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RESEARCH ARTICLE

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Feasibility of using pyranometers for continuous estimation of ground cover fraction in table grape vineyards

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Abstract

This paper evaluates the feasibility of using pyranometers for continuous estimation of ground cover fraction (GCF) at remote, unattended sites. Photographical techniques were used for measuring GCF (GCF_{ref}) at a table grape vineyard grown under a net. Daily pyranometer-driven GCF estimates (GCF_{pyr}) were obtained from solar radiation measurements above and below the canopy. For GCF_{pyr} computation, solar radiation was averaged for two hours around solar noon (midday periods) and for daylight periods (8:00 to 18:00 Universal Time Coordinated). GCF_{pyr} and GCF_{ref} (daylight periods) showed a good agreement: mean estimation error, 0.000; root mean square error, 0.113; index of agreement, 0.967. The high GCF attained, the large measurement range for GCF and the presence of the net above the table grape were the likely reasons for the good performance of GCF_{pyr} in this crop despite the short number of pyranometers used. Further research is required to develop more appropriate calibration equations of GCF_{pyr} and for a more detailed evaluation of using a short number of pyranometers to estimate GCF.

Additional key words: shading; PAR; *Vitis vinifera*; global solar radiation.

Introduction

Several biophysical parameters exist to characterize plant growth. For the aerial part, the most commonly used are: 1) leaf area index (LAI), *i.e.* the one-sided green leaf area per unit ground surface area; 2) fraction of absorbed photosynthetically active radiation (fPAR) also known as midday canopy light interception fraction, *i.e.* the ratio of ground measured PAR to full sun PAR subtracted from 1; and 3) ground cover fraction (GCF), *i.e.* the fraction of the ground covered or shaded by the crop canopy near solar noon as observed from directly overhead (Allen *et al.*, 1998; Williams & Ayars, 2005; Allen & Pereira, 2009). LAI can be measured through destructive leaf sampling; some indirect methods have been developed but they generally require measurements to be taken under overcast skies (Li-COR, 2010) or sophisticated equipment which strongly limits their application at unattended sites. On the other hand, the fPAR and the GCF can be considered as practically identical (Ayars *et al.*, 2003). This paper assumes this similarity thereafter.

GCF (and therefore fPAR) is well related to such paramount meteorological variable as global solar radiation. GCF is also directly related to several plant characteristics such as the canopy size and the proportion of solar radiation captured by plants for potential conversion into evapotranspiration (Allen *et al.*, 1998; Williams & Ayars, 2005). For row crops, GCF has been used as an auxiliary variable in the estimation of water

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Abbreviations used: fPAR (fraction of absorbed PAR); GCF (ground cover fraction); GCF_{pyr} ('pyranometer-driven' estimated ground cover fraction); GCF_{ref} (measured ground cover fraction used as a reference); IA (index of agreement); LAI (leaf area index); MEE, mean estimation error; MSE_s, systematic mean square error; MSE_u, random mean square error; PAR (photosynthetically active radiation); RMSE, root mean square error; Rs_b (global solar radiation below the canopy); Rs_a (global solar radiation above the canopy); UTC (Universal Time Coordinated).

use (Goldhamer & Synder, 1989; Allen & Pereira, 2009) or development of crop coefficient (Kc) curves as a function of GCF as the main variable (Williams & Ayars, 2005; López-Urrea *et al*., 2012; Marsal *et al*., 2014). Williams & Ayars (2005) stated that the dynamics of GCF along the season explained better the dynamics of Kc than that of LAI. Therefore GCF turns up as a useful and relatively simple variable to be determined in a variety of experimental research works performed at a field plot scale to assist in the interpretation of the experimental results.

Several procedures have been used to determine GCF at that scale such as a grid inscribed on a wooden board beneath the crop canopy (Williams & Ayars, 2005), digital photography and digital image processing software (Williams & Ayars, 2005; López-Urrea *et al*., 2009; Bojaca *et al*., 2011) and solarimeter bars such as ceptometers due to the close similarity between GCF and fraction of light interception by crop canopies (Ayars *et al*., 2003; Moratiel & Martínez-Cob, 2012, 2013). Please note that solarimeter bars are also commonly used for LAI determination but this application requires a detailed knowledge of extinction coefficients appropriate for the studied canopy as well as the separate measurement of direct and diffuse solar radiation thus making LAI determination quite complex.

All of these methods are quite accurate and reliable. However they are relatively time consuming, require the work of a qualified technician and, in the case of digital photography, may require an intensive maintenance work. Thus they can be difficult to be applied when the measurements must be performed at remote field sites. In these situations, an automatic relatively cheap and low maintenance instrumentation could be more suitable. A set of pyranometers connected to a datalogger could be adequate at those remote sites. Ideally, the number of pyranometers should be such that the spatial variability of GCF can be adequately sampled. However, setting pyranometers at ground level at commercial farms or unattended sites is quite risky due to the farm activities. Under these situations, the pyranometer sets should include a limited number of sensors and should be placed as close to the rows as possible to avoid any damage by the farm machinery. Such setting may provide biased results and then a complete calibration is absolutely mandatory to correct such bias.

The objective of this paper was to evaluate the feasibility of using a set of few pyranometers for continuous estimation of ground cover along the crop season for a table grape vineyard under netting. The estimated GCF values were compared to those derived from a 'reference' method, digital photography, in order to check the feasibility of the proposed 'pyranometer-driven' method and to eventually calibrate it.

Material and methods

This work was performed from 2007 to 2009 at a commercial table grape (*Vitis vinifera* L.) vineyard (2.0 ha) located at the Santa Bárbara Farm (Caspe, Zaragoza, northeast Spain). Following the weather network SIAR (MAGRAMA, 2013), the long-term annual average meteorological conditions (2004-2013) in the area were: annual precipitation, 319 mm; mean air temperature, 15.2°C; mean global solar radiation, 199 W m^{-2}; and annual reference evapotranspiration (FAO Penman-Monteith method), 1456 mm.

The geographical coordinates of the farm were 41°16'N latitude, 0°02'W longitude, and 147 m elevation above the sea level. The 4-year old (in 2007) seedless cultivar 'Crimson' was grown in the vineyard; this cultivar was grafted on 'Richter 110' rootstock (*V. berlandieri* × *V. rupestris*). Row direction was approximately northwest to southeast (about 113° azimuth). Row and vine spacing were 3.5 and 2.5 m, respectively. The vineyard was trained on an overhead trellis system such that the canopy developed within 2.0 to 3.0 m above ground, *i.e*. the vertical canopy width was about 1.0 m at the maximum development stage. Thus total vine height was about 3.0 m. A net made of a thread warp of high-density white polyethylene (Criado and López, Almería, Spain) covered the vineyard to protect it from hail, birds, and insects. This netting was translucent with individual pores of 12 mm^2 (2.2 mm × 5.4 mm). It was placed at a height of 3.0 m above ground level just above the canopy level (Fig. 1). The vineyard was fully irrigated with a drip irrigation system which included one lateral in each row of vines with integrated self-compensating emitters of a discharge of 2.2 L h^{-1} spaced 0.5 m. Daily drip irrigation from May to September, herbicide and fertilizer were applied following the farm manager's criteria. Vines were winter pruned. An additional summer pruning of the shoots in a strip 0.5 m wide between vine rows was performed in 2009 around veraison, to allow a better penetration of light in the canopy thus enhancing berry quality and color uniformity. Suvočarev *et al*. (2013) provides further details of the vineyard.

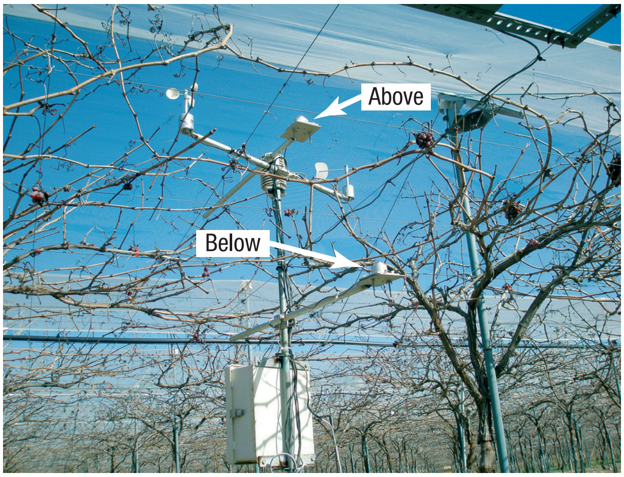

Figure 1. View of the trellis system of the table grape vineyard before budbreak and location of the two pyranometers below and above the canopy to calculate the 'pyranometer-driven' ground cover fraction (GCF_{pyr}).

Two methods for obtaining GCF were applied:

— Method 1, considered the 'reference' method, used digital imagery and post processing (Blanco *et al.*, 2010). Pictures were taken at six different sites in the vineyard by a digital camera (Olympus, model µ810, Tokyo, Japan) that was placed on the ground and focused upwards to a quarter of the whole spacing of a vine (1.25 m × 1.75 m). The images were processed with the GIMP program (available at www.gimp.org), by selecting exactly the quarter of the vine area. The program transformed the picture into black (leaves and branches) and white (clear screen) pixels (Fig. 2). The histogram of the black and white pixels was calculated, giving a value of the fraction of the black pixels which represents the GCF at the site. The digital photography as used here does not require taking the images at a specific time of a day. For each measurement date, the six GCF values at the sites were averaged to get the 'reference' GCF value (GCF_{ref}) for that date. The total number of available GCF_{ref} values was 22 in 2007, 13 in 2008, and 28 in 2009. The images were taken every 7 to 14 days, from 15 February to 26 September in 2007, 26 March to 15 October in 2008, and 23 March to 9 November in 2009.

— Method 2 consisted of two pyranometers (Kipp & Zonen, model CM3, Delft, The Netherlands), located one above the canopy just below the net, at about 2.8 m above the ground, and the second one completely below the canopy, at about 2.0 m above the ground and 0.5 m horizontal distance from the vine row (Fig. 1). Both pyranometers were placed over a horizontal plate set at the end of an aluminium bar facing toward southwest (about 223° azimuth). Due to the housing the sensor measured the solar energy received from the whole hemisphere (180° field of view). The spectral sensitivity of the sensor was 300 to 3000 nm. Both sensors were connected to a datalogger (Campbell, model CR10, Shepshed, Leicestershire, UK) that monitored them and continuously recorded hourly averages of global solar radiation above (Rs_a) and below (Rs_b) the vine canopy from 15 February 2007 to 20 November 2009. The average values of Rs_a and Rs_b from 11:00 to 13:00 Universal Time Coordinated (UTC) (midday) and from 8:00 to 18:00 UTC (daylight) for each day were used to get the 'pyranometer-

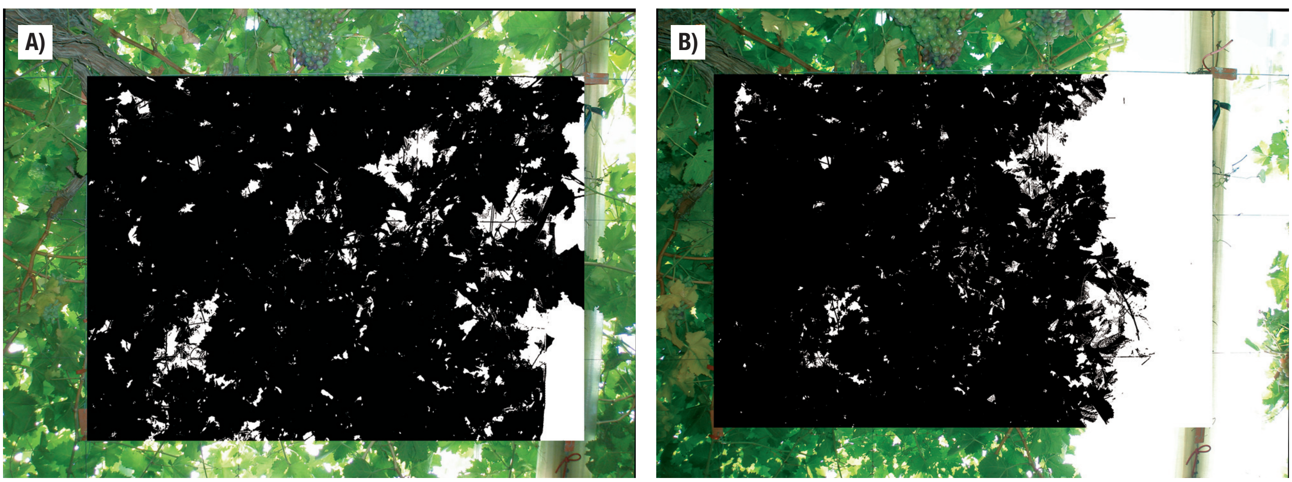

Figure 2. Images taken by digital camera after post-processing for the measurement of reference ground cover fraction (GCF_{ref}). A, 28 July 2009; B, 5 August 2009.

Table 1. Phenology of the table grape vineyard under study. Values between parenthesis are days after budbreak

Year	Budbreak	Flowering	Veraison	Harvest
2007	13 Mar (0)	23 May (71)	30 Jul (139)	1 Oct (202)
2008	5 Mar (0)	20 May (76)	7 Aug (155)	20 Oct (229)
2009	23 Mar (0)	20 May (58)	22 Jul (121)	5 Oct (196)

driven' GCF at this site (GCF_{pyr}) following this expression:

$$GCF_{pyr} = 1 - Rs_b / Rs_a \quad [1]$$

A total of 865 GCF_{pyr} values were available for each averaging time period.

Values of GCF_{pyr} were compared to those of GCF_{ref} computing several statistics (Willmott, 1982): mean estimation error (MEE), root mean square error (RMSE), index of agreement (IA), and systematic (MSE_s) and random mean square error (MSE_u). Regression analyses and curve fitting for eventual calibration of the 'pyranometer-driven' method were also performed using the application SigmaPlot v. 11.2 (Systat Software, San Jose, CA, USA). Please note that GCF_{ref} values correspond to the fraction of intercepted PAR while GCF_{pyr} values correspond to fraction of intercepted global solar radiation. Thus, that calibration is intended to correct the biases due to the limited number of sensors used as well as the different radiation transmitted through leaves depending upon the radiation wavelength (Kiniry, 1999).

Results

The phenology of the studied table grape vineyard reflects to some extent the different average meteorological conditions for the different years causing the inter-year variability in development (Table 1). Thus the length of crop cycle during 2008 was larger than the other two years despite an earlier bud breaking date due to cooler temperatures in 2008. The average daily air temperature from April to September was 20.5°C for 2008, while it was 20.8°C for 2007 and 22.0°C for 2009. Likewise, 2008 was more humid (355 mm total annual precipitation) than 2007 and 2009 (259 and 315 mm, respectively).

Fig. 3 shows the dynamics of the 63 GCF_{ref} values and the 865 GCF_{pyr} values for each of the two averaging time periods, 11:00 to 13:00 (GCF_{pyrM}) and 8:00 to 18:00 (GCF_{pyrD}) at the table grape vineyard. It can be seen that high values of GCF (above 0.85-0.90) were attained for each season as expected for an overhead trellis system. These maximum GCF values were attained around the second half of June, about one month after flowering.

At first glance, a general good agreement was observed between the GCFpyr (regardless of averaging time period) and the GCF_{ref} values except from August to November 2009 as it will be discussed later in the Discussion section. A general good agreement was also observed between the two averaging time periods for GCF_{pyr} although the midday averaging time period provided lower GCF values than the daylight averaging time period for days for which true GCF was low, *i.e.* during fall and winter.

There were 54 available dates with both GCF_{ref} and GCF_{pyr} values. Fig. 4 and Table 2 present the regression and error analyses of the comparison between GCF_{ref} and GCF_{pyr} for both averaging time periods. These analyses were in accordance with the results displayed in Fig. 3. The agreement between GCF_{ref} and GCF_{pyr} was relatively high as shown by a coefficient of determination (R^2) above 0.84, the low values of MEE and RMSE, and the high values of IA. Nevertheless the regression intercepts and slopes were significantly different than 0 and 1, respectively ($p = 0.05$). When the solar radiation values recorded by the pyranometers were averaged for the whole daylight period (8:00 to 18:00 UTC), there was an improvement in the performance of the 'pyranometer-driven' GCF method as compared to the midday period (11:00 to 13:00 UTC).

Discussion

A general good agreement was observed between the GCF_{pyr} (regardless of averaging time periods) and the GCF_{ref} values. The largest disagreement between GCF_{ref} and GCF_{pyr} was observed from August to November 2009. As mentioned earlier, the farmer performed an

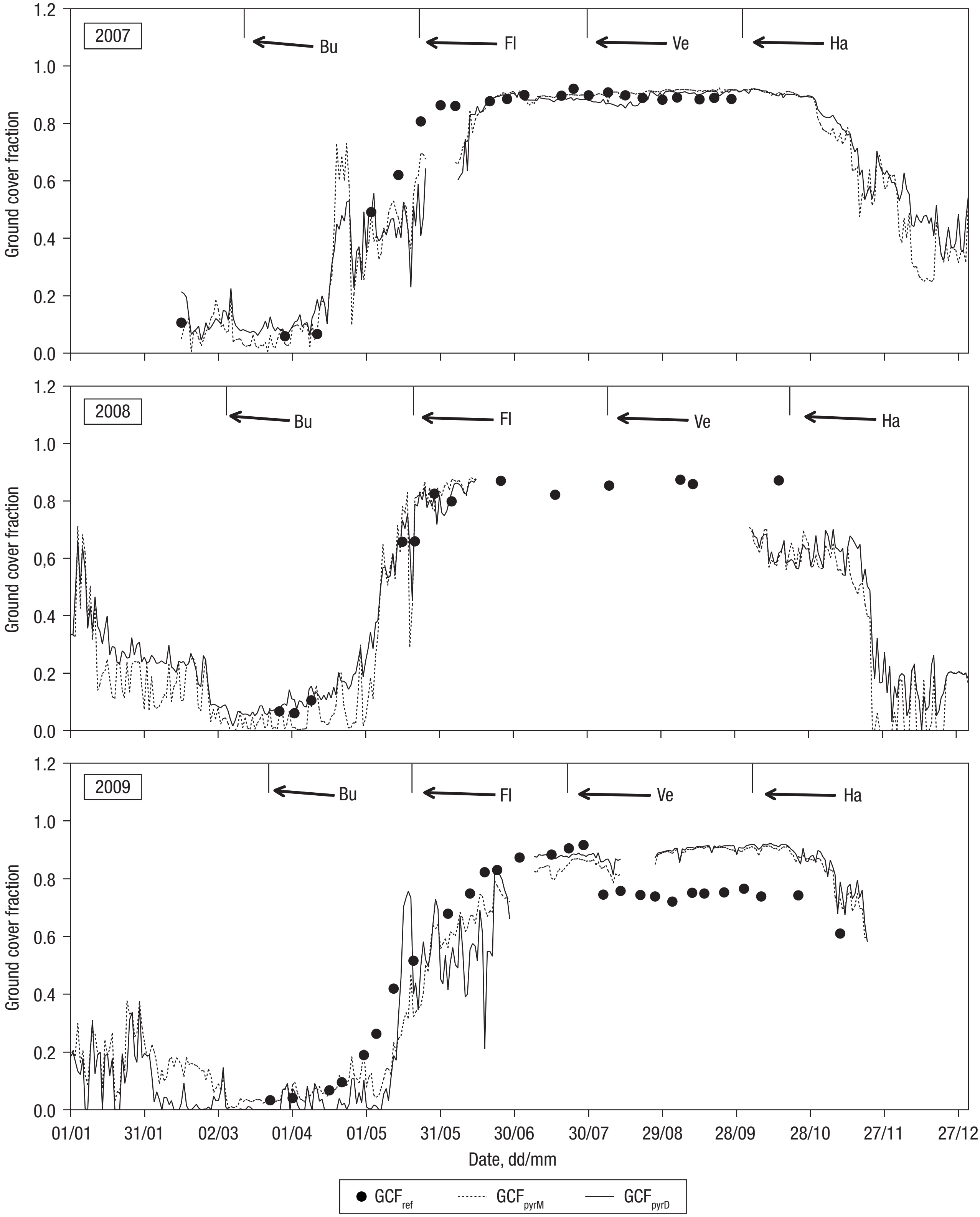

Figure 3. Dynamics of 'reference' (GCF_{ref}) and 'pyranometer-driven' ground cover fraction for both averaging time periods, 10:00 to 12:00 Universal Time Coordinated (UTC) (GCF_{pyrM}) and 8:00 to 18:00 UTC (GCF_{pyrD}). Bu, budbreak; Fl, flowering; Ve, veraison; Ha, harvest.

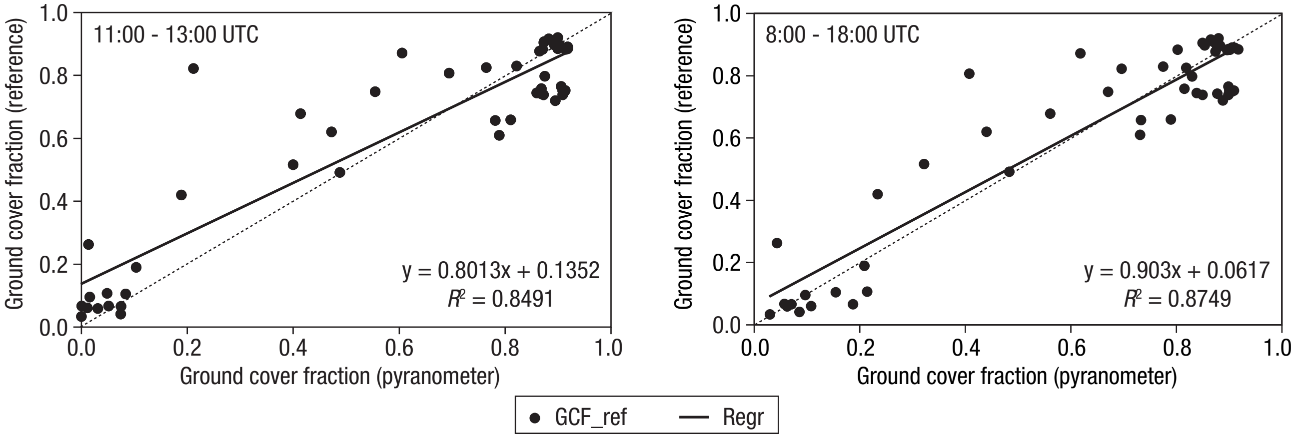

Figure 4. Simple linear regression between 'pyranometer-driven' (GCF_{pyr}) and 'reference' (GCF_{ref}) ground cover fraction for both averaging time periods, 11:00 to 13:00 Universal Time Coordinated (UTC) and 8:00 to 18:00 UTC.

Table 2. Error analyses of the comparison between 'reference' (GCF_{ref}) and 'pyranometer-driven' (GCF_{pyr}) ground cover fraction for both averaging time periods, 11:00 to 13:00 Universal Time Coordinated (UTC) and 8:00 to 18:00 UTC. N, sample size; MEE, mean estimation error; RMSE, root mean square error; MSE_u and MSE_s, random and systematic mean square error, respectively; IA, index of agreement, unitless

Averaging time[a]	N	MEE fraction	RMSE fraction	MSE_u (fraction)^2	MSE_s (fraction)^2	IA
11:00-13:00	54	–0.012	0.139	0.019	0.000	0.955
8:00-18:00	54	0.000	0.113	0.013	0.000	0.967

[a] Universal Time Coordinated.

additional summer pruning of the shoots in a strip 0.5 m wide in 2009 around veraison, just in the middle of the distance between two consecutive rows (Fig. 2B). This strip only represented 14% of the total row spacing. Comparison of Figs. 2A and 2B displays the limited size of that summer pruning in 2009, just located at one end of the scenes taken by the digital camera. In other words, when the open spaces (*i.e.* those not occupied by leaves) in the optical camera images were random, only due to the free crop development, the pyranometer below the canopy was able to match reasonably well the ground cover fraction evolution (Fig. 3).

A general good agreement was also observed between the two averaging time periods for GCF_{pyr}. Nevertheless, the GCF_{pyrM} values tended to provide lower GCF than the GCF_{pyrD} values, mainly for days of low GCF, *i.e.* for winter and fall days. While the GCF_{ref} values do not depend on time period within a given day, the GCF_{pyr} values do. As shading changes along the day, it was hypothesized that the GCF_{pyr} values derived from average midday solar radiation (11:00 to 13:00 UTC) could be biased as only one sensor at a fixed spot was used below the canopy, and thus may only represent shade at just a reduced portion of the total area corresponding to each vine. Thus the GCF_{pyr} values derived from average daylight solar radiation (8:00 to 18:00 UTC) could represent better the true GCF; that averaging daylight period could be seen as if the pyranometer below canopy has been moved around the vine during the midday readings because of the change of the angle of the solar radiation during that period. Sun angle above the horizon increases along the season (Allen *et al.*, 1998). Subsequently, the bias introduced by using just the midday hours reduced for summer days and the agreement between GCF_{pyrM} and GCF_{pyrD} improved for high GCF values. The uncertainty of GCF_{pyrM} values was also affected in part by the occurrence of scattered clouds running over the study area during midday hours. Thus the agreement between GCF_{pyrD} and GCF_{pyrM} was slightly better for 2007 which was the sunniest year: annual average of daily solar radiation was 17.6 MJ m^{-2} day^{-1}, while it was 17.1 and 16.7 MJ m^{-2} day^{-1} in 2008 and 2009, respectively.

All mean square errors were random (Table 2), meaning that the uncertainty in the 'pyranometer-driven' GCF values was completely random in this case. Nevertheless, the regression parameters were statistically different than 0 (intercept) and slope (slope), indicating that calibration of GCF_{pyr} is completely required. Naturally, using only one pyranometer below the canopy did not warrant an accurate measurement of the shade below the table grape canopy. But the averaging of values for the whole daytime period likely compensated in part this problem. This daylight averaging (8:00 to 18:00 UTC) could be seen as if the pyranometer was being moved around the shaded area and thus representing somewhat better the GCF.

The reliability of the 'pyranometer-driven' GCF method may depend to some extent on the magnitude of the true GCF. This method was less reliable when applied to a peach orchard with a much lower true GCF (data not shown). It must be also pointed out that the table grape vineyard was under a net which reduced the incoming global solar radiation above the canopy by around 15% (Moratiel & Martínez-Cob, 2012). This net was covering the whole vineyard and thus the shading effect of the net was uniform anywhere in the vineyard. This shading effect could explain in part the good agreement observed between GCF_{ref} and GCF_{pyr} for the table grape vineyard even for early crop development stages when GCF was still low. It is quite likely that more differences between GCF_{ref} and GCF_{pyr} would have been observed under a similar table grape orchard but without the presence of the net.

The regression analysis requires that the regression parameters are computed minimizing errors in respect to the dependent variable. In addition, this work aimed to use directly the regression equation as calibration equation. Subsequently, a simple regression of GCF_{pyr} (daylight period 8:00 to 18:00 UTC) as independent variable versus GCF_{ref} as dependent variable was performed in order to get a calibration equation for the 'pyranometer-driven' method at the table grape vineyard (Fig. 4). The regression parameters obtained clearly indicates that this calibration equation must be applied to 'correct' the 865 GCF_{pyr} values obtained in this work to get a reliable continuous curve of GCF for the table grape along the season. This calibration should correct the bias of GCF_{pyr} due to the limited number of sensors and the different transmitted radiation through leaves depending upon radiation wavelength (Kiniry, 1999).

The use of a short number of pyranometers placed near the rows of trees was necessary to avoid the sensors being damaged by the machinery in these remote, relatively unattended locations. Of course, this short number of pyranometers (without replicates) highly reduces the possibilities for recording accurate values of GCF. The 'pyranometer-driven' method is biased towards overestimation of GCF. Thus calibration is mandatory. The good performance of the 'pyranometer-driven' method in the table grape vineyard even for development stages with low GCF indicates that this method can also provide good results for periods when the sun angle above the horizon is low (*i.e.* during winter, early spring and late fall) likely in part to the presence of the net.

Further research is required. Because this work was a first attempt to evaluate the feasibility of the 'pyranometer-driven' method, a short number of measurements were taken. The number of replications for GCF_{pyr} should be increased. Better calibration equations should be developed taking into account the whole range of variability of GCF.

In summary, the results obtained with the 'pyranometer-driven' method improved when the solar radiation was averaged for daylight periods (8:00 to 18:00 UTC) as compared to averaging only for midday periods (two hours around solar noon). For the daylight averaging period, the 'pyranometer-driven' method showed a good agreement with the GCF_{ref} values as shown by MEE = 0.000, RMSE = 0.113, IA = 0.967 although regression parameters were significantly different than 0 (intercept) and 1 (slope) ($p = 0.05$) indicating that calibration is necessary. This agreement was likely due to several factors: a) the use of a net above the vineyard; b) the almost complete GCF attained; c) the measurements taken along the whole season, *i.e.* along a whole range of values of sun angle above the horizon. It is clear that a calibration of the 'pyranometer-driven' method is required to take into account the bias and the different transmission of light through leaves depending upon radiation wavelength. While the 'reference' method provides more accurate estimations of GCF, these results suggest that the 'pyranometer-driven' method could be used as an alternative approach when GCF must be obtained at remote, relatively unattended sites located at extension or commercial farms. Further research is required. Measurements should be taken along all the season and the number of replications for both GCF_{ref} and GCF_{pyr} should be increased. Better calibration equations should be developed.

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