Automated estimation of leaf area index from grapevine canopies using cover photography, video and computational analysis methods

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Abstract

Background and Aims: Monitoring of canopy vigour is an important tool in vineyard management to obtain balanced vines (vegetative vs reproductive organs). Leaf area index is the main parameter representing canopy vigour. Our aim was to test an automated computational method to obtain leaf area index and canopy vigour parameters from grapevines with digital photography and video analysis using MATLAB programming techniques for rapid data uptake and gap size analysis.

Methods and Results: The proposed method was tested against allometry at a Chilean experimental site planted with cv. Merlot. A temporal and spatial assessment of the method was also tested in a drought and drought/recovery experiment with cv. Chardonnay in the Riverland, South Australia. These data were geo-referenced and compared to the normalised difference vegetation index extracted from the WorldView-2 satellite images at a 2 m^2 per pixel resolution.

Conclusions: The maximum leaf area index data obtained with cover digital photography and video analysis are an accurate, cost-effective and easy-to-use method to estimate spatial and temporal canopy LAI and structure when compared to standard measurements (allometry and plant canopy analyser).

Significance of the Study: This study has demonstrated that the method proposed is an accurate and inexpensive tool for application in experiments and by the industry to monitor spatio-temporal distribution of vigour.

Keywords: *canopy cover, digital image analysis, MATLAB programming, porosity, satellite imagery*

Introduction

Leaf area index (LAI) has been defined as the total one-sided area of leaf tissue per unit ground surface area (Watson 1947). Most of the currently available methods for monitoring LAI are based on manual measurement points, which have low spatial resolution and are time consuming. Thus, it is difficult to assess efficiently the spatial and temporal variability of LAI from vineyards, usually caused by differences in soil characteristics and management.

Studies based on remote sensing have shown that monitoring variation in LAI could be a good spatial indicator of canopy vigour for grapevines using airborne platforms (Johnson et al. 2003b, Hall et al. 2008) and satellite platforms (Johnson 2003a, Zarco-Tejada et al. 2005, Martin et al. 2007). These same studies, however, pointed out that the canopy discontinuity from vineyards posed an analysis problem for accurate LAI estimation due to the inter-row component, especially when a cover crop is present.

Measuring leaf area index and canopy structure as vigour indicators for management purposes

Canopy vigour can be managed with different training systems to regulate the microclimate of canopies to affect yield and grape composition (Smart 1985). Adjusting canopy vigour to decrease disease incidence can be also achieved by removing leaves (English et al. 1989) or by summer pruning (Wermelinger and Koblet 1990, Guidoni et al. 1997, Rügner et al. 2002).

It is well known that canopy structure and size can also be altered, as a management strategy, by reducing the amount of water applied to control vigour. Increments in irrigation have resulted in increased LAI, indicative of a more vigorous vine (Esteban et al. 1999, 2001, Acevedo-Opazo et al. 2010). Another effect sought by reducing LAI is to obtain greater light penetration to bunches and the renewal zone (area where the fruiting canes originate) to improve fruit composition and productivity for the next season (Dokoozlian and Kliewer 1995). Berries with increased sun exposure are generally higher in phenolic substances along with decreased acidity when compared to that of non-exposed fruit (Bergqvist et al. 2001). Therefore, there is an inverse relationship between vigour and gap fraction that affects fruit composition. This effect needs to be taken into account for optimal management purposes and has been the main subject for many experimental trials in the past.

Monitoring canopy cover and LAI has been also proposed as a way to estimate accurately crop coefficients (Kc) for grapevines to assess water requirements for irrigation scheduling purposes (Williams and Ayars 2005). In general, the Kc value for grapevines can be obtained from the literature (Allen et al.

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1998). These values, however, are generic, developed in different agroclimatic conditions and do not account for differences between canopy size, row orientation, training system and vine spacing, among other factors (Martin et al. 2007, Poblete-Echeverría et al. 2012, Poblete-Echeverría and Ortega-Farias 2013).

Measuring leaf area index as an indicator of vigour for experimental purposes

For experimental purposes, LAI is a critical parameter widely used for: (i) experiments that involve the estimation of growth and development of plants (Fuentes et al. 2008); (ii) modelling growth and water use (Williams and Ayars 2005); (iii) functional plant modelling (Whitley et al. 2008); and (iv) scaling up leaf-based physiological measurements to the whole plant or tree (Ewert 2004) and tree-based measurements (e.g. sap flow) that can also be upscaled to the whole field or region (Zeppel et al. 2008). The magnitude of LAI in a vineyard depends on environmental and management factors, such as training systems, water and nutrient supply and the use of cover crops, among others (Oliveira and Santos 1995). Therefore, there is the requirement to determine accurately spatio-temporal variations of LAI for scientific experiments to verify the effect of treatments on canopy vigour and, from the management perspective, to assess precision irrigation strategies, such as regulated deficit irrigation and partial root-zone drying, to maximise yield and quality of grapes.

Current methodologies to estimate leaf area index

Leaf area index can be directly measured using destructive methods or indirectly estimated with a variety of instrumentation. Direct measurement of LAI (allometry), by either scanning every single leaf from the canopy or generating empirical shoot length versus leaf area per shoot, is difficult and time consuming to perform (Cutini et al. 1998). Furthermore, these methods do not easily allow a representative spatial and temporal resolution of LAI, which is required in grapevine research experiments and/or for management purposes. There are also non-destructive direct methods to estimate LAI, such as the Li-Cor-3000 portable area meter (LI-3000C, Li-Cor Inc., Lincoln, NE, USA), which requires scanning of individual leaves from canopies. This method can be used as an in situ calibration for indirect LAI estimation methodologies, such as the one proposed in this paper.

Consequently, non-destructive, ground-based or indirect methods have been developed and are more commonly used to estimate LAI in practical terms. Typically, these are based on measurement of radiation transmission through the canopy, for example, the LAI-2000 and 2200 (Plant canopy analyser; Li-Cor Inc.) (Villalobos et al. 1995, Cutini et al. 1998, Bréda 2003, Arias et al. 2007). The cost of these instruments, however, can be prohibitive, and it has been reported that they can underestimate LAI by between 10–40% in forests and crop trees (Macfarlane et al. 2000).

Indirect estimation of LAI by digital or cover photography and gap fraction analysis has been developed recently and provides an accurate and rapid estimation of LAI (Macfarlane et al. 2007a,b, Fuentes et al. 2008). One disadvantage of the cover photography method was that it could not be automated using the available analysis software (Macfarlane et al. 2007a,b,c). An automated and semi-automated method, however, has been developed for trees and crops using MATLAB (The Mathworks Inc., Natick, MA, USA) programming techniques (Fuentes et al. 2008). This study aims at testing a modified automated and semi-automated method using digital imaging and MATLAB programming on grapevines compared to destructive and non-destructive techniques applied in Chile and Australia from downward-looking and upward-looking images, respectively. The technique has been developed further to allow the automated analysis of zenith-orientated videos of grapevine canopies taken from moving vehicles, such as tractors, quad bikes, remote controlled vehicles and robotic vehicles. By geo-referencing these data, the new analysis module allows data mapping to assess spatial distribution of LAI and canopy vigour parameters within the vineyard. Furthermore, in this paper, we contrast geo-referenced LAI data obtained using the cover photography method against the Normalised Difference Vegetation Index (NDVI) from satellites.

Materials and methods

Description of the Chilean site

Data were collected from a drip-irrigated Merlot vineyard located in the Talca Valley, Maule Region, Chile (35° 25′ LS; 71° 32′ LW; 125 m.a.s.l.) during the 2009/10 and 2010/11 growing seasons. The climate of the study area is classified as Mediterranean semi-arid with an average daily temperature of 17.1°C and an average annual rainfall of 679 mm. The summer period is usually dry and hot (2.2% of annual rainfall), while the spring is wet (16% of annual rainfall). The soil at the vineyard is classified as Talca series (Fine family, mixed, thermic Ultic Haploxeralfs) with a clay loam texture and average bulk density of 1.5 g/cm^3. The vineyard was irrigated daily using 4 L/h drippers spaced at intervals of 1.5 m. The vines were planted in 1999 in north-south oriented rows, 2.5 m apart, with 1.5 m within-row spacing and were trained on a vertical shoot-positioned system with the main wire 1 m above the soil surface. The shoots were maintained on a vertical plane by three wires, the highest one located 2 m above the soil surface.

Description of the Australian site

Data were collected during November 2010 and January 2011 in a drought and drought-recovery experiment (DDRE) within a commercial Chardonnay vineyard at Qualco, South Australia, (Yalumba Nurseries: 37º 25.8′ N; 122 º 05.4′ W). This experiment started in the 2008/09 season using a total area of 3.69 ha with a split-plot randomised complete block design with four replicates. Main plots consisted of three adjacent rows of 30 vines per row that were split into three sub-plots of three adjacent rows of 10 vines per row. The vines in the trial were 8 years old grafted on Ramsey rootstock and trained on a two-wire vertical trellis system with row spacing of 1.8 m between vines and 3 m between rows. The experiment consisted of five main deficit irrigation treatments split into three recovery treatments. The deficit irrigation treatments were: full irrigation or control (C), and reduction to 50 (50S), 30 (30S), 20 (20S) and 10% (10S) of the control. The C treatment represented the amount of irrigation that is normally applied to the vineyard (5 ML/ha in year 1). Recovery treatments consisted of continued deficit irrigation, reverting back to C in 2009/10 (RR) and reverting back to C in 2010/11 (R). All measurements were made on a panel of three vines in the middle of each sub-plot. All treatments were irrigated for 4 h with Netafim Dripmaster pressure compensated in-line drippers with a 2.3 L/h of flow. To apply the reduction in irrigation volume, the interval between irrigations was increased using the Irrigated Crop Management Service (ICMS) Water Budgeting Tool (South Australian Research and Development Institute).

Leaf area index of grapevine canopies measured by allometry

At the Chilean site, LAI was estimated using an allometric relationship between total leaf area per shoot and shoot length as ground truth. Total leaf area per shoot was calculated using scanned images of leaves and total leaf number per shoot. A customised MATLAB code was created to obtain automatically total leaf area per scanned image. Finally, the length of shoots was measured manually with a flexible measuring tape to generate the following empirical equations:

$$LA_{shoot} = -634.86 + 3543.92(SL) \quad (1)$$

$$LAI_a = \frac{\sum_i^j LA_{shoot}}{A_V} \quad (2)$$

where LAI_a corresponds to LAI by allometry, LA_{shoot} corresponds to the total leaf area per shoot (m^2), A_v was the area designated to the vine (m^2), SL was the shoot length (m), and j was the total shoot number per vine (Poblete-Echeverría and Ortega-Farias 2013).

To follow the development of LAI_a from plants during the two seasons, total shoot length per vine was measured once per week on three representative vines. Digital images from these same plants were captured at the same dates to obtain maximum leaf area index (LAI_M). This allometric procedure is a semi-direct method that relates canopy parameters, such as shoot diameter, shoot length and leaf length, to total leaf area per vine. Allometric equations are widely used in the calculation of LAI_a in vineyards (Montero et al. 2000, Johnson et al. 2003b, Williams and Martinson 2003, Poblete-Echeverria and Ortega-Farias 2009). Because of their accuracy, allometric equations are commonly used as a standard way to validate other methods of LAI estimation (Gower et al. 1999). But allometric equations are site specific and vary with the canopy and climatic conditions (Mencuccini and Grace 1995, Le Dantec et al. 2000).

Measurement of leaf area index of grapevines by plant canopy analyser

At the DDRE, LAI_{2000} was measured with the Li-Cor LAI2000 plant canopy analyser (Li-Cor Inc.); measurements were made at the same time and locations as the digital image acquisition per irrigation treatments following the manufacturer's protocol. Measurements were made in triplicate around the middle plant per irrigation replicate to generate an averaged LAI_{2000} value per replicate ($n = 12$ averaged values per treatment) (Dokoozlian and Kliewer 1995).

Digital image and video acquisition

At the Chilean site, a Samsung camera with a resolution of 5.2 megapixels (Digimax A503, Samsung Group, Seoul, South Korea) mounted on a pole with a bubble level was used to acquire downward looking digital images (at nadir angle) from canopies using the Joint Photographic Experts Group format. Digital images were collected at 3.9 m from the ground covering the area assigned to the vine. Camera settings were configured following the methodology proposed by Fuentes et al. (2008).

For the DDRE, a Nikon SLR D90 (Resolution 12.9 megapixels) with an AFS-Nikon 18–55 mm f/3.5–5.6 G lens (Nikon Corporation, Chiyoda, Tokyo, Japan) was mounted on a flat wooden platform with a bubble level at the zenith angle to acquire upward-looking digital images from approximately

Figure 1. Typical digital image taken at zenith angle from grapevine canopies. The automated system can deal with clear, cloudy or partially cloudy days as described by Fuentes et al. (2008).

20 cm from the soil surface (Figure 1). Images were acquired and measured LAI_{2000} data collected in November 2010 and January 2011. The camera was set to automatic exposure using F16 lens with the zoom adjusted to cover the whole canopy. Settings were the same for all the pictures taken. Three digital images were obtained from around the middle plant on every replicate per irrigation treatment ($n = 120$ per date). Video was acquired with a high definition (640×480 resolution) sport video camera (DVR-460, Swann, Melbourne, Australia) mounted on top of a remote control car.

MATLAB script to analyse cover photography

A code developed using MATLAB (version 2011b) and the Image Processing Toolbox (The Mathworks Inc.) was modified and tested to generate a script specific for grapevine canopies to batch process numerous upward-looking digital images taken from vineyards. This methodology has been explained in depth in Fuentes et al. (2008). The image subdivisions used for grapevines was five (total subdivisions = 25) and the big gap criteria = 0.75.

The algorithms used were: the fractions of foliage projective cover (f_f), crown cover (f_c) and crown porosity (Φ), which were calculated from Macfarlane et al. (2007a) as:

$$f_f = 1 - \frac{\text{tg}}{\text{tp}} \quad (3)$$

$$f_c = 1 - \frac{\text{lg}}{\text{tp}} \quad (4)$$

$$\Phi = 1 - \frac{f_f}{f_c} \quad (5)$$

where lg = large gap pixels; tg = total pixels in all gaps and tp = total pixels in images.

LAI_M is calculated from Beer's Law.

$$LAI_M = -f_c \frac{\ln \Phi}{k} \quad (6)$$

where k corresponds to the light extinction coefficient k used = 0.7 (Herwitz et al. 2004) and the clumping index at the zenith, $\Omega(0)$, was calculated as follows:

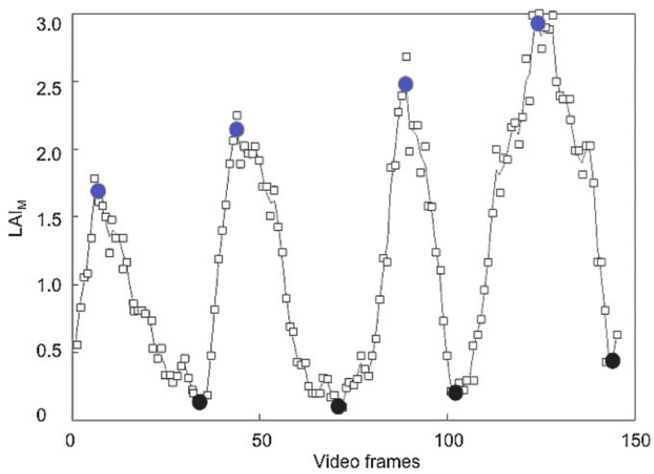

Figure 2. Maximum leaf area index (LAI_M) from automated analysis of video frames (□) using the code developed in MATLAB. Maxima [LAI_M (●)] and minima [LAI_{irowM} (●)] correspond to LAI from the canopy and contribution from the inter-row, respectively.

$$\Omega(0) = \frac{(1-\Phi)\ln(1-f_f)}{\ln(\Phi)/f_f} \tag{7}$$

The clumping index is a correction factor to obtain effective LAI (LAI_e), which is the product of:

$$LAI_e = LAI_M\,\Omega(0) \tag{8}$$

Equation 7 describes the non-random distribution of canopy elements. If $\Omega(0) = 1$, means that the canopy displays random dispersion; for $\Omega(0) < 1$, the canopy is defined as clumped.

Automated module to analyse leaf area index from videos

An automated module was added to the original code presented in Fuentes et al. (2008) to analyse upward-looking videos taken from grapevine canopies. The module uses commands from the Image Analysis Toolbox to extract frames (images) from videos that are automatically batch analysed by the original code to obtain LAI_M and canopy vigour parameters (Fuentes et al. 2008). Calculated LAI_M data were obtained per video frame automatically, which were treated as individual images, represented as small open squares in Figure 2. These data were later interpolated using a smooth spline technique (continuous line) and automatically filtered to obtain LAI_M from the row (blue circles) and from the inter-row (LAI_{irowM}). The latter values correspond to the minima values (black circles). This module allows the use of video cameras mounted on small vehicles that can travel under the canopies transversally through the rows. Videos can also be obtained with a camera mounted on a quad bike along the row. This code was tested on the DDRE.

Satellite remote sensing data

Remote sensing data were obtained from the WorldView-2 satellite (DigitalGlobe, Longmont, CO, USA). Images were acquired for the DDRE on the 7 and 21 November 2011. WorldView-2 is the first commercial high-resolution satellite to provide eight spectral sensors in the visible to near-infrared range. WorldView-2 provides the only high-resolution eight-band multispectral commercial satellite imagery currently available. Along with the four typical multispectral bands: blue (450–510 nm), green (510–580 nm), red (630–690 nm) and near infrared (NIR) (770–895 nm), each sensor is narrowly focused on a particular range of the electromagnetic spectrum that is sensitive to a particular feature from the ground, or a property of the atmosphere. In this study, the values of red NIR_1 were extracted from a fusion image for each grid sample points from the DDRE using the geo-statistical software package ArcGIS version 9.0 (ESRI, Redlands, CA. USA), giving a resolution of 2 m^2 per pixel. Subsequently, these values were used to calculate the classical normalised vegetation index (NDVI) (Rouse et al. 1974) using the following equations:

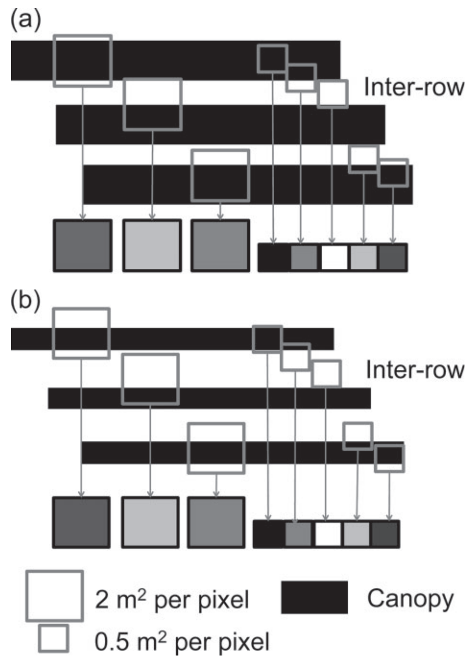

Figure 3. Representation of different pixel resolution obtained at low (0.5 m^2 per pixel) and high resolution (2 m^2 per pixel) from the WorldView-2 satellite near-infrared bands for (a) vigorous canopies and (b) less vigorous canopies.

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{9}$$

The resolution of images obtained from WorldView-2 can be increased to 0.5 m^2 using a fused WorldView-2 image and the panchromatic image. Data obtained using Equation 9 were compared to geo-referenced LAI_M obtained using the photographic method proposed in this paper. For this, the NDVI data corresponding to geo-referenced positions of ground-truth measurements (LAI_M) per treatment were extracted from the 2 m^2 image using a customised code developed in MATLAB. A linear model was obtained from the NDVI versus LAI_M. This model was used to generate a LAI_{sat} model from the Australian experimental site.

The image resolution of 2 m^2 gave more representative results to be compared to ground-measured LAI_M according to the irrigation treatments and canopy sizes within the experiment. This pixel size corresponds to the integrative values of the canopies and inter-row for grapevines (Figure 3). Using the maximum resolution possible of 0.5 m^2 (by a fusion between NIR and panchromatic bands) resulted in an overestimation of NDVI for the water stressed treatments (<30% full irrigation), since pixels falling inside the area of canopies corresponding to vigorous and less vigorous canopies which can both present values of NDVI = 1 (Figure 3a,b).

Statistical analysis

The performance of the measured LAI values was compared by linear regression analysis against the estimated values: (i) LAI_M with LAI_a; (ii) LAI_M with LAI_{2000}; and (iii) NDVI with LAI_M. The statistical analysis was performed with MATLAB R2011b Statistical Toolbox and the Curve Fitting Toolbox (The Mathworks, Inc.). The slope and intercepts for each linear regression analysis was tested with a *t*-test using Statgraphics Centurion (Statpoint Technologies Inc., Warrenton, VA, USA). The root mean squared error (RMSE), mean bias error (MBE) and the mean absolute error (MAE) were calculated with the same program following standard methodologies of analysis (English et al. 1989, Wermelinger and Koblet 1990, Haselgrove et al. 2000).

Results

Temporal estimation using LAI_M compared to LAI_a and LAI_{2000}

The allometric model, developed for the cultivar Merlot at the Chilean site, has been previously presented in Poblete-Echeverria and Ortega-Farias (2009). A strong and significant correlation was obtained between LAI_a and LAI_M for both seasons measured at the Chilean site ($r^2 = 0.96$ with $P < 0.05$). The mean absolute error obtained was 8.9% (Figure 4a) and the RMSE = 11.5%. In the same figure, it can be seen that LAI_M values consistently overestimated LAI_a. This overestimation, however, corresponded only to 3% (Table 1). Figure 4b shows the temporal evolution of LAI_a within the 2009/10 and 2010/11 seasons. Both seasons showed a gradual increment in LAI_a from basal values of $LAI_a = 0.2$, at the beginning of the season (budburst), to flowering for the 2009/10 season (DOY = 345), which was 10 days earlier for the 2010/11 season compared to that for the 2009/10 season. Values of LAI_a at flowering corresponded to $LAI_a = 0.92$ and $LAI_a = 0.65$ for the 2009/10 and 2010/11 seasons, respectively. The maximum LA_a value for both seasons was found in pre-veraison (DOY = 14) for the 2009/10 season and DOY = 362 for the 2010/11 season. The first season showed a maximum LAI_a value of 1.71 (reached at DOY = 5, 2010/11 season), which was higher than the second season with LAI_a value of 1.22 (reached at DOY = 14, 2010/11 season) corresponding to a decrease of 29% for cv. Merlot. The clumping index for the Chilean site was close to 1 [$\Omega(0) = 0.986$, data not shown]. Therefore LAI_M and LAI_e were considered equivalent.

For the DDRE, a strong and significant linear correlation across all treatments (Figure 5) was found for LAI_{2000} compared to LAI_M ($r^2 = 0.92$ with $P < 0.05$) for the months of November 2010 and January 2011. The MAE obtained was 6% and RMSE = 7.39% (Table 1). Minimum LAI_M and LAI_{2000} values of around 2.0 were found in November 2010, and maximum values of around 5.5 were found in the month of January 2011 for cv. Chardonnay. January 2011 corresponded to the maximum LAI_M found for this particular site and season, which corresponded to pre-veraison. The clumping index for the DDRE was close to 1 [$\Omega(0) = 0.976$, data not shown]. Therefore LAI_M and LAI_e were considered equivalent.

Spatial estimation of LAI_M compared to NDVI and LAI_{sat}

A linear correlation was obtained from the relationship between NDVI, extracted from the WorldView-2 image and LAI_M (Figure 6). The r^2 was equal to 0.93, which corresponded to a strong and statistically significant correlation ($P < 0.05$) with an MAE = 13%. The model obtained, considering the linear regression passing through the origin, was $LAI_M = 4.44 * NDVI$.

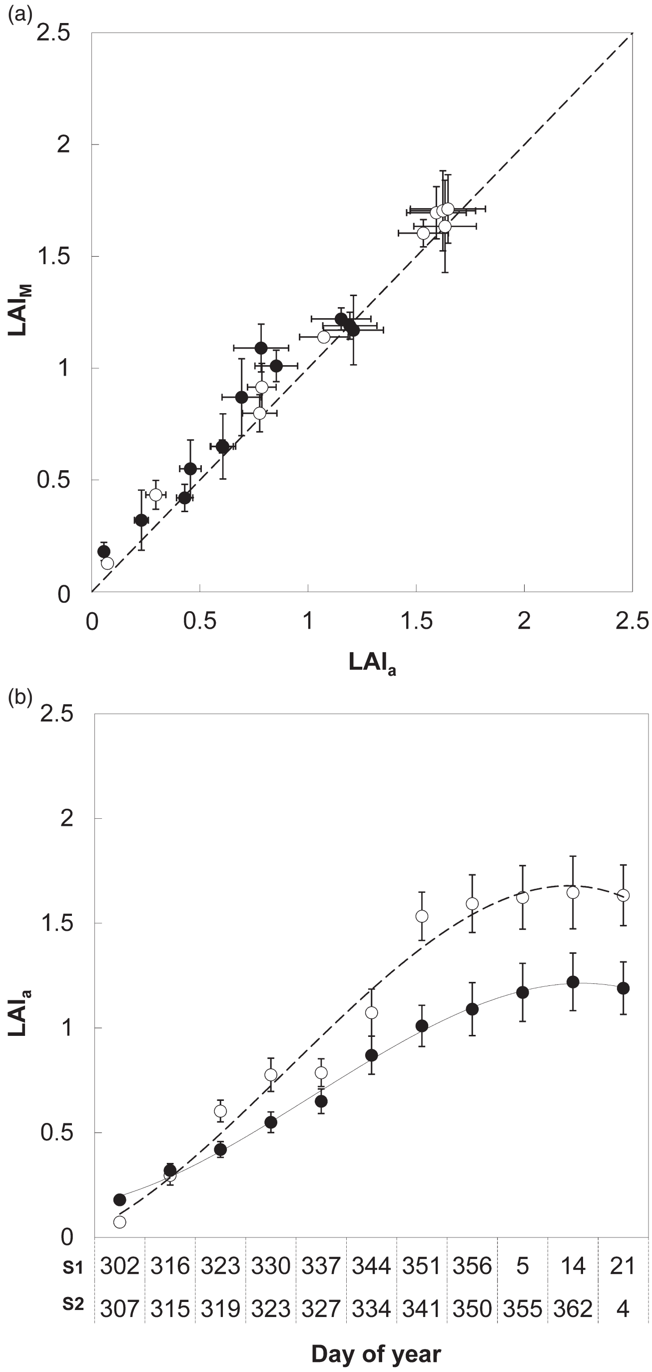

Figure 4. (a) Relationship between the leaf area index measured by allometry (LAI_a) and by the cover photography method (LAI_M) for the cv. Merlot during the seasons 2009/10 (○) and 2010/11 (●) for the Chilean site and (b) seasonal evolution of LAI_a for the two growing seasons studied at the Chilean site. Error bars correspond to the standard deviation of measurements for the LAI_a and LAI_M methods.

Minima values obtained from videos and automated analysis proposed in Figure 2 (LAI_{irowM}) show the contribution of the inter-row for different irrigation treatments (Figure 7). Stressed treatments showed values close to zero (10 and 20%, and 10R). The highest contribution was found for 30%, 30RR, 30R, 50RR, 50R and C, with values of LAI_{irowM} of around 0.35. The

Table 1. Statistical analysis for relationships obtained between (i) LAI_M and LAI_a and (ii) LAI_{2000} and LAI_a:

Approach	RMSE	MAE	MBE	r^2	d	a	*n*
LAI_M versus LAI_a	11.5%	8.9%	−8.4%	0.97	0.99	0.11	22
LAI_a versus LAI_{2000}	7.39%	6.01%	−0.34%	0.91	0.98	0.01	25

a, intercept; b, slope; LAI_a, leaf area index measured with allometric procedure; LAI_{2000}, leaf area index measured with the Li-Cor LAI2000 plant canopy analyser; LAI_M, leaf area index estimated with digital photographs; MAE, mean absolute error; MBE, mean bias error; *n*, total number of observations; r^2, coefficient of determination; RMSE, root mean square error.

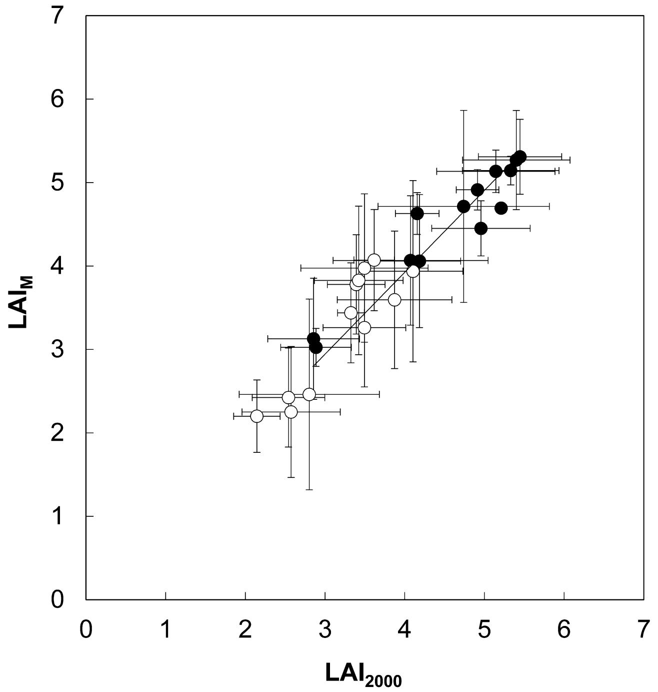

Figure 5. Relationship between the leaf area index measured using the LAI2000 PCA instrument (LAI_{2000}) and the cover photography method (LAI_M) for Chardonnay at the drought and drought-recovery experiment for the months of November 2010 and January 2011. Error bars correspond to the standard deviation of measurements for the LAI_{2000} and LAI_M methods.

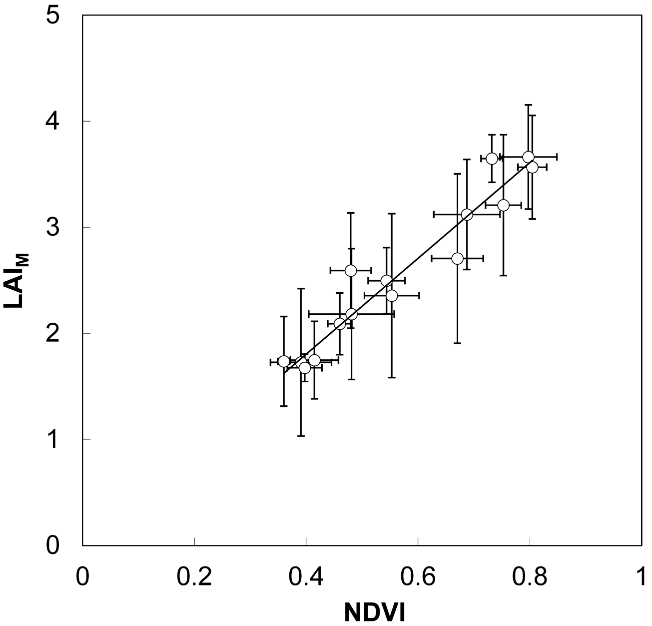

Figure 6. Relationship between the normalised differential vegetation index (NDVI) obtained from WorldView-2 satellite imagery (resolution of 2 m^2 per pixel) and the cover photography method (LAI_M) for Chardonnay at the drought and drought-recovery experiment in November 2010. Error bars correspond to the standard deviation of measurements for the NDVI and LAI_M methods.

stabilisation of the camera needs to be improved for future research to obtain stable videos from irregular terrain.

Discussion

The robustness of the digital image method to estimate LAI of grapevines presented in this paper allows monitoring of LAI through the season. It has been shown that there is a strong and significant correlation between LAI measured in the field and the Kc for grapevines obtained by weighing lysimeters (Williams and Ayars 2005) and by using the micrometeorological approach combined with sap flow sensors (Martin et al. 2007). Usually, Kc can be obtained from tables available from a variety of sources such as FAO paper 56 (Allen et al. 1998). These Kc values, however, were obtained from different agroclimatic conditions than those in which they were intended to be used. Therefore, errors in this factor can result in over or underestimation of crop evapotranspiration within the season (Poblete-Echeverria and Ortega-Farias 2009). Such under or overestimations can result in excessive stress and reduced yield, or overirrigation, which could increase canopy vigour, yield and alter berry composition (Acevedo-Opazo et al. 2010). Therefore, our method could contribute to obtaining specific Kc values adjusted by LAI (Allen et al. 1998).

A clear seasonal effect in canopy growth can be seen in Figure 4b for the Chilean site. Season 2010/11 corresponded mainly to a warmer season (data not shown), which resulted in an advance of phenological stages of around 1 week for flowering and fruitset and 2 weeks for veraison.

Temporal assessment of canopy vigour can be determined by a variety of instrumentation available in the market, such as the Li-Cor LAI-2000 (or LAI-2200) plant canopy analyser as shown in Figure 4 (Li-Cor Inc.), or the AccuPAR LP-80 (Decagon Devices, Pullman, WA, USA). For practical applications, however, these instruments can be cost prohibitive. The method proposed was developed using a digital camera for the Chilean site and a semi-professional camera for the DDRE. Similar results and comparisons with allometric and indirect LAI measurements were obtained. These results are consistent with LAI studies using cover photography and comparisons between low-cost digital cameras with single-lens reflex (SLR) cameras (Nikon D80) (Fuentes et al. 2012). Therefore, the cover photography method is an accurate and cost-effective method for

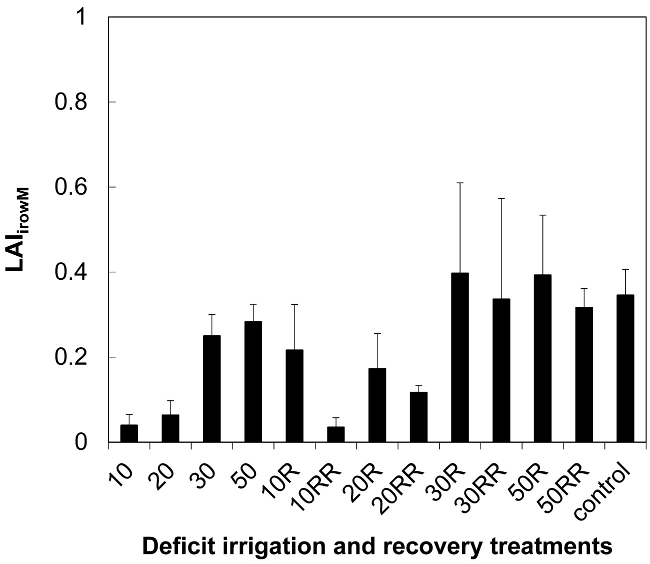

Figure 7. Effect of irrigation treatment on the vegetative inter-row contribution (LAI_{irowM}) obtained by analysing minima values from video outputs at the drought and drought-recovery experiment for Chardonnay in November 2010. Error bars correspond to the standard deviation of measurements for the LAI_{irowM} method. The deficit irrigation and recovery treatments were: full irrigation or control (C), and reduction to 50 (50S), 30 (30S), 20 (20S) and 10% (10S) of C. The C treatment represented the amount of irrigation that is normally applied to the vineyard (5 ML/ha in year 1). Recovery treatments consisted of continued deficit irrigation, reverting back to C in 2009/10 (RR) and reverting back to C in 2010/11 (R).

practical applications and scientific research involving canopy size assessments.

For practical reasons, the upward-looking images (Australia) are easier to obtain compared to the downward-looking images (Chile). The latter was only possible due to the absence of green material in the inter-row (bare soils). This method will not work with the inclusion of weeds or cover crops in the inter-row, since it will make difficult the discrimination between the canopy and the background for an automated method.

It is important to note that according to data presented in Figure 4a, the overestimation of LAI_M compared to that of LAI_a can be explained by the inclusion of cordons and shoots in the images obtained to calculate LAI_M, which were not considered in the development of the LAI_a model. The non-leaf material included can be assessed early in the season (budbreak), in which most of the LAI_M registered corresponds to the contribution of grapevine cordons and pruned shoots (Figure 4a, LAI < 1).

Spatial assessment of LAI_M and geo-referenced LAI_M compared to NDVI

Temporal and spatial assessment of LAI and canopy cover obtained using satellite platforms (downward-looking images) has been reported as a suitable method compared to upward-looking digital images as ground truth for forestry environments (Fuentes et al. 2008, Palmer et al. 2008, 2010). Some of these environments, however, showed an overestimation up to 17% approximately of LAI due to the incorporation of the understorey component from satellite imagery (Fuentes et al. 2008). The latter will pose a problem for the use of satellite imagery for vineyards in Australian growing regions, since the use of cover crops could introduce an overestimation of real LAI, especially at early and mid-season.

Satellite-based imagery has limited application in crop management in general due to the low spatial and temporal resolution of these platforms (Herwitz et al. 2004, Torres-Sánchez et al. 2013). Spatial and temporal resolution has been improved in new commercial satellites, such as Ikonos, Quickbird, WorldView (1 and 2), GeoEye, RapidEye and Pleyades; however, images from these new satellites images are expensive. They also require a high level of know-how to treat and analyse images to obtain meaningful results that can be transferable to growers. Currently, free satellite images are limited to medium-resolution sensors, such as Landsat 7ETM+ providing 60 m pixel size images and Moderate Resolution Imaging Spectroradiometer (MODIS) providing 500 m pixel size images, which are impractical for site-specific agricultural applications, since a significant level of spatial variability of vegetative growth can be commonly found in vineyard blocks (Hall et al. 2008) and for extensive experimental trials. These differences will probably result in variability of fruit composition, yield and grapevine physiology among other factors, because of the modification of light interception by the fruit zone and the renewal zone of grapevines.

The method proposed in this paper using cover photography and a rapid method of data acquisition and analysis, with still and video cameras mounted on robotic vehicles, can result in inexpensive and accurate growth and LAI maps, offering a valuable tool for scientific experiments and viticultural management in general. Furthermore, results comparing the LAI_M and NDVI from this study indicate that the method proposed is highly correlated to high-resolution satellite data.

In previous studies, it has been shown that NDVI may be a poor indicator of vegetation index for vineyard canopy characteristics (Zarco-Tejada et al. 2005). The main problem of NDVI as a vegetation index for grapevine canopies is that vineyards present a non-continuous canopy consisting of grapevine rows and inter-row space, which are different for those found in broad-acre crops, such as cereals and legumes. Furthermore, grapevine canopies are distributed in a three-dimensional wall array, the shape of which will depend on the training system. The cover photography method showed a high correlation with NDVI obtained from high-resolution satellite data; therefore, it can be a suitable tool to obtain spatial two-dimensional maps of vineyards or of research experiments of grapevines without considering the cover crop contribution (used in the inter-row to take up excessive soil moisture from winter time and heavy rainfalls) (Barbeau et al. 2005a,b). The advantage of satellite or airborne NDVI maps is that they are instant snapshots of spatial distribution of vegetative cover in a large area. Remote sensed imagery, however, can also be cost prohibitive to achieve a temporal assessment of canopy growth within a season.

The versatility of the analysis method described by using MATLAB computations and cover image analysis allows the handling of large data sets, such as those acquired with digital cameras or videos. By either geo-referencing a large number of digital images obtained spatially, it is possible to compare LAI_M with airborne or satellite NDVI data from vineyards. Such comparisons have been previously done for LAI_M obtained in different Australian forests and LAI_{MODIS} obtained from satellite at low-spatial resolution (250 m^2 per pixel) (Fuentes et al. 2008). Analysis of satellite imagery at low-spatial-resolution (Ikonos with 4 m^2 resolution per pixel) has resulted in a significant correlation between LAI and NDVI for multiple vineyards (Johnson et al. 2001, Johnson 2003a). Our study selected the 2 m^2 per pixel resolution, since it integrates the proportion of canopy to inter-row space, which is independent of pixel location relative to grapevines and inter-row (Figure 3a). Imagery from the WorldView-2 satellite allows a maximum resolution of 0.5 m^2 (using a fusion between NIR and panchromatic bands). Using the latter to compare LAI_M and NDVI could present a problem in the pixel extraction method, which can be a source of bias due to the high NDVI values (NDVI = 0.75–0.95) from pixels that fall covering just the top canopies without inter-row inclusion (Figure 2).

The video analysis capabilities from the code developed in MATLAB allow the extraction of LAI_M from videos obtained from a vehicle travelling under the canopies transversally to the rows (continuous data using robots). Values exactly below the canopy (maxima) and values in the middle of the inter-row (minima) can be automatically extracted (Figure 2). LAI_M from the inter-row may not be necessarily zero for vigorous canopies (i.e. 50% and C treatments), in which shoots can grow towards the middle of the inter-row and in extreme cases touch with shoots from the following row (partial canopy closure) (Figure 7).

Conclusions

This work has demonstrated the strong relationships that exist between the proposed method (LAI_M) and allometry (LAI_a), specialised LAI instrumentation (LAI_{2000}) and spatial assessment using satellite platforms (NDVI). Digital image and video acquisition, coupled with MATLAB image data analysis, provides a rapid, robust, cheap and simple method to obtain LAI of grapevine canopies. This method can be applied for managerial purposes on commercial vineyards to assess the spatial variability of canopy growth within a field and for experimental research of the effect of treatments on canopy growth and vigour. Finally, the LAI_M method can be used to develop models to calibrate indices obtained by remote sensed data (airborne or satellite). Through application of the latter method it will be possible to obtain more accurate and representative spatial maps for larger spatial scales.

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