dipartimento di Colture Arboree
Università degli Studi di Bologna
Bologna
Italy

F. Nerozzi
ARPA, Servizio Meteorologico
Regione Emilia-Romagna
Bologna
Italy

H. Sinoquet
UMR PIAF, INRA-Université Blaise Pascal
Clermont-Ferrand
France

T.M. DeJong
Department of Pomology
University of California
Davis
USA

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Abstract

In the present study the probabilistic geometrical reconstruction of an adult peach tree crown (28.41 m^2 surface area; 14,260 leaves) was simulated from a leaf data sample identifying less then 1/20 of canopy leaves (i.e. less than 600 elements). More precisely, the data extraction was performed by applying a Monte Carlo method, whereas the foliage synthesis was accomplished by a non-parametric procedure, based on the *adaptive Kernel* method used in spatial statistics. A bootstrap technique was used to generate (sub-)samples from the collected data making it possible to match the possibility to sample the canopy only once with the requirement of having a sufficient number of reconstruction to perform a statistical analysis. The artificial tree crowns were evaluated from both structural and functional perspectives by comparing artificial geometrical traits and canopy carbon gain against the corresponding values computed on the real tree. In general, a satisfactory agreement of all parameters was shown: the *adaptive Kernel* reconstruction procedure appears therefore a promising tool to be exploited in eco-physiological studies aimed to explain short- and long-term tree canopy responses.

INTRODUCTION

The opportunity to reproduce a canopy architecture by identifying the spatial coordinates of each leaf element makes it possible to identify the canopy geometrical parameters playing a main role in deciding canopy-atmosphere energy and gas exchanges (Norman and Campbell, 1989; Monteith and Unsworth, 1990). More precisely, since the geometrical leaf traits (dimensions, Cartesian coordinates of the blade insertion point, and blade orientation angles) decide the energy components representing the driving forces for CO_2 and H_2O leaf fluxes (Nobel, 1999), their detailed acquisition contributes to explain tree canopy short- and long-term photosynthetic and transpiration responses. In addition, focusing on fruit trees, canopy geometry sensibly affects growth and development processes bounding crop production (Neri and Sansavini, 2004).

Electromagnetic (Sinoquet et al., 1997) and laser (Smith et al., 1992) digitizing are methodologies appropriate for a precise and accurate acquisition of leaf geometrical traits composing a tree canopy making a canopy reproduction possible. Unfortunately, since the massive number of measurements and the difficulty of canopy access are often prohibitive, the application of the digitizing techniques on fruit trees tends to be limited to an eco-physiological modeling context (Sinoquet et al., 2001).

A convenient compromise between the necessity to dispose of detailed and comprehensive geometrical canopy information and the time required to perform the corresponding measurements may be represented by a foliage probabilistic reconstruction

procedure (Giuliani et al., 2005) inferred from a leaf data sample (Poni et al., 1996; Succi et al., 1997) extracted by a Monte Carlo method (Hammersley and Handscomb, 1964). A random data sampling is preferred to systematic data samplings such as *point-quadrat* (Levy and Madden, 1933) and *modified point-quadrat* (Warren Wilson, 1959): these techniques, which have found wide application on herbaceous covers, do not make a leaf by leaf vegetation reconstruction possible and therefore do not seem useful to compute the canopy geometrical parameters necessary to quantify the complex canopy-atmosphere functional interaction.

Given this context, the present study was aimed to: 1) Simulate a Monte Carlo (MC) leaf data sampling on an adult peach tree canopy; 2) Verify the probabilistic *adaptive Kernel* procedure (*aK*) to reconstruct that canopy: *aK* refers to a non-parametric method (Silverman, 1986) widely used in spatial statistics (Cressie, 1991).

Geometrical traits and net photosynthetic responses of the reconstructed canopies output by a simulation-visualization software were corroborated against the corresponding parameters computed on the real tree canopy that was reproduced by electromagnetic digitizing of all leaves.

MATERIALS AND METHODS

Monte Carlo Leaf Data Sampling and Estimate of Foliage Area and Number of Leaves

A MC leaf data sample was extracted from a data set collected at PIAF-INRA in Clermont Ferrand (France) by electromagnetic digitizing all 14,260 leaves of a peach tree canopy having a foliage surface area of 28.41 m^2. The MC sampling was performed after Giuliani et al. (2005), in particular, 200 random points were identified in the minimum ground area including the canopy projection (rectangular having x = 2.92 m and y = 3.08 m) and used to verify the presence of *contacts* (leaves) on the vertical axis (z = 2.38 m). A data sub-set identifying about 600 leaves, that is about 1/20 of leaf elements composing that canopy, was extracted and *bootstrapped* (Efron and Tibshirani, 1993) 30 times to generate 30 leaf data samples. Since in the field it would be possible to sample a tree canopy only once, the opportunity to generate 30 canopy samples by applying a bootstrap technique would make it possible to reconstruct a sufficient number of canopies to perform a statistical analysis of the results.

The surface area of all 30 reconstructed canopies inferred from the 30 bootstrapped samples was computed after Warren Wilson (1959): given the mean leaf area estimated on the leaf data sample, the number (N) of leaf elements composing each reconstructed canopy was then provided.

Canopy Reconstruction by *adaptive Kernel* Method

To reconstruct the peach tree canopy geometry, blade length, maximum width, Cartesian coordinates of its insertion point and orientation angles had to be assigned to each of the N artificial leaves previously computed. A canopy reconstruction by *adaptive Kernel* method required to identify a Probability Distribution Function (PDF, Silverman, 1986) on the extracted leaf data sample.

More precisely, a local density function was assigned to each value of each determinant and the sum of all local functions provided the PFD for that variable associated to all points in the canopy volume. The geometrical parameters associated to each artificial leaf were then randomly extracted from the corresponding PDFs.

Statistical Variability Associated to the Reconstructed Canopies

The computations of geometrical traits such as Silhouette (Sunlit surface area projected orthogonal to sunbeam direction, m^2) and STAR (Silhouette To canopy Area Ratio, Oker-Blom and Smolander, 1988) under Standard Overcast Conditions (Moon and Spencer, 1942), and the simulation of the single tree canopy net assimilation activity (CA, (μmol CO_2 canopy^{-1} s^{-1}) were performed by VegeSTAR 3.0 software (Adam et al., 2002).

In particular, simulations were run under the environmental conditions of clear sky summer days in Bologna, Italy.

Structural and functional canopy traits, such as foliage area (m^2) and its vertical density (LAD, m^2 m^{-3}), leaf number, Silhouette (m^2), $STAR_{SKY}$ and CA (μmol CO_2 $canopy^{-1}$ s^{-1}), and leaf traits such as blade area ($m^2 * 10^{-4}$) and orientation angles (°) were computed.

The simulated parameter's distribution (or single data) were analyzed according to a non-parametric statistics and corroborated against the corresponding distributions (or single data) of the digitized canopy (C_d).

RESULTS AND CONCLUSIONS

The geometrical traits of the reconstructed canopies resulted in agreement with the corresponding of the real canopy (Table 1). The architectural correspondence between the representative *aK* canopy identified on the basis of the results of Table 1 and the digitized one was shown by the corresponding images rendered from the same perspective (Fig. 1A and B).

Maximum vertical LAD resulted at 1.0 m height, whereas linearly and symmetrically decreasing values were observed at higher and lower heights. More precisely, the maximum median vertical LAD for *aK* canopies resulted of 3.5 m^2 m^{-3}, whereas the corresponding maximum LAD for the real canopy resulted of 3.0 m^2 m^{-3} (Fig. 1C).

Daily Silhouette showed a bell shaped behavior in both digitized and *aK* reconstructed canopies with general lower values (about 15%) for *aK*. A maximum C_d Silhouette of about 4.25 m^2 was observed at midday (Fig. 1D).

Canopy net assimilation rate in both C_d and *aK* canopies resulted almost constant for most part of the daytime (at incoming photon flux densities ≥ 1000 μmol m^2 s^{-1}): in particular, the real canopy showed a net photosynthetic rate of about 95.0 μmol CO_2 s^{-1}, whereas the *aK* canopies showed rates about 20% lower.

The results obtained on a peach tree with 28.41 m^2 foliage surface area evidence the capacity of the MC-*aK* probabilistic procedure to satisfactory reconstruct an adult tree canopy from both a geometrical and a functional perspective. In general, the convenience in applying the MC-*aK* procedure to reconstruct an adult broad-leaf fruit tree canopy resides in the opportunity to sample the foliage in a fast (field measurements could be accomplished by two people working half day) simple, inexpensive and non destructive way.

The MC-*aK* procedure could find wide application in eco-physiological, growth and development plant studies to provide the canopy geometrical information crucial to explain the functional and/or productive canopy plant performances.

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Tables

Table 1. Foliage and leaf statistical parameters for digitized and reconstructed canopies. IQR = Inter-quartile range = 75th-25th percentiles. $1S_{boot}$ = one canopy data sample bootstrapped 30 times; 30aK = 30 *adaptive Kernel* reconstruction. * = angles are considered as deviations from 0.

Level	Parameter	Reconstruction	Nº of observations	Mean	Median	Min.	Max.	Range	25th	75th	IQR
Canopy	Foliage area (m^2)	Digitized	1		28.4						
		$1S_{boot}$>30aK	30	27.8	26.8	21.8	38.4	16.6	25.7	29.2	3.5
	Leaf number	Digitized	1		14,260						
		$1S_{boot}$>30aK	30	13,982	13,541	11,289	19,048	7,759	12,932	14,773	1841
	$STAR_{SKY}$	Digitized	1		0.13						
		$1S_{boot}$>30aK	30	0.12	0.12	0.11	0.15	0.04	0.12	0.13	0.01
Leaf	Blade area (m^2*10^{-4})	Digitized	14,260	19.9	20.9	4.28	29.9	25.62	15	24.3	9.3
		$1S_{boot}$>30aK	419,460	18.6	20.2	7.1	29.3	22.2	14.4	23.9	9.5
	*Elevation angle (º)	Digitized	14,260	28.9	26	0	90	90	16	39	23
		$1S_{boot}$>30aK	419,460	29.2	26.5	-5	111	116	17	41	24

Figures

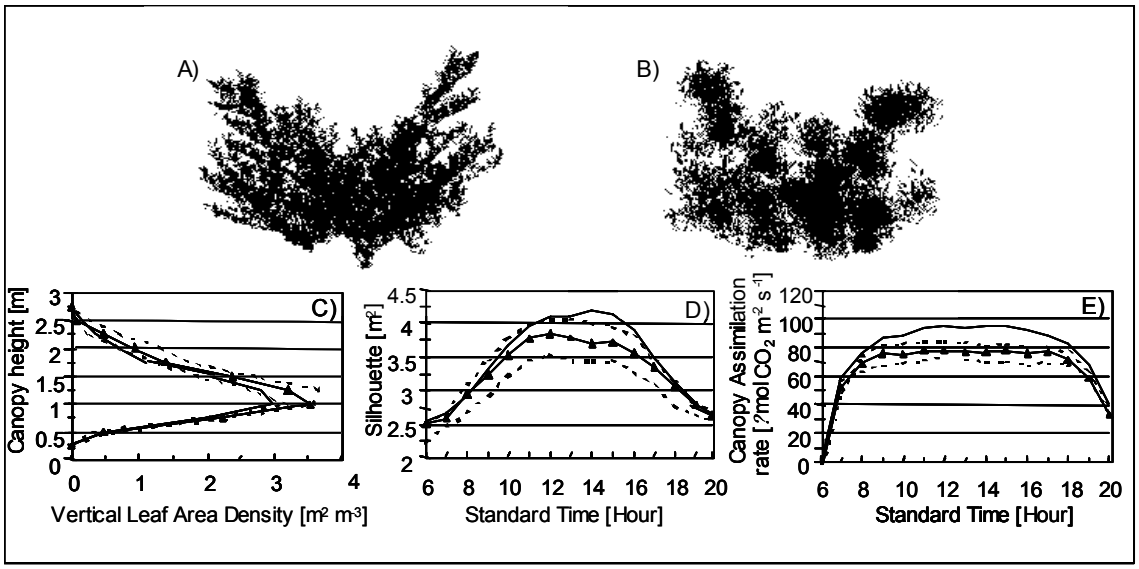

Fig. 1. (A) Digitized and (B) Representative *aK* reconstructed canopies, shown from the same view point. (C) Vertical leaf area density distribution of Digitized (___) and *aK* canopies (▲ = *aK* median; --- = 25th and 75th *aK* percentiles). (D) Hourly Silhouette simulation performed at DOY = 200 in Bologna, Italy under clear sky conditions. ___ = Digitized canopy; ▲ = *aK* canopy median; --- = 25th and 75th *aK* percentiles. (E) Hourly canopy assimilation rates of Digitized (___) and *aK* canopies (▲ = *aK* median; --- = 25th and 75th *aK* percentiles) simulated under the same (D) atmospheric conditions.