Simplifying data acquisition in plant canopies: Measurements of leaf angles with a cell phone

Adrián G. Escribano-Rocafort, Agustina B. Ventre-Lespiaucq, Carlos Granado-Yela, Antonio López-Pintor, Juan A. Delgado, Vicente Muñoz, Gabriel A. Dorado and Luis Balaguer

Summary

1. Canopies are complex multilayered structures comprising individual plant crowns exposing a multifaceted surface area to sunlight. Foliage arrangement and properties are the main mediators of canopy functions. The leaves act as light traps whose exposure to sunlight varies with time of the day, date and latitude in a trade-off between photosynthetic light harvesting and excessive or photoinhibitory light avoidance. To date, ecological research based upon leaf sampling has been limited by the available technology, with which data acquisition becomes labour intensive and time-consuming, given the overwhelming number of leaves involved.

2. In the present study, our goal involved developing a tool capable of measuring a sufficient number of leaves to enable analysis of leaf populations, tree crowns and canopies. We specifically tested whether a cell phone working as a 3D pointer could yield reliable, repeatable and valid leaf angle measurements with a simple gesture. We evaluated the accuracy of this method under controlled conditions, using a 3D digitizer, and we compared performance in the field with the methods commonly used. We presented an equation to estimate the potential proportion of the leaf exposed to direct sunlight (SAL) at any given time and compared the results with those obtained by means of a graphical method.

3. We found a strong and highly significant correlation between the graphical methods and the equation presented. The calibration process showed a strong correlation between the results derived from the two methods with a mean relative difference below 10%. The mean relative difference in calculation of instantaneous exposure was below 5%. Our device performed equally well in diverse locations, in which we characterized over 700 leaves in a single day.

4. The new method, involving the use of a cell phone, is much more effective than the traditional methods or digitizers when the goal is to scale up from leaf position to performance of leaf populations, tree crowns or canopies. Our methodology constitutes an affordable and valuable tool within which to frame a wide range of ecological hypotheses and to support canopy modelling approaches.

Introduction

Canopies are complex multilayered structures resulting from the coalescence of individual plant crowns within any community, from forests to grasslands and from terrestrial to freshwater and marine environments (Moffett 2000). Canopies expose a multifaceted surface area of phytoelements, such as leaves and stems, which intercept sunlight, precipitation, wind, particulates and aerosols (Monteith 1973; Gutschick 1999; Huang et al. 2007; Asner & Martin 2011). Canopy processes (e.g. primary production, evapotranspiration, gas exchange, etc.) and concomitant phenomena such as heat absorption, light reflection, temperature regulation or erosion reduction are among the ecosystem functions supporting some of the most important ecosystem services (see for instance Lowman & Schowalter 2012). Canopy performance integrates multiple contributions and synergies across scales, from community overstorey to plant crown and to individual leaves (Barthélemy & Caraglio 2007). At the crown level, plant performance depends not only on the environmental conditions experienced by the plant but, to a large extent, on the modulation of the plant's environment by tree crown development and architecture (Rubio de Casas et al. 2007, 2011). The light environment within crowns is highly
heterogeneous at the spatial and temporal scale. Spatially, tree crown structure mediates the exponential decrease in light intensity (Wang & Jarvis 1990; Uemura et al. 2006). Temporally, light intensity is determined by the interplay between crown anisotropy, the daily and seasonal motion of the sun and the atmospheric conditions (Granado-Yela et al. 2011). Foliage characteristics, arrangement and properties are the main mediators of the biological processes occurring within crowns (Halk, Oldeman & Tomlinson 1978; Room, Mailletta & Hanan 1994; Steck & Bongers 2001). Indeed, leaves are functional units that link global climate and ecosystem dynamics, participating in food webs, biogeochemical cycles and constituting an important microhabitat in the biosphere (Wright et al. 2004; Pinecebourde & Woods 2012). Leaf size and arrangement ultimately reflect functional strategies evolutionarily shaped to optimize light harvesting (Hansen 1917; Walter 1973; Lowman & Schowalter 2012). Overall light interception by leaves depends on abiotic factors (e.g., wind conditions, atmospheric transmissivity) and on biotic factors, such as leaf anatomy and position within the canopy (Campbell & Norman 1989; Terashima & Hikosaka 1995; Vogelhann, Bornsmit & Yates 1996; Smith et al. 1997; Gu et al. 2003). The leaves of some annuals or ephemerals form sparse canopies that track changes in solar elevation and azimuth throughout the day (Ehleringer & Forseth 1980). In denser canopies, however, solar tracking by the upper leaves reduces the light available to the lower ones, in turn reducing net canopy photosynthesis (Denison, Fedders & Harter 2010). Most species, particularly perennials, are static-leaved plants, that is, they maintain leaf orientation through the leaf life span (minimum variation in leaf angles caused by active or passive movements). These leaves act as fixed light traps whose exposure to sunlight varies with time of the day, date and latitude. In these cases, leaf position represents a trade-off between photosynthetic light harvesting and excessive or photoinhibitory light avoidance, which acquires its full ecological and evolutionary meaning once contextualized within the geometry and dynamics of a plant's crown (Givnish 1988; Smith et al. 2004).

Unfortunately, to date, ecological research on canopies and crowns based on leaf sampling has been limited by the available technology. In many studies, data acquisition is labour intensive and time-consuming due to the overwhelming number of leaves present in tree crowns and their limited accessibility (Wang & Jarvis 1990; Parveaud et al. 2008). Field measurements of leaf angles have been customarily performed with clinometers, compasses, protractors, angle finders, rulers, plumb lines and callipers (hereafter, traditional methods; Comstock & Mahall 1985; Ehleringer & Werk 1986; Fleck et al. 2003; Granado-Yela et al. 2011) or with three-dimensional motion trackers or digitizing systems (hereafter, digitizers; Peaney & Yang 1996; Sinouquet & Rivet 1997; Falster & Westoby 2003; Hanan & Wang 2004). Traditional methods are portable but require at least three sequential measurements (see below) to characterize a single leaf's spatial position, which increases data acquisition time and the accumulated error. Additionally, traditional methods are frequently analogue, a fact that reduces measurement resolution. These disadvantages have been emphasized in previous studies (Jennings, Brown & Shell 1999; Jonckheere et al. 2004; Seidel et al. 2011). Digitizers are highly accurate, precise and effective for characterizing leaves in reference to others (Falster & Westoby 2003). Digitizers, however, are difficult to implement under field conditions for a number of reasons. They require a static point of reference, are expensive and, in practical terms, are not portable because of their size and weight. Moreover, they are usually wired, which limits their use in the field. Wiring tends to impose movement constraints – particularly when working within the canopy – and limits the equipment's reach, which consequently restricts the data acquisition range. It also implies the relocation of the reference point within a single crown, increasing the time required for measurements and for subsequent conversion of coordinates. Finally, digitizers most often require an external power supply, which increases expenses and can make its use in remote locations unfeasible. For all these reasons, when traditional methods and digitizers are used to describe forest canopies or tree crowns, they fail to characterize a representative number of leaves within a reasonable time, and consequently, any attempt to scale up from the leaf to higher functional and architectural levels will be considerably hindered, or even thwarted, by this severe drawback.

The aim of the present study involved developing a user-friendly, simple, fast, precise, digital, affordable and highly autonomous tool capable of measuring a sufficient number of leaves to enable analysis of leaf populations, tree crowns and canopies. This tool should be sufficiently small, light and manageable to be used single-handed within the canopy. It should also measure all angles describing a leaf's position simultaneously without requiring an external reference point. We specifically tested whether a cell phone equipped with an ad hoc software application is more effective than both, traditional methods and digitizers. We evaluated the accuracy of this method under controlled conditions using a 3D digitizer and compared performance in the field with traditional methods. We presented an equation to estimate the potential proportion of the leaf exposed to direct sunlight at any given time and compared the results with those obtained by means of a graphical method. Furthermore, we describe our research experience, highlighting the advantages and drawbacks of our method when used in intensive field campaigns at several sites.

**Materials and methods**

**DEVICE IMPLEMENTATION**

In order to measure the leaf lamina angles, we developed a specific application software to be implemented on a cell phone operating under Symbian OS (Nokia N86, Nokia Group, Espoo, Finland). This device incorporates a 3-axis accelerometer and a magnetometer that records its spatial position in relation to magnetic north (m) and to gravitational force (g) as XYZ coordinates (Fig. 1). These electromechanical sensors, however, have been common features in most of the commercialized cell phones for the past decade. Fitted with our
LEAF LAMINA CHARACTERIZATION

To describe leaf spatial position, we assume that leaves lie on a plane with adaxial/abaxial sides and a longitudinal axis running along the leaf midrib. Thus, a leaf, as a three-dimensional object, can be parameterized with spherical coordinates (Fig. 2). This system allows us to calculate leaf lamina course angle and leaf inclination angle, which we used to estimate the area of the leaf lamina exposed to the sun in per cent of the total leaf area. Lamina course angle (β) is the angle between north and the horizontal projection of a normal vector to the leaf lamina. Lamina inclination angle (p) is the angle of the maximum slope of the leaf from vertical. These two angles can be determined through a matrix of three vectors, which comprises leaf pitch, roll and midrib azimuth angles (α, γ, i). Pitch angle (α) is the angle between the vertical and the midrib of the leaf lamina. Roll angle (γ) is the angle of rotation from horizontal along the longitudinal axis of the leaf (Fig. 2) and combined with α defines the maximum slope of the leaf above horizontal or lamina inclination angle (p). Midrib azimuth angle (i) defines lamina course angle (β) with respect to magnetic north and the projection of the midrib from petiole insertion to the tip of the leaf. Together with α and γ midrib azimuth angle defines lamina course angle (β) (Fig. 2).

Using the above-described angles (α, γ, i), the device mathematically determines a trihedron in space according to the following form:

\[
\begin{pmatrix}
\sin(\alpha) \cos(\gamma) \\
\sin(\alpha) \sin(\gamma) \cos(\beta) + \cos(\alpha) \sin(\gamma) \\
\cos(\alpha) \sin(\gamma)
\end{pmatrix}
\]

Each column in the matrix is a vector; the first column accounts for the leaf midrib, the second and the third columns define the leaf plane, and the third column is the normal vector to the leaf lamina surface. Thus, (p) and (β) can be calculated (Eqn. 1 and Eqn. 2) from pitch angle (α), roll angle (γ) and midrib azimuth angle (i):

\[
p = a \sin(\sin(\alpha) \cos(\gamma))
\]

\[
\beta = \pi - \tan(\sin(\gamma) / \cos(\alpha))
\]

VALIDATION OF SAL EQUATION

In order to evaluate the results obtained from the proposed estimation of leaf exposure (Eqn. 3), we recalculated the instantaneous silhouette area of the leaf blade (SAL) from the angles of the leaves included in the study by Granado-Yela et al. (2011). These authors measured the lamina angles of 385 leaves of Olea europaea L. by means of traditional methods. They calculated the instantaneous silhouette area of the leaf blade (SAL) graphically through AutoCAD for 250 leaves. We calculated Pearson’s correlation coefficient for both estimates of leaf exposure.

CELL PHONE CALIBRATION

In order to assess the error in the measurement of the leaf angles caused by the inaccuracy of the cell phone sensors, we built a custom-made desk. The desk bears a hinge enabling different positions. The main panel has an inscribed circumference and a stand to hold a digitizer. Specifically, we used a 3D motion tracker (Fastrak, Polhemus, Vermont, USA). The desk was built without any metal parts to avoid electromagnetic interferences (Fig. 4). It was set on a range of elevations from the horizontal to the vertical plane every 5°. At each elevation, we made 26 measurements following the graduated notches in the drawn circumference (one measurement every 10°). Desired angles in the adjustable desk were fixed using the digitizer. Using trigonometric functions, we calculated the expected values for the study angles (α, γ, i).
Figure 1. Device's coordinate system and equations which relate the three Euler’s angles $\alpha$, $\gamma$, and $\beta$: 

$$
\alpha = \text{Atan} \left( \frac{P_y \times Q}{P_z \times Q} \right), \quad \gamma = \text{Atan} \left( \frac{P_x \times Q}{P_z \times Q} \right)
$$

where $P_x$, $P_y$, and $P_z$ are the axis projection of $\mathbf{g}$ on $\mathbf{F}$, $\mathbf{n}$ is the vector to the device surface, and $\mathbf{F}$ is the vector of the geomagnetic field $m$ from magnetic north projected on a normal plane to $\mathbf{g}$. 

Figure 2. Leaf angles, $\alpha$: spans from 0 to $\pm 180$ degrees where 0° and $\pm 180$° refer to a vertical leaf and $\pm 90$° to a horizontal leaf. $\gamma$: spans from 0 to $\pm 180$ degrees. Negative values account for a right turn from petiole to leaf tip. In the figure, if $\gamma = -90$°, the reader should picture a leaf facing North = $+Z$. $\beta$: projection of leaf midrib vector from petiole insertion to leaf tip into polar coordinates; 0° north, clockwise. $\mathbf{n}$: normal vector to the lamina surface. $L$: Leaf lamina.

Figure 3. Device set in parallel to a leaf. Device and leaf lamina facing East ($\beta = 90$°). Angles of interest are the same for the leaf and the device. $x = x'$, $y = y'$, $\mathbf{n} = \mathbf{n}'$, and $\beta = \beta'$; $\mathbf{n}$: normal vector to the leaf lamina surface, $\mathbf{n}'$: normal vector to the device. $F_T$: Top part of device's front side, $F_B$: Bottom part of device's front side, $L$: Leaf lamina. Insertion angles between leaf and petiole are parallel in this situation in which angle $\alpha$ is the same in leaf and petiole. Setting the device in parallel to a leaf with different insertion angle between petiole and leaf midrib will record $\alpha$ regarding leaf pitch and not petiole pitch.

**Field Validation of the Device**

In order to evaluate whether our device could provide a tool as reliable as the traditional methods used in previous studies, but much easier to operate, we measured the leaf angles of 100 leaves using (i) a protractor and a compass, and (ii) our cell phone. Leaves were haphazardly chosen within the crown of ten wild olive trees (Olea europaea L.), c. 1.5 m high and located at the Alfonso XIII Royal Botanical Garden in Madrid (40°26’57”N, 3°43’41”W). Each leaf was measured with our device and then with a protractor ($\alpha$ and $\gamma$) and a compass ($\alpha$ and $\gamma$), as used elsewhere (Rubio de Casas et al. 2007, 2011; García-Verdugo et al. 2010; Granado-Yela et al. 2011). We analysed the differences between the measurements taken with the cell phone ($\alpha_c$, $\gamma_c$, $\alpha_T$, $\gamma_T$, $\mathbf{n}_c$, and $\beta_c$) and with the traditional methods ($\alpha_T$, $\gamma_T$, $\mathbf{n}_T$, and $\beta_T$) by means of Pearson’s correlations. In addition, we assessed the discrepancies in the instantaneous silhouette area of the leaf blade through a Pearson’s correlation between those calculated from the angles measured with the cell phone ($SAL_c$) and those calculated from data obtained with traditional methods ($SAL_T$). Mean relative error between methods was quantified for each angle as performed for the calibration process. We adopted the presented method during four field campaigns conducted in Aldea del Fresno (Madrid, Spain), San Luis (Mahón, Spain), Langalanga (Gilgil, Kenya) and Limuru (Nairobi, Kenya), which differed in accessibility and tree size. Effectiveness was described in terms of averaged ratio of measurements per hour, among other important considerations examined in the discussion.

**Results**

**Validation of SAL Equation and Cell Phone Calibration**

The values of instantaneous silhouette area of the leaf blade ($SAL_c$) calculated graphically by Granado-Yela et al. (2011) and by means of eqn 3, were strongly correlated ($R = 0.98$, $P < 0.05$; Fig. 5). Mean relative error was below 10% for all
angles. Pitch angle (\(\theta\)) showed the biggest differences between measured and expected values with a standard deviation close to 15\% (Table 1). Estimations of the response variable between expected values and the angles measured with the cell phone (\(SAL_e - SAL_o\)) differed by <2\% with a standard deviation below 3\% (Table 1).

The expected angles (i.e. angles simulated by spatial geometry) and the angles measured with the cell phone were highly correlated in all cases (\(R > 0.93, P < 0.05; \text{Fig. 6}\)). Nevertheless, we detected a bias for the measurements of the pitch angle and roll angle due to cross-axis sensitivity. Inclination angle (\(\beta\)), however, was not apparently affected by this bias (Fig. 6c). The values of \(\beta\) angle showed greater deviations when the adjustable panel was set near the horizontal plane (no specific orientation), but it remained constant at higher elevations (Fig. 6f).

**FIELD VALIDATION OF THE DEVICE**

Estimations of the leaf angles measured with the cell phone and by means of traditional methods showed less than 1\% of mean relative error for each angle (Table 1). Roll angle experienced the biggest discrepancies and standard deviation between methods. The mean relative error between the SAL calculated from angles measured with traditional methods and with our cell phone was 5.5\% with a standard deviation below 7\% (Table 1). A strong correlation was found for each angle between methods (\(R > 0.93; \text{Fig. 7}\)). Correlations between measurements were significant for all angles (\(P < 0.05, n = 100; \text{Fig. 7}\)). The estimated SAL between traditional methods and our cell phone showed a strong correlation (\(R = 0.95, P < 0.05, n = 100\) (Fig. 7f).

On average, we were able to obtain 146 ± 24 valid measurements per hour and cell phone during the field campaigns, where over 4000 leaves were measured. In practice, a single device could perform up to 720 measurements in a single day without running out of battery.

**Discussion**

Our tests in the laboratory and under field conditions demonstrate that the present method provides accurate and reliable measurements of leaf angles and SAL estimations. The method described constitutes an advance in direct data acquisition based on a widespread, affordable, easy-to-use, portable and wireless methodology that enables leaves to be spatially monitored by any researcher, educator or student. Our method proved to be satisfactory and highly convenient for field designs involving planar leaves/leaflets (leaves and leaflets that can be broken down into planar elements), thus providing many advantages over methods reported in the literature. Nonetheless, the presented method may still require canopy lifters, scaffolds or ladders to reach tree crowns and canopy elements.

**CALIBRATION AND VALIDATION**

The coefficients of correlation between the measurements taken with the cell phone and the expected values simulated by spatial geometry during the calibration process were strong and statistically significant for all angles and estimated SAL. Most values for all angles tested and SAL were tightly clustered around the expected ones, denoting great accuracy and precision (Fig. 6; Table 1). We found a strong linear relationship for all angles, although during the calibration process we detected a bias resulting from low cross-axis sensitivity in pitch and roll angles (Fig. 6a-c). The cross-axis sensitivity is the measure of how much output is seen on one axis when acceleration is imposed on a different axis. It is a product of the 3-axis accelerometer architecture and is a key factor to be implemented and tested by manufacturers (Amarasinghe et al. 2006; Kal et al. 2006; Sankar Das & Lahiri 2009). The sensor is most sensitive to changes in tilt when the axis involved is perpendicular to the acceleration and is least sensitive when it is parallel. Despite this fact, the effect was negligible in relation to our goals due to the combination of pitch and roll angles in the maximum slope angle (\(\rho\); Eqn. 1), which minimizes the

![Figure 4. Adjustable deck outline used for calibration. a: cell phone holder (allows turn on Z axis), b: circumference inscribed in panel surface (notched every 10°), c: deck surface, d: supporting legs, e: hinge that allows elevation, f: space for digitizer, g: digitizer holders.](image)

![Figure 5. Correlation of recalculated SAL with eqn 3 (SAL_r) and that obtained by graphical methods (SAL_g) in Granado-Yela et al. (2011). n = 250. Negative values indicate underside exposure](image)
Table 1. Mean relative error and SD (%) for each angle and leaf exposure. The error was calculated as the difference between the expected values (digitizer, traditional methods) and the cell phone measurements (observed) for each angle.

| Angle                  | Cell phone vs. DT | Cell phone vs. TM |
|------------------------|-------------------|-------------------|
|                        | Error (%)         | SD (%)            | Error (%) | SD (%)          |
| Pitch (α)              | 6.5               | 14.9              | 8.5       | 6.1             |
| Roll (γ)               | 1.6               | 1.0               | 10.7      | 100             |
| Midrib A. (t)          | 2.0               | 0.7               | 3.4       | 2.8             |
| L. Course (δ)          | 4.3               | 5.3               | 3.8       | 2.5             |
| Max. Slope (p)         | 4.0               | 2.0               | 7.3       | 6.2             |
| SAL_E - SAL_o          | 1.5               | 2.5               |           | 5.5             |
| SAL_C - SAL_E          | -                 | -                 |           | 6.8             |

DT: digitizer, TM: traditional methods. SAL_E: estimations of SAL from expected angle values during calibration. SAL_o: estimations of SAL from angles measured by the device during calibration. SAL_C: estimations of SAL from angles measured with traditional methods during field validation. Cell phone vs. DT n = 684 except L. Course n = 648. Cell phone vs. TM n = 1010.

The coefficients of correlation between the field measurements taken with the cell phone and traditional methods, and SAL estimated from them, were strong and statistically significant (Fig. 7). The differences between methods of angle measurement remained low in the validation process and for SAL estimations (Table 1). Likewise, the coefficients of correlation of SAL calculated between graphical methods and the equation presented were strong (Eqn. 3; Fig. 5). These findings support our method as a reliable tool for assessing the spatial position of leaves and for calculating potential SAL over time under field conditions.

**Functional Considerations: Opportunities and Limitations**

The method presented for estimating SAL does not account for leaf overlapping within canopy layers. Despite this limitation, we found it highly relevant to measure leaf angles and to estimate SAL in the whole canopy regardless of whether the leaves could be directly or indirectly exposed to wind, particulates, irradiation or other effects. At the individual level, recent reports point towards spatial and temporal specialization...
through photosynthetic harvesting of complementary light resources (direct and diffuse radiation) and/or segregated time windows in woody plants, which can be explored with our method (Rubio de Casas et al. 2007; Granado-Yela et al. 2011). Indeed, optimization of leaf photosynthetic efficiency through modulation of leaf inclination angle, lamina orientation and lamina exposure will certainly help to scale photosynthesis from leaves to individual crowns and canopies, as suggested by Posada, Lechowicz & Kitajim (2009). The spatial position of leaves and their potential exposure to direct sunlight are relevant to many functional processes operating at the individual level (Givnish 1987; Smith et al. 1997; Falster & Westoby 2003; Pearcy, Muraoka & Valladares 2005; Granado-Yela et al. 2011). The mean relative error in SAL calculations was always below 10%, reaching maximum absolute values at full leaf exposure to the sun. As SAL decreases, sunlight absorption is not expected to decrease in proportion to the reduction in the projected leaf surface, but rather at higher rates due to the expected increase in light reflection and the smearing of the incident photon flux over a larger leaf area.

FIELD EXPERIENCE

The field performance of our device during the research campaigns was remarkable. Its portability was crucial to our research, enabling tree crowns to be sampled and logistic requirements to be fulfilled in remote locations. We wish to stress the ease of travelling, particularly on regular commercial flights, with such an affordable and commonplace device. In the field, the presented device was effortless to carry and to operate several metres above the ground. We found highly advantageous to take measurements with a single hand under these circumstances.

USE RECOMMENDATIONS

In order to improve field estimations, we recommend avoidance of wind and magnetic interferences (e.g. metallic structures adjacent to the individuals selected, grounded conductive structures, power lines, etc.) during measurements. Magnetic declination at each location should be considered to correct for true north. For use in humid environments, we recommend that the device be placed in a resealable, transparent, plastic bag, which can protect the electronic components without interfering with measurements. There is a need to minimize interactions between crown and canopy elements and structural supplementary tools (e.g. ladders, lift platforms, etc.) or between the above-mentioned elements and the researchers themselves. We also highly recommend survey measurements during the day for leaves presenting sun-tracking behaviour. It should be highlighted that the present methodology can involve several devices working together. Efficient field campaigns can therefore be performed by a small work force in relation to time of sampling and coverage of measurements. Finally, the

**Figure 7.** Relationship between traditional methods ($\alpha_T$, $\gamma_T$, $\pi_T$, $\beta_T$ and $\beta_L$) and the cell phone ($\alpha_C$, $\gamma_C$, $\pi_C$, $\beta_C$ and $\beta_L$) with the coefficient of correlation (R) given for each scatter plot. a: pitch angle, b: roll angle, c: midrib azimuth-angle, d: maximum slope, e: lamina coarse-angle, f: estimations of SAL between methods ($SAL_T-SAL_C$, negative values account for underside exposure), $n = 100$. 
application included in the presented methodology was kept simple regarding software development in order to facilitate portability for the more common mobile operating systems, such as Android, iOS (the Symbian version is available upon request and a free Android version can be downloaded from Google Play website, Ahmes). Ultimately, users should estimate the state of preservation of the sensors and their resolution in order to successfully achieve specific aims. We strongly recommend determining whether the device’s resolution is suitable for the desired design. This can be achieved by following a calibration process similar to that described herein.

Conclusions

We successfully avoided common constraints in canopy characterization by combining sensitivity, portability and speed of measurements in an affordable and relatively commonplace device. The tests performed support our method as a remarkable tool excelling in field campaigns. Our results demonstrate that the equation implemented in our methodology constitutes a firm estimation of potential instantaneous leaf exposure. The method presented involves direct field measurements providing valuable data in a wide range of ecological scopes (e.g. geometrical approaches, plant modelling, etc.) and functional hypotheses.

We believe that our method is highly relevant in a wide range of scientific approaches. We briefly outline the potential applications in which our methodology could provide insight due to its versatility, even when some of its features are not necessarily involved, such as pollutant deposition/evaporation on planar surfaces, leaf microclimate (proxy for leaf dwelling organisms), radial location through triangulation (namely, objects of interest within crowns: nests, epiphytes, plagues), slope characterization, termite mound irradiation patterns, spider web spatial arrangement, and many others. To conclude, we would like to emphasize that the methodology presented can play an important role in ecophysiological and educational projects due its affordability to many institutions, researchers and students world-wide.

Acknowledgments

We wish to thank MD Jiménez, A Vázquez, J Serrano, K Carrillo for their valuable assistance during the experimental design. Thanks to F Martínez and to Wasabi App Factory for their expertise and help with the programming and to M Escudero for graphing assistance. We also gratefully acknowledge (anonymouse referees for their constructive comments. Special thanks to Mr. Cemal de Brun for revision of the English. The presented methodology is a Spanish Patent Pending 201200481. This research was funded by the Spanish Ministry of Science and Education (project REMEDINAL-2, S2009/AMB-1783).

Abbreviations

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| m      | Geomagnetic field                                |
| g      | Gravitational force                              |
| φ      | Latitude                                         |
| δ      | Declination                                      |
| h      | Hour angle                                       |

References

Amarasinghe, R., Doe, D.V., Toriyama, T. & Sugiyama, S. (2006) Simulation, fabrication and characterization of a three-axis piezoresistive accelerometer. Smart Materials and Structures, 15, 1691-1699.

Aner, G.P. & Martin, R.E. (2011) Canopy glycolyseomic, chemical and spectral assembly in lowland Amazon forest. New Phytologist, 189, 999-1012.

Barron, D. & Cao, G. (2007) Plant architecture: a dynamic, multilevel and comprehensive approach to plant form, structure, function and evolution. Annuals of Botany, 99, 372-407.

Campbell, G.S. & Norman, J.M. (1993) The description and measurement of plant canopy structure. Flora Carpa: Their Growth, Form and Function (eds C. Russell, B. Marshall & P.O. Bock). pp. 1-19. Cambridge University Press, Cambridge.

Cereceda, J. & Smallman, B.E. (1985) Drought and changes in leaf orientation for two California chaparral shrubs, Ceanothus crassifolius and Ceanothus leucodermis. Oecologia, 65, 531-535.

Nilsen, R.F., Felder, J. & Harter, B. (2010) Individual fitness versus whole-plant photosynthesis: solar tracking backflows in alfalfa. Evolutionary Applications, 3, 466-472.
