Comparison of different protocols for indirect measurement of leaf area index with ceptometers in vertically trained vineyards

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Abstract

Background and aims: Most optical devices for indirect measurement of leaf area index (LAI) from canopy-transmitted light are tailored for homogeneous canopies, thus limiting their application to discontinuous canopies such as vertically trained vineyards. This study evaluates the influence of sun position on the reliability of LAI estimates provided by a ceptometer and proposes a measurement protocol for use of such instruments on vineyards under direct illumination.

Methods and Results: Ceptometer readings at several sun elevation and azimuth angles were recorded in two fields. Leaf area index estimated at different sun positions using several measurement protocols were then compared against destructive leaf area measurements. The best results when the sun position departs from the zenith (sun elevation < 40°) are achieved by reading the transmitted, photosynthetically active radiation (PAR) in all the inter-row spaces, whereas measurements below the vines are suitable only when the sun illuminates close to the zenith.

Conclusions: The homogeneity of the canopy fraction measured along the ceptometer at each individual reading is a major requirement in order to obtain non-biased LAI estimates. Therefore, the protocol followed to measure the transmitted PAR at every sun position proved critical for the accuracy of LAI determination.

Significance of Study: This study provides guidelines for reducing LAI uncertainties associated with vineyard canopy structure in LAI estimation with linear-array optical devices such as ceptometers.

Keywords*:* *indirect leaf area index (LAI) estimation, ceptometer, vertically trained vines*

Introduction

Leaf area index (LAI, the total one-sided leaf area per unit soil area) is one of the most important agronomic biophysical parameters indicating crop development and productivity. In the specific case of vineyards, different studies have shown the relation between LAI and the rate of fruit ripening, diseases and infestations, water status and berry and wine quality (Smart 1985, Johnson et al. 2003) underlining its relevance for vineyard monitoring.

Direct (destructive) measurement of LAI requires plant defoliation making it a non-operational, intensive and laborious method. Indirect measurement by optical devices, based on the proportion of transmitted light in the PAR region throughout the canopy, presents major advantages over destructive methods – it is fast and easy to conduct in operational conditions – although the uncertainties are assumed to be larger.

One of the most widely used instruments is LAI2000 (Li-Cor, Lincoln, NE, USA), for both agricultural and forest canopies (Gower et al. 1999, Olesen et al. 2000, He et al. 2007), based on a fisheye lens divided in five concentric rings with a total field of view of 148°. The instrument registers PAR in the blue region, and it has to be used under diffuse illumination condition for an optimal performance. Specific view orientations can be achieved through the use of different cups covering the lens and limiting the azimuth of incoming radiation.

Digital hemispherical Photography (DHP) represents an interesting alternative. It can be used both under direct and diffuse illumination conditions, allowing to differentiate between green and woody organs through image classification techniques. Furthermore, available post-processing software (Demarez et al. 2008) permits the application of canopy-specific algorithms and optical configurations to estimate LAI.

Ceptometers such as SunScan (Delta-T Devices, Cambridge, UK) or AccuPAR (Decagon Devices, Pullman, WA, USA) constitute a different approach: linear arrays of hemispherical sensors operating simultaneously to register transmitted PAR along a probe of 1 m approx. Ceptometers are well suited for crops, often sown or planted in rows, since they allow the sampling of the inter-row space with a reduced number of measurements. They have been applied extensively both for estimation of LAI and fIPAR (fraction of intercepted photosynthetically active radiation) (Cohen et al. 1997, Wilhelm et al. 2000; Hale 2003, Vear et al. 2010), with its application possible both under direct and diffuse illumination conditions, but in the first case another PAR sensor must be used simultaneously measuring incident PAR and beam light fraction to produce non-biased LAI estimates.

Most of these optical devices rely on the relationship between canopy leaf area and light interception based on the Beer-Lambert law (Campbell and Norman 1998), which describes light attenuation within a homogeneous canopy, also known as a turbid medium. A complete review of the instrument and operating principles can be found in Bréda (2003), Jonckheere et al. (2004) and Weiss et al. (2004).

Consequently, the homogeneity of leaf area distribution in the observed canopy (also known as turbid medium assumption) is a major requirement for the application of these methods in LAI estimation from transmitted light measurements, due to the non-linear relationship between LAI and transmitted light described by the Beer-Lambert law.

That makes these methods unsuitable *a priori* for clumped, discontinuous canopies. A so-called clumping parameter can be included in Beer-Lambert law to account for non-randomness of leaf area distribution within the canopy (Nilson 1971, Chen and Black 1992), thus extending its application to discontinuous canopies. Nevertheless, that clumping parameter varies along with the crop growth season and is dependent also on viewing and illumination directions (España et al. 1998, López-Lozano et al. 2007) and this limits its usefulness in operational conditions.

Moreover, vertically trained vineyards constitute a specific case of non-homogeneous canopy, being at the same time discontinuous – with a low fraction of vegetation covering the soil – and row-structured. Under these conditions the sampling geometry becomes critical (Welles and Cohen 1996) to avoid any possible bias associated with the joint effect of a discontinuous and directional leaf distribution in LAI estimation.

Several studies (Grantz and Williams 1993, Sommer and Lang 1994, Johnson and Pierce 2004) report systematic underestimation in LAI retrieved using an LAI2000 instrument when applied to vineyards. That underestimation is attributed to the violation of the turbid medium assumption (Weiss et al. 2004) that will produce biased results. Nevertheless, the works of Ollat et al. (1998) and López-Lozano et al. (2009) demonstrate that the use of angular constraints to incoming light and specific sampling patterns may help in overcoming the limitations associated to vineyard architecture in LAI2000 and other hemispherical devices.

As it was mentioned before, one of the main advantages of ceptometers against hemispherical devices and LAI2000 is their performance under direct illumination conditions, and therefore they are not constrained to overcast conditions or diffuse illumination before dawn/after sunset. Although the performance of ceptometers for LAI estimation in several types of discontinuous canopies has been studied by several authors (Brenner et al. 1995, Cohen et al. 1995, Peper and McPherson 1998, Hyer and Goetz 2004, Serrano and Peñuelas 2005), few researchers, however, have explored their potential application in vertically trained vineyards (Cohen et al. 2000, López-Lozano et al. 2009). A systematic LAI underestimation is, again, reported by most authors when non-optimal configurations are adopted to mitigate the effect of foliage clumping. In contrast to hemispherical devices, angular constraints to the incoming light are difficult to implement in ceptometers, and therefore the efforts should be focused in establishing adequate sampling patterns and indicating measurement conditions where the eventual effects of vineyard architecture in LAI estimations would be minimal.

The present study points to that direction: providing guidelines to estimate LAI in vertically trained vineyards with ceptometers under direct illumination conditions. The pertinence of several measurement protocols will be evaluated, comparing indirect estimations against destructive measurement. Special attention will be paid to the contribution of the sun position in LAI uncertainties associated with canopy structure, and how the different sampling protocols at canopy scale can help to mitigate them.

Material and methods

This study was undertaken in two experimental field plots located in the municipalities of Movera (41.81ºN, 0.81ºW) and Longares (41.40ºN, 1.17ºW) in Zaragoza, Spain, with a wide range of cultivars. Each plot was about 1 ha in size and in both the planting pattern was 3 x 1.5 m with vertically trained vineyards. At both sites the row orientation was approximately NW-SE (120º azimuth for Movera and 142º for Longares).

The experiments took place on 6 June (Movera) and 7 July 2005 (Longares). Ten sample points were randomly selected at each of the two sites. Vine age varied between 2 and 14 years old in both experiments, producing substantial canopy LAI differences between younger and older vines.

At all 20 sample points selected, transmitted PAR readings to estimate LAI indirectly were repeated approximately every 30 min between 7:15 and 10:25 solar time with the purpose of covering a wide range of sun positions (see Table 1). Row width and row height at each sample point were measured manually on site.

Photosynthetically active radiation (PAR) readings were taken with a SunScan ceptometer. SunScan measures the PAR transmitted by the canopy on a 64-sensor array placed below the canopy. A BFS-3 beam fraction sensor (Delta-T Devices, Cambridge, UK) attached to the ceptometer records simultaneous measurements of incident PAR above the canopy and the direct light fraction. The support of a beam fraction sensor is thus required to operate under direct light conditions. Based on the Beer-Lambert law and radiative transfer equations, the SunScan dedicated software uses the ratio between the transmitted and incident PAR, the fraction of direct light and sun position to derive LAI (see Delta-T (1996) for further details).

Four measurement protocols were tested (see Figure 1). In the first one (protocol M1) the ceptometer was placed parallel to the vineyards in the middle of the inter-row space. The purpose of this protocol is to register the transmitted PAR along the row direction, assuming that direct light transmitted in the middle of the inter-row space is a good proxy to estimate LAI, especially when the vine shade is projected there. This protocol was followed in the study of Ollat et al. (1998) using the LAI2000 instrument.

Protocol M2 consisted of placing the ceptometer below the row, thus measuring row LAI instead of canopy LAI. Row LAI is equal to the ratio between the leaf area and the area of the vertical projection of the row. To derive canopy LAI from row LAI the following formula must be used:

$$LAI_c = LAI_r \frac{W}{D} \qquad (1)$$

where LAI_c is canopy LAI, LAI_r stands for row LAI, W is row width and D equals the distance between rows (3 m).

Protocols M3 and M4 measure transmitted light along all the inter-row space, thus targeting canopy LAI. The difference between both protocols lies in the sampling pattern: in M3 three consecutive readings were taken perpendicular to rows, whereas in M4 there were twelve parallel readings, in both cases covering all the inter-row space (Figure 1). Estimated LAI values derived for each of the individual readings were then averaged to calculate the integrated canopy LAI at each sample point.

In all the protocols the parameters ELADP (ellipsoidal leaf angle distribution probability) and the fraction of PAR absorbed by leaves – both used by the SunScan software to estimate LAI – were set at the default values (1 and 0.85, respectively). A value of 1 for ELADP stands for a spherical leaf angle distribution, which is considered as the default value for the manufacturer (Delta-T 1996), when no leaf inclination measurements are taken. Louarn (2005) indicated that leaf inclination in vineyards is mainly determined by the trellis system, so more vertical training systems, e.g. with three wires, produce more inclined leaves (close to 60°) , whereas systems with two wires or one wire would result in an average leaf inclination between 40°-50°. The choice of the default ELDAP is therefore considered adequate in the experiment presented here in the absence of field measurements. Furthermore, leaf area inclination does not have a strong influence on the LAI-transmitted PAR relationship when sun or view zenith is close to 57.5° (Wilson 1963, Baret et al. 2010), so it would not have, theoretically, any impact on LAI estimates, at least when sun is in position 1 and 2 (Table 1).

Once the measurements of the transmitted PAR were concluded, the sample points were defoliated. Two-metre lines were delimited along the measured rows and all leaves falling within them were cut, placed in paper bags and transported to the laboratory. The leaf area per sample point was then calculated using the LI-3000 area meter (Li-Cor, Lincoln, NE, USA). The actual canopy LAI was then obtained by:

$$LAI_c = \frac{LA}{D \times L} \qquad (2)$$

where LA is the leaf area collected at each sample point, D stands for the distance between rows (3 m) and L is the linear row distance defoliated (2 m). To evaluate the accuracy of LAI estimates by the different measurement protocols and for different sun positions, the root mean square error (RMSE) between the estimated and actual canopy LAI was calculated.

Results and discussion

The LAI values obtained from destructive measurement ranged from 0.2 to 2.2, which correspond to actual plant vigour conditions in commercial vineyards. The average LAI at the two sites, however, suggests that vegetation vigour is slightly higher in Longares (0.99) than in Movera (0.74). Only 2 out of the 20 points selected present a canopy LAI higher than 1.5. The distribution of measured LAI values, however, is considered representative of the regional conditions, given that planting density is relatively low (2222 vines/ha) and thus LAI values exceeding 1.5-2 are uncommon. It should be considered also that in Mediterranean regions vines are subjected to moderate water stress in order to maintain grape quality standards (Santos et al. 2005, Chaves et al. 2010). Vine dimensions also vary between the two sites, mainly related to the row width: 66 cm on average in Longares against 52 cm in Movera. Average vine height was 1.67 m in Movera site and 1.60 m in Longares.

The performance of the different measurement protocols, depending on sun position, is shown in Figure 2. As it can be seen, the measurement protocol has a substantial influence on LAI accuracy under different illumination conditions.

In general, protocols M3 and M4 perform better when the sun position at the time of measurement is far from the zenith (sun zenith angle > 45°), with a gradual decrease in their accuracy as the sun zenith decreases (sun positions 5, 6 and 7). Under appropriate illumination conditions (high sun zenith angle, see Figure 3a and 3c), these two protocols yield the lowest root mean square error (RMSE) of all the configurations. Nevertheless, the linear regression parameters between the observed and estimated LAI indicate a moderate bias, especially in protocol M4 (intercept 0.34, slope 0.58). The overestimation at low LAI values is attributed to the possible effect of the wooden parts and the trellis system on light interception. In contrast, at a high local LAI value the saturation of the LAI/transmitted PAR relationship can introduce large uncertainties, which could be responsible for the outliers found when canopy LAI > 1.5. Moreover, protocol M3 exhibits a stronger influence of sun position on the results than M4 (see Figure 2), with uncertainties increasing rapidly – especially at the Movera site – when illumination conditions depart from optimal (sun position far from zenith and not parallel to rows).

These differences are explained by the validity of the turbid medium assumption – which is critical for the accuracy of LAI optical measurements – under the different measurement protocols. Due to the non-linear relationship between transmitted PAR and LAI, the reliability of these optical methods is conditional on the homogeneity of the observed canopy fraction for each individual transmitted PAR reading. In other words, the transmitted PAR measured along the sensor probe – given that it is calculated from the average for all the 64 individual sensors – must correspond to a homogeneous fraction of the canopy, either the row or the inter-row space. Otherwise the measurements will exhibit systematic LAI underestimation as a consequence of foliage clumping.

This is critical in the case of protocol M3, since PAR readings perpendicular to rows are expected to have some level of heterogeneity. When the row shades most of the inter-row space (at high sun zenith angles), the effect of clumping on measurements is, theoretically, low. Actually, as it was demonstrated by Baret et al. (2010), the relationship between LAI and transmitted PAR in row canopies can be entirely explained by Beer-Lambert law only when the following condition is fulfilled:

$$W + H * \tan(\theta) \geq D \tag{3}$$

here θ stands for sun zenith angle. Equation 3 was proposed for illumination perpendicular to the rows. In the case of non-perpendicular illumination, $\tan(\theta)$ must be multiplied by $\sin(\varphi)$, where φ is the sun-row relative azimuth. Therefore, when the sun is close to the zenith, clumping severely affects some individual ceptometer readings: a small fraction of the probe is heavily shaded by the leaves while the rest of the sensors are sunlit. This invalidates the turbid medium assumption and produces systematic underestimation of the LAI (see Figure 3d) as reported as well by Cohen et al. (2000).

Moreover, in actual vines, the distribution of leaf area is not homogeneous within the row volume: usually the leaf density is higher in the cluster zone and decreases gradually with height (López-Lozano et al. 2011), resulting in a gradient of transmitted PAR in the inter-row space perpendicular to the direction of the rows. That would produce a moderate clumping effect on M3 individual readings.

In contrast, protocol M4 is, in principle, less affected by clumping, given that, in most cases, individual readings with the probe placed parallel to the row would correspond to homogeneous parts of the canopy (only in the case of young vines or measurements at early phenological stages discontinuities along the row would limit the accuracy of parallel readings). That explains the better results obtained at sun positions 4 to 7 (Figure 2) compared with protocol M3. Therefore, protocol M4 appears to be more adequate for vertically-trained vineyards than protocol M3. However Lang and Xiang (1986) recommend a perpendicular sampling for sorghum and wheat. Also Wilhelm et al. (2000) reported satisfactory results in maize canopies with a protocol equivalent to M3. In contrast Johnson et al. (2010) retrieved more accurate LAI estimations with a transect method (similar to M4 protocol) in buffelgrass and switchgrass row-planted canopies. Actually, perpendicular readings are adequate in canopies with small-size discontinuities where the turbid medium assumption may still be valid, e.g. in most of the cereals (Baret et al. 2010) or perhaps also in vineyards planted at high densities (>4000 vines/ha). The main disadvantage of the M4 protocol occurs at low sun zenith angles, when there is a risk of undersampling the small shaded fraction of the inter-row space. That introduced substantial bias in LAI retrieval, producing systematic underestimations, as depicted by Figure 3b.

In any case, for protocols M3 and M4 the sensitivity of transmitted PAR to LAI decreases dramatically when the sun is close to the zenith: only a small proportion of the incoming light passes throughout the vines and ceptometer readings are therefore marginally affected by leaf area. This can be seen in Figure 3b and 3d, where the regression coefficient r^2 suggests a poor relationship between the actual and estimated LAI in both cases. Application of these two measurement protocols under the above-mentioned illumination conditions is, consequently, not recommended.

Protocol M2, with readings taken below the vines, improves on the accuracies of M3 and M4 when measurements are taken closer to solar noon (sun position 7), especially at the Longares site, where it performs even better than M3 and M4 under their optimal illumination conditions, although it exhibits a slight bias towards underestimating LAI (Figure 3f). Actually, protocol M2 is tailor-made for sun positions close to the zenith. Measuring the transmitted PAR below the vine row has the advantage of avoiding any possible contribution by canopy heterogeneity, enhancing the sensitivity of the transmitted PAR to LAI. The regression coefficient (r^2 = 0.79) between the observed and estimated LAI is the highest of all the configurations tested (Figure 3f). The use of this protocol, however, requires accurate determination of the canopy width (see Equation 1), which is not always easy given the fuzzy dimensions of vine rows (López-Lozano et al. 2011). Another possible disadvantage in operational conditions is the eventual saturation of transmitted PAR at high LAI values, but in these experiments that limitation was not observed (Figure 3f) in this specific protocol.

In contrast, application of protocol M2 when the sun position is far from the zenith and perpendicular to the direction of the rows is not appropriate and will produce systematic LAI underestimation. Under these conditions conversion from row LAI to canopy LAI (Equation 1) theoretically should not be applied, but even so this protocol produces systematically biased estimates (Figure 3e).

It should be noted that, under direct light conditions, row LAI – often used instead of canopy LAI in viticulture to evaluate plant vigour – can only be retrieved with ceptometers when sun illuminates parallel to the rows. Conversely, when illumination is not parallel to the rows, measurements of PAR transmitted through the rows would not yield an estimation of row LAI, but an effective LAI (Chen and Black 1992) strongly determined sun position. Thus, effective LAI equals row LAI when the sun position is parallel to the rows and, as a result, approximates canopy LAI when sun departs from zenith and illuminates perpendicular to the row (Equation 3).

An alternative protocol combining M2 and M4 would consist of measuring that effective LAI and then rescaling it using a scaling factor, as it was proposed by Cohen et al. (2000). To do so, parallel measurements of transmitted PAR should be taken – similar to protocol M4 – sampling only the shaded fraction of the inter-row (the area where row shade is projected into the soil), instead of all the inter row space. Then, the effective LAI resulting from averaging individual local LAI results can be rescaled to produce canopy LAI by multiplying it by the fraction of the inter-row distance shaded by the rows. Therefore, this protocol becomes identical to M2 when sun is illuminating parallel to the rows (the shaded fraction of the inter-row space equals the row width, see Equation 1). Conversely, the scaling factor is 1 when Equation 3 becomes true. This alternative protocol would mitigate the eventual undersampling of the shaded fraction, identified in this experiment when using M4 at low zenith angles (Figure 3b). The work of Cohen et al. (2000) presented highly correlated, but sometimes biased, relationships between measured and estimated LAI.

Finally, protocol M1 produced poor LAI estimates in all cases. This protocol is not suitable for LAI estimations under direct illumination conditions. In this experiment, protocol M1 tends to overestimate the LAI when the sun elevation is low but produces systematic underestimations when the sun reaches the zenith. This is due to the strong effect of canopy clumping on measurements made only in the middle of the inter-row space biasing canopy LAI.

Conclusions

The performance of several measurement protocols for SunScan ceptometers was studied under direct illumination conditions in LAI determination. The results underline the strong influence of sun position on the accuracy of LAI estimates. Protocols M3 and M4 (PAR readings along all the inter-row space) provided the best overall accuracy with RMSEs of 0.24 and 0.25, respectively – although in both protocols moderate bias is observed. These satisfactory results, however, are achieved only when the sun zenith is higher than 40° and, therefore, the turbid medium assumption is valid, especially in the case of protocol M3. At lower sun zenith the performance of both protocols deteriorates, with substantial underestimation of LAI.

Conversely, when the sun position is close to solar noon, protocol M2 – measurements only below the vines – is recommended (RMSE = 0.29). It targets, however, row LAI – instead of canopy LAI – and therefore conversion is needed (Equation 1) based on row width measurements.

In summary, the best performing protocol is the one that fulfils the basic requirement of the turbid medium approach under the different illumination conditions: homogeneity in the canopy fraction observed by each individual PAR reading. When this basic condition is not achieved, the model used to convert the fraction of transmitted PAR into LAI will produce systematic underestimation. An alternative solution to the protocols presented in the study would overcome that limitation by sampling the shaded part of the inter-row space and then multiplying the estimated effective LAI by a correction factor based on the length of the inter-row shaded fraction.

The findings highlighted in this study are valid only under direct illumination conditions. The experiments covered only a fraction of all the possible sun positions in the field, especially sun zenith, ranging from 28° to 63°. That range, however, includes the most representative direct illumination conditions in mid-latitudes, where sun zenith can reach a minimum of 20° at noon during summer. In earlier measurements with high zenith angles (> 70°) the diffuse fraction of incident PAR starts to become more significant and use of ceptometers on open canopies is not recommended. For diffuse illumination conditions the results presented in Ollat et al. (1998) and López-Lozano et al. (2009) based on LAI-2000 measurements and hemispherical photographs, respectively, can be considered as a reference.

Moreover, this study covers only a single planting pattern, although conclusions can be extrapolated to other row patterns in vertically trained vineyards. Further investigation would be needed, however, to assess the performance of the methods presented here on other vine-training systems.

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Figure legends

Figure 1. Description of the measurement protocols tested to estimate canopy LAI on vertically trained vineyards.

Figure 2. Evolution of LAI Root Mean Square Error (RMSE), depending on sun position and measurement protocols in the (a) Movera and (b) Longares sites. In parenthesis sun zenith and relative sun-row azimuth at each measurement. Measurement protocols: M1 (readings in the middle of inter-row space); M2 (readings below the row); M3 (readings perpendicular to rows), M4 (readings parallel to rows).

Figure 3. Root mean square error (RMSE) and regression coefficients between true canopy LAI and SunScan estimated LAI in Longares (Lo) and Movera (Mo) sites for measurement protocols M4 (readings parallel to rows), M3 (readings perpendicular to rows) and M2 (readings below the row). Dotted line is 1:1 line.*In graph (e) the estimated LAI was kept as provided by the ceptometer and no row LAI to canopy LAI transformation (Equation 2) was applied.

Table captions

Table 1. Sun position angles (in degrees) at the moment of ceptometer reading. Sun-row azimuth is the sun azimuth relative to rows direction.

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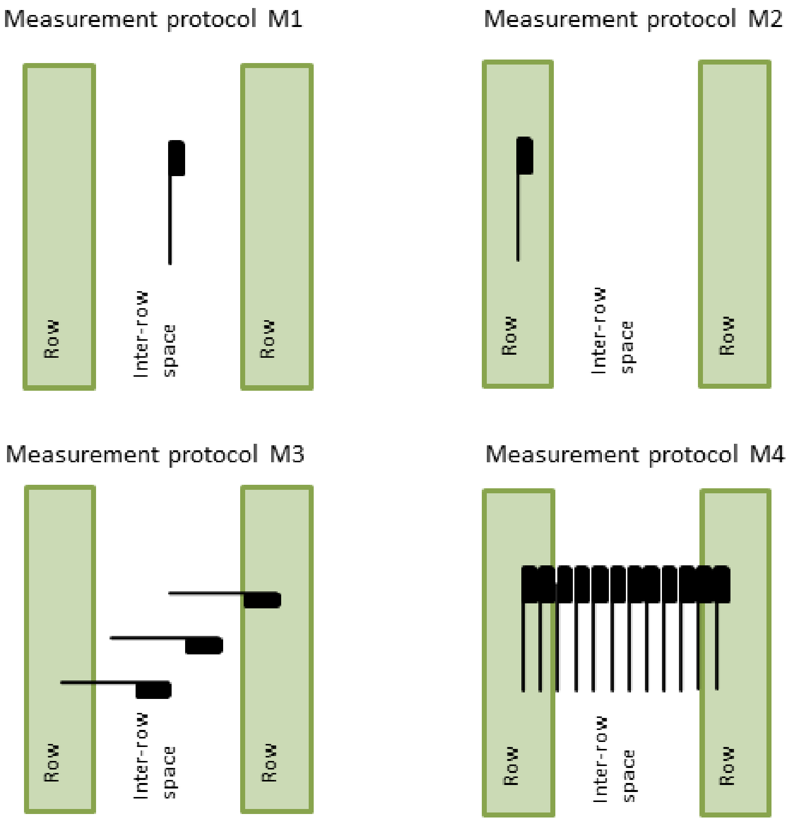
	Movera				Longares			
Sun position number	Solar time	Sun zenith	Sun azimuth	Sun-row azimuth	Solar time	Sun zenith	Sun azimuth	Sun-row azimuth
1	7:30	58.30	86.36	33.64	7:10	62.51	83.23	58.77
2	8:10	52.39	91.55	28.45	7:45	55.98	88.73	53.27
3	8:25	48.38	95.33	24.67	8:20	49.82	94.30	47.70
4	8:55	43.62	100.24	19.76	8:45	44.81	99.30	42.70
5	9:20	38.12	106.84	13.16	9:15	39.25	105.70	36.30
6	9:55	32.85	114.68	5.32	9:45	33.54	113.86	28.14
7	10:25	27.82	115.23	4.77	10:20	29.03	122.33	19.67



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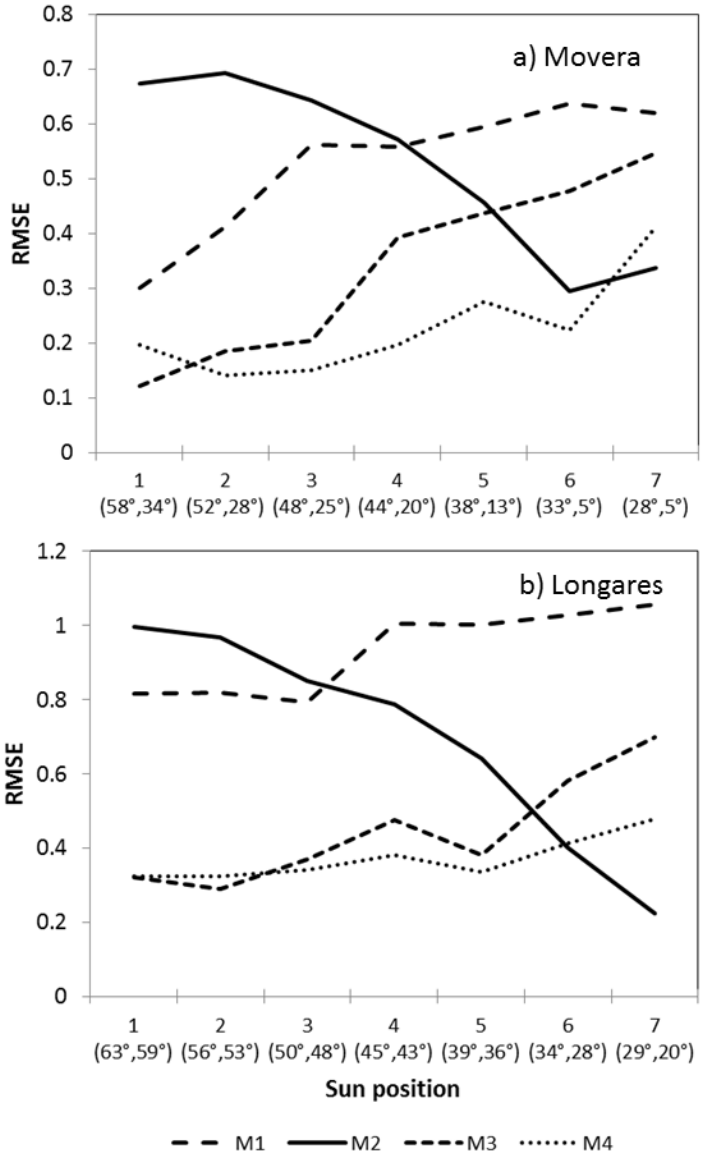

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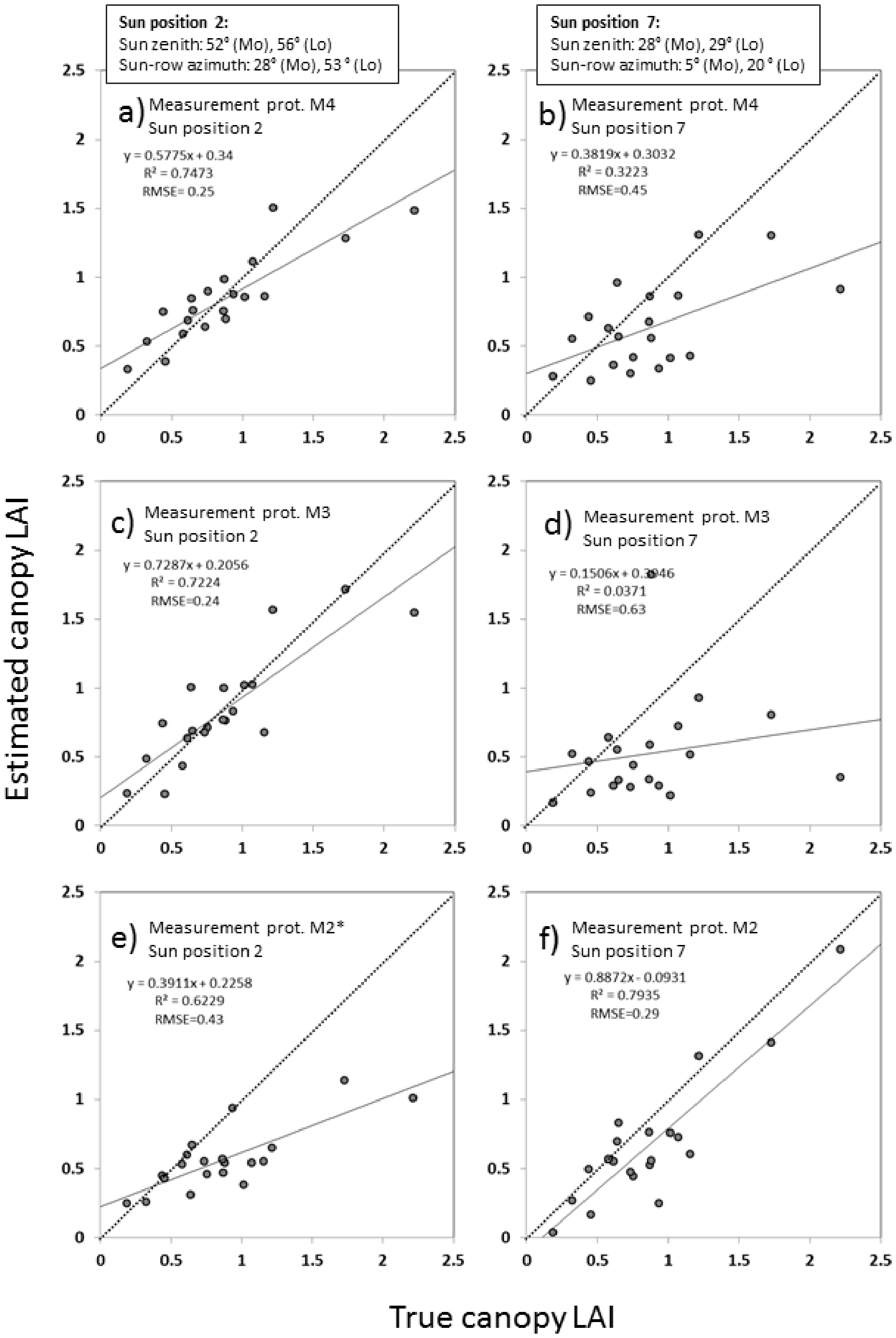

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