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Evaluation of photosensitive films for light measurements in the fruiting zone of grapevine canopies

A. Bontempo[1), 2)], J. Smith[1)], M. Brandt[1)], E. Peterlunger[2)] and M. Stoll[1)]

[1)] Hochschule Geisenheim University, Department of General & Organic Viticulture, Geisenheim, Germany
[2)] Department of Agricultural, Food, Environmental and Animal Sciences, University of Udine, Udine, Italy

Summary

The potential influence of fruit exposure and canopy manipulations on grape berry composition is well recognized. However, a simple and low cost method for quantifying the amount of light reaching the fruiting zone is lacking. The objective of the present study was to test the application of a commercial system of photosensitive azo-dye coated plastic films for characterizing light conditions within grapevine canopies. The fading rates of three films of differing light sensitivity were initially monitored in a fully exposed position, and these all showed a linear or near linear relationship with radiation measured by an adjacent global solar radiation sensor. When mounted in the fruiting zone of a vertically trained cool climate 'Riesling' vineyard for two periods following early and late leaf removal treatments, the films were able to quantify the change in light exposure within the fruiting zone. Total radiation values calculated using an on-site calibration or manufacturer´s equation were comparable. While some consideration is needed with regard to the choice of film sensitivity and positioning within the canopy, these initial evaluations suggest these light sensitive films can provide a simple and accurate method for characterizing light conditions and quantifying cumulative radiation within the fruiting zone.

K e y w o r d s: light interception; microclimate; solar radiation; training system; light sensitive dyes.

Introduction

The management of light interception is an important aspect of wine grape production, and many viticulture practices are linked to the control of light interception by foliage and the internal light environment of grapevine canopies (Smart *et al.* 1980). The effect of sunlight exposure on berry composition, and on subsequent wine quality, is of direct practical interest to grape growers as there is significant scope to modify the amount and timing of light exposure through trellis design and within season canopy manipulations. However, without quantifying the effects of canopy management practices on fruit light exposure, it is difficult to make more than empirical links between changes in fruit microclimate and specific responses of fruit and wine composition.

Individual sensors or arrays of sensors can be used for direct light measurements, but to integrate light exposure over longer time periods, and provide sufficient measurement points to overcome heterogeneity, multiple sensors and associated data logging equipment are required (eg. Casadesus *et al*. 2011). An alternative approach to quantifying solar radiation involves the use of light sensitive dyes. Price *et al.* (1995), for example, demonstrated the application of light sensitive papers (Sunprint Kit, University of California, Berkeley) in grapevine canopies with rolled tubes placed in the fruiting zone of vertically trained and minimally pruned canopy systems for periods of 5 min. The pattern of colour change after development was used to characterize potential differences in bunch light exposure within the two canopy types, but the high light sensitivity of the paper would suggest it is less suited for the characterization of canopy light conditions over more extended periods. For longer term measurements, an alternative approach has been to stack sheets of diazo paper and calibrate total radiation received against the number of layers exposed (Friend 1961). Although it has subsequently been shown that the exposed layer number correlates more closely with light intensity than cumulative radiation exposure (Bardon *et al.* 1995), other authors still report useful correlations with instrument based canopy and light measurements, and suggest the method is still of value for characterizing canopy effects on light exposure where other options are not available (Buckley *et al.* 1999).

A second class of compounds that have been used to quantify light exposure are the azo dyes. These pigments undergo photo-decomposition to colourless bi-products, and when coated on transparent plastic films the change in absorbance following light exposure can be measured using a spectrophotometer (Yoshimura *et al.* 1990). The dyes are also water-fast, and following an initial demonstration in green algae containing water by Yoshimura *et al.* (1990), an early application of the films was the characterization of under water light environment around mangroves (Hirano *et al.* 1996). Subsequent studies have seen these films used

Correspondence to: Dr. J. Smith, Hochschule Geisenheim University, Department of General & Organic Viticulture, Von-Lade-Str. 1, 65366 Geisenheim, Germany. Fax: +49-(0)6722-502-140. E-mail: jason.smith@hs-gm.de

to measure variability in greenhouse light distribution (FITZ-RODRÍGUEZ *et al.* 2011), light distribution under forest canopies (KAWAMURA *et al.* 2005), modelling light interception of tomato leaves (HIGASHIDE 2009), and measuring the light exposure of apples as a predictor of fruit temperature (YAMADA *et al.* 2004).

The objective of the present study was to test a viticulture application for the current commercial system of these photosensitive azo dye based films. This system consists of a hand-held spectrophotometer and three different film options ranging in sensitivity from one to seven days to fade in full sunlight. For characterizing light conditions within grapevine canopies, such films are of potential interest as they provide a simple, weather resistant and low cost option for large numbers of cumulative light measurements. In this study, the fading rate of the three films were compared against a reference pyranometer, and for situations where users may not have access to local solar radiation data or their own sensors, a simple comparison was also made with calibrations provided by the manufacturer. In addition, the medium sensitivity film was then used in vertically trained 'Riesling' vineyard to determine if changes in bunch light exposure following standard cool climate leaf removal practices could be quantified with films mounted in the fruiting zone.

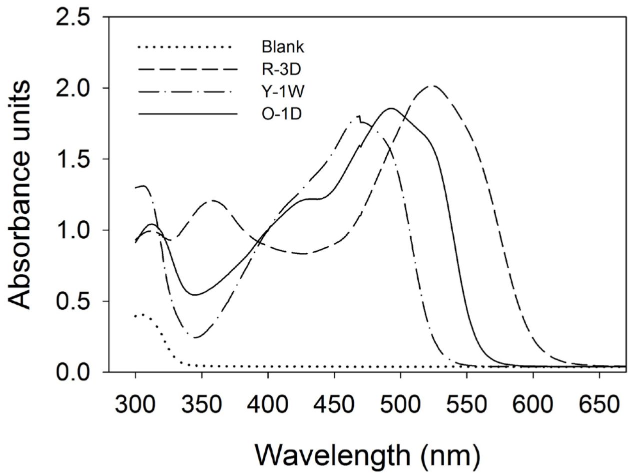

Fig. 1: Absorbance spectra of the three light sensitive film types, and blank tricellulose acetate substrate.

Material and Methods

Light sensitive films: The "OptoLeaf" light sensitive films used in the study were supplied by Taisei-Environmental & Landscape Group, Tokyo, Japan. Films of three differing light sensitivities are available, and are identified according to the colour of their respective dyes and approximate fading time in full sunlight. These are "O-1D", the most sensitive orange 1 day film with an absorbance maximum at 493 nm, "R-3D" the medium sensitivity red 3 day film with an absorbance maximum at 521 nm, and "Y-1W" the least sensitive yellow 7 day film with approximately one week of exposure time available in full sunlight and absorbance maximum at 468 nm. The absorbance spectra of each film, together with that of the blank tricellulose acetate backing films, is shown in Fig. 1.

Film calibrations: Two outdoor calibrations were undertaken with samples of the three film types and compared with calibration equations provided by the manufacturer in their supporting printed material (unpublished). The manufacturer calibrations provide an option for conversion to global solar radiation ($MJ \cdot m^{-2}$) or photosynthetically active radiation ($\mu mol \cdot m^{-2} \cdot s^{-1}$), and for each film there is an equation for winter, summer and spring/autumn. As the rate of fading is influenced by ambient temperature, and the provided calibrations were produced locally in Japan, the manufacturer suggests using an on-site calibration if higher accuracy is required. For this reason we did not make any direct statistical comparison with their equations and ours. However, as site specific calibrations may not always be possible, we do present a comparison of radiation values calculated from the manufacturers´ summer calibration with our own version in the subsequent field component of this study. For each calibration, each film type was cut into four replicates pieces of 20 x 35 mm and mounted in re-useable plastic slide frames (Kaiser Fototechnik, Buchen, Germany). An aluminium stand with horizontal level adjustment was built to support the mounted films at a height of 110 cm, and then placed 3.3 m from a weather station located at the Geisenheim University campus. Readings were made at regular intervals with the portable spectrophotometer (D-Meter RYO-470 Taisei-Environmental & Landscape Group, Tokyo, Japan) until the films faded below 0.6 absorbance units. The absorbance of films below the readers range were recorded with a laboratory spectrophotomer (SPECORD® 50 PLUS, Analytik Jena, Germany). In accordance with the manufacturer's instructions, the film absorbance was then expressed as a percentage of initial absorbance for use in subsequent calibrations. Radiation received between each measurement interval was calculated from the global solar radiation data recorded by the weather station pyranometer at 15 min. intervals (CMP6, Kipp and Zonen, Delft, Netherlands).

UV filter, orientation and background screening: To test the influence of film orientation, UV screening, and background reflected radiation, three additional calibration comparisons were conducted with the R-3D film. The first calibration compared films mounted horizontally and according to the manufacturer's instructions (dye side facing the sun) with films mounted in reverse so the triacetylcellulose backing film faced the sun. An additional set of films was screened with a UV filtering plastic with a cut-off at 400 nm. The second calibration compared films mounted in the recommended orientation to the sun with films that had either a black or white shade cloth background placed immediately under the films. The white shade cloth grade was specified to block up to 60 % of photosynthetically active radiation and the black cloth 80 % (TVV Transport- und Versand-Verpackungen UG & Co. KG, Nattheim, Germany).

Field evaluations: The intermediate sensitivity R-3D film was selected to compare fruiting zone light exposure following leaf removal treatments in an established 'Riesling' vineyard during 2016. Early and late leaf removal treatments were applied on July 5 and August 25 respectively, with the manual removal of approximately 75 % of leaves from the fruiting zone on both sides of the canopy. Based on measurements from the ground to mid-bunch height on a random selection of vines, the fruit was distributed between 81 and 126 cm, with 50 % of the bunches between 96 and 110 cm. The trial was arranged in a randomized block design with four replicates, and 18 vines per treatment. A third group of non-defoliated vines served as the control for both defoliation treatments. The field site was located near Rüdesheim am Rhein (49°59'20" N, 7°55'56" E), approximately 1.7 km west from the weather station used for the film calibrations. The vines were planted at a spacing of 105 cm with 205 cm between rows and pruned to a single cane (10-12 nodes) and trained with a vertical shoot positioned (VSP) trellis system to a canopy height of 220 cm aligned in a north-south orientation.

The films were deployed between July 29 and August 11 to compare the control and early defoliation treatments, and again between August 25 and September 12 to compare the control with both defoliation treatments. The absorbance of each film was recorded prior to exposure, and then measurements were made in the field to record the progressive rate of fading with the portable spectrophotomer. The films were positioned within the canopy using 6 mm diameter metal grapevine training rods that were pushed into the ground below the vine and clipped to a fixed trellis wire. Metal clips were attached to the top southern side of each rod, and then used to hold the film pieces horizontally in the fruiting zone at a height of 108 cm. The location of the rods was adjusted slightly if needed to avoid direct shading from bunches but any leaves in the immediate vicinity of the films were left in position. Based on measurements from the ground to mid-bunch height on a random selection of vines, the films were on average located just below the third quartile of the fruiting zone at 110 cm. The films were installed at every second vine, giving 9 per replicate and 36 in total per treatment. On each occasion, sets of films were also exposed adjacent to the weather station to produce concurrent calibrations as described in the previous section.

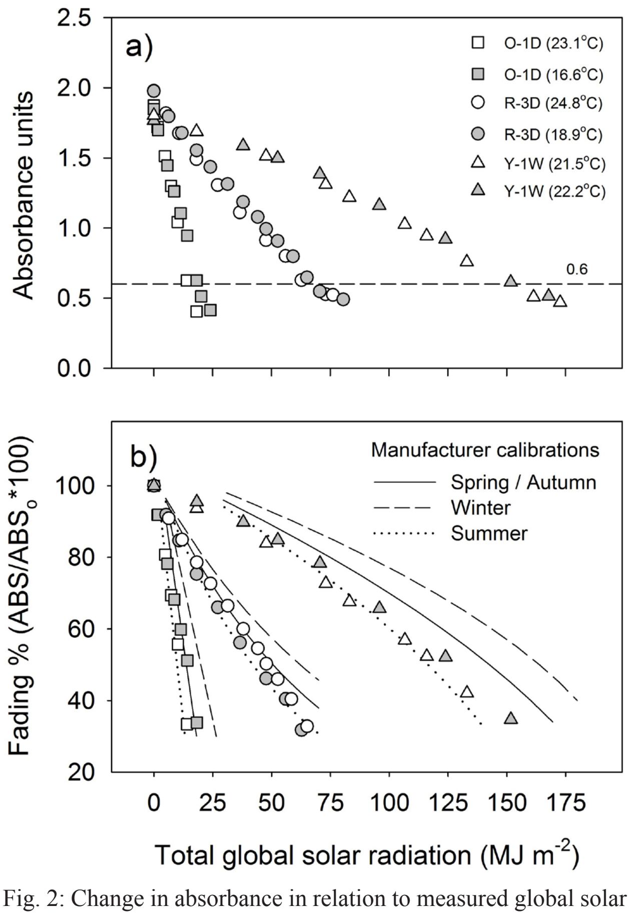

Fig. 2: Change in absorbance in relation to measured global solar radiation during the two calibration periods for each film with mean daytime temperature during each calibration indicated in the legend (**a**), and comparison with manufacturer's calibrations after conversion to fading percentage and removal of values below 0.6 absorbance units (**b**).

For the first deployment period, additional measurements were made with a plant canopy analyser (LAI 2200, LiCOR Biosciences, Lincoln, Nebraska, USA) to characterise the potential light exposure at each film position. In diffuse light conditions on three evenings between August 1 and August 8, a reading was made with the optical sensor held immediately above the position of each film in the trial. A 180° view cap was installed such that only the canopy visible perpendicular and to the south of the film was in the field of view of the optical sensor. The transmittance values for each of the 5 rings were used to provide an independent assessment of the directional effect of the defoliation treatment on film exposure, and the diffuse non-interceptance (DIFN) value was used to compare to the film radiation values. The DIFN value ranges from 0 to 1 (range from no sky visible to no foliage visible) and only requires the assumption of no light scattering by the canopy. Statistical analysis was undertaken with Genstat V18 (VSN International, Hemel Hempstead, UK).

Results

Calibration comparisons: Above the recommended absorbance threshold of 0.6 absorbance units, the rate of colour loss from all three films exhibited a near linear relationship with the amount of global solar radiation measured at the weather station (Fig. 2a). For the O-1D and Y-1W films the relationship was still linear at the final readings of 0.4 and 0.5 absorbance units respectively, suggesting that values below the recommended absorbance could be used and included in calibrations. Under the partly cloudy conditions that were experienced during the two calibration periods, the O-1D faded in just over 1 day, the R-3D between 4 and 5 and the Y-1W films between 8 and 9 days. When converted to a relative fading value, with the remaining absorbance expressed as a percentage of the starting value (F%), and removing data for films below 0.6 absorbance units, the film responses to intercepted radiation in the present study were comparable with the manufacturers summer calibration for each film type (Fig. 2b). Although a statistical comparison has not been made with the manufactures calibration, the rate of fading for both the O-1D and R-3D was slightly, but significantly faster for the two warmer calibration runs. The fading response of the Y-1W films, which was best explained by a second degree polynomial, did not differ between the two calibration runs.

Table 1

Effect of film orientation, UV filtering and background screen colour on film fading

Film orientation and UV filtering		
Control	y = -0.0232x+1.85[a]	-
Reversed	y = -0.0234x+1.86	ns[b]
UV filter	y = -0.0128x+1.85	$P < 0.001$
Background screen colour		
Control	y = -0.0218x+1.77	-
White	y = -0.0246x+1.77	$P < 0.001$
Black	y = -0.0210x+1.78	$P < 0.01$

[a] y = absorbance, x = MJ m^{-2} [b] difference of slope from control films, ns indicates not significant.

Mounting films in reverse orientation, with the non-dye coated surface of the backing film facing the sun, caused a reduction in the rate of fading (Tab. 1). As the transmission of UV light through the backing films decreases through 50 % at 310 nm, and is absorbed completely by 280 nm, the small reduction in the rate of colour loss in reverse orientation suggests minimal influence of solar radiation below these wavelengths. However, filtering out all of the UV component below 400 nm with a filter placed in front of the films slowed the rate of fading by approximately 45 %. When the effects of reflected radiation were evaluated with different coloured shade cloth, fading was accelerated above a white background by about 6 % compared to control films. A black background caused a slight reduction in the rate of fading of 0.5 % compared to films with no background (Tab. 1).

F i e l d e v a l u a t i o n s : When the films were positioned within the fruiting zone in the field trial following the early defoliation treatment, the absorbance of the most exposed film fell to 0.53 and below the recommended value of 0.6 absorbance units by August 8 (Fig. 3c). Further films faded below this value when the final measurement was made on August 11 (not shown), while a slight unexplained increase in absorbance was observed for some films. Cumulative radiation values were therefore only calculated until August 8, although the single value below 0.6 was in this case retained in the data-set. Using a calibration equation derived from films that were exposed between July 27 and July 31, which included a set of readings with a mean absorbance of 0.54, the amount of radiation measured in the fruiting zone of the non-defoliated treatment was 16 MJ m^{-2} compared to 21.1 MJ m^{-2} for the early defoliation treatment (Tab. 2). For our calibration the relationship between film fading and cumulative radiation could be adequately described by simple linear regression forced to a y-intercept (F%) of 100, but the calculated value was otherwise very similar to the radiation values obtained using the manufacturers summer calibration. Although there was no significant difference between the two treatments, these values represented 9.3% and 12.2% respectively of the 172 MJ m^{-2} of radiation recorded at the weather station.

The initial rate of fading following the second deployment was more rapid with less overcast skies, and from the third measurement date onwards a number of films in more exposed positions needed replacing. By September 12, this had extended to exchanging 52 out of the total 108 films and it became difficult to manage the field spectrophotometer readings such that films could be replaced before excessively fading. As for the first deployment, the calculations have therefore been restricted to shorter period from August 25

Table 2

Effect of early defoliation on July 5, and late defoliation on August 25 on the subsequent exposure of R-3D films mounted in the fruiting zone of vertically trained Riesling. Values show comparison between the manufacturers summer calibration and on-site calibration produced during each deployment period.

	July 29 to August 8		August 25 to September 2	
	Cumulative radiation (MJ m^{-2})	Proportion of incident radiation (%)	Cumulative radiation (MJ m^{-2})	Proportion of incident radiation (%)
Manufacturers calibration[1]				
Control	15.9	9.2	19.4	12.4
Early defoliation	20.4	11.8	22.5	14.4
Late defoliation	-	-	30.0	19.2
	ns		ns	
On-site calibration[2,3]				
Control	16.0	9.3	21.0	13.4
Early defoliation	21.1	12.2	24.3	15.5
Late defoliation	-	-	31.5	20.1
	ns		$p < 0.05$	

[1] MJ m^{-2} = 265.6 - 131.6 × (Log_{10}(F%)), [2] MJ m^{-2} = (F% - 100)/ - 1.22,
[3] MJ m^{-2} = (F% - 100)/ - 1.13.

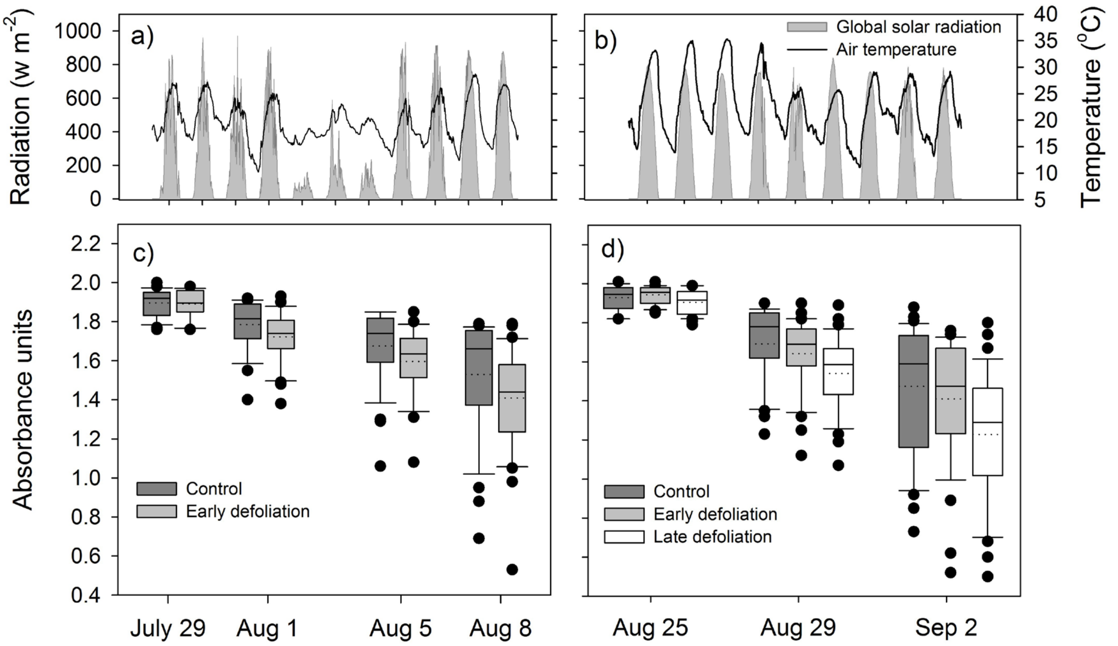

Fig. 3: Overview of weather conditions and change of film absorbance from deployment following the early defoliation treatment on July 5 (a,c), and late defoliation treatment on August 25 (b,d).

to September 2 (Fig. 3d). This data set again included some films that had faded below an absorbance of 0.6, and four replicate points with a mean of 0.52 absorbance units were therefore included in the calibration regression. Despite higher temperatures during the second deployment, with an average maximum of 30.8 °C compared to 24.6 °C in the first measurement period, the calculated values were again very similar for the concurrent calibration (August 26 to 29) and the manufacturers summer calibration (Tab. 2). For the values calculated from our calibration we also found a significant difference between the late defoliation and control treatment at 21.0 and 31.5 MJ·m^{-2} for the deployment period. The total radiation above the canopy was 156 MJ·m^{-2} with 13.4, 15.5 and 20.1 % received by the films in the control, early defoliation and late defoliation treatments respectively.

For the canopy light measurements made with the LAI-2200 during the first deployment, light transmittance measured by ring 5 was significantly higher than the control in the early defoliation treatment, but not at the higher elevation angles from ring 4 to ring 1 (Fig. 4a). There was also no significant difference in the mean DIFN value between the two treatments (0.084 for the control, and 0.111 for early defoliation), but there was a clear positive relationship between the DIFN value and the total amount of radiation received by the film at that point (Fig. 4b).

Discussion

In this initial evaluation of light sensitive films for quantifying light in the fruiting zone of grapevine canopies, it was found that the OptoLeaf medium sensitivity R-3D films were able to characterize differences in the canopy light environment, and provide an absolute measure of cumulative light exposure changes following the application of a commonly used defoliation practices. In the first measurement period

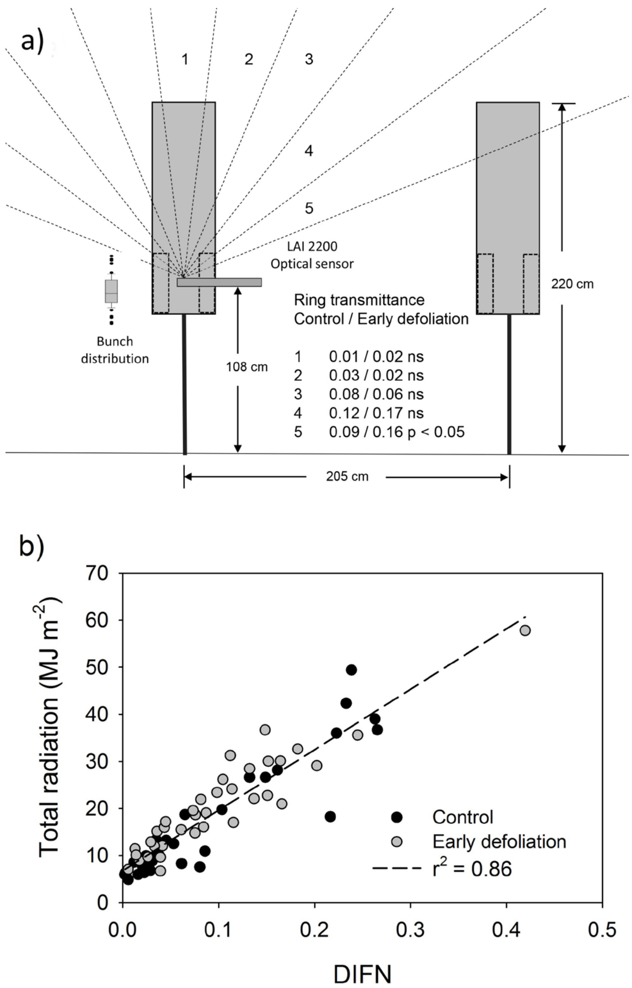

Fig. 4: Scale diagram showing position of canopy light measurements and mean transmittance for each ring of the LAI 2200 optical sensor (a), and relationship between the DIFN parameter at each film position and total radiation received by the corresponding film in the first field deployment (b).

following an early defoliation treatment, the films in the control treatment received 9.3 % of the incoming radiation, which is consistent with the upper range indicated by daily estimates for bunches located at a similar position within the fruiting zone of VSP canopies (Louarn *et al.* 2008). For the early defoliation treatment the average film exposure was 12.2 %, and while not significant, deploying the films 3 weeks after the treatment may have reduced exposure differences due to lateral regrowth. For the second set of measurements immediately following the late defoliation treatment, the amount of light exposure was increased with the control treatments receiving 13.4 % compared 20.1 % for the late defoliation treatment. With this second set of measurements the difference in total radiation calculated using our own concurrently run linear calibration was also significant. While for the same calculations with the manufacturers calibration was not significant, the total radiation values were close, and with the significance reflecting a slight difference in the output from the linear and exponential calibration equations.

Despite the lack of a consistent statistical difference between the treatments applied, there was a strong linear relationship between the canopy analyzer DIFN value and calculated radiation received by the film at each point. For the R-3D film calibrations there was also a strong linear relationship with received radiation and good agreement when the manufacturers calibration was used to calculate the amount of radiation received by the same films. The canopy analyzer transmittance values indicate that the lack of large treatment differences, particularly when 75 % of the leaves were removed from the fruiting zone, may instead reflect the position of the films. While the films were located within the area of defoliation, the transmittance data show the defoliation only made a significant difference to the amount of sky visible from lower sensor ring with a field of view from 22 to 35° elevation from horizontal. Although the films were positioned within the fruiting zone in this study, our main interest was to gain experience with using the system in a viticulture context. If taking the next step to make a representative measure of the entire fruiting zone, additional consideration would be needed for film positioning and mounting.

For the other film types tested in the study, the O-1D film is possibly too sensitive for viticulture applications unless deployed for very short periods or in heavily shaded canopies. The rate of fading also appeared more sensitive to temperature than the other two films. The Y-1W films showed the least difference between the two calibrations, maintained a near linear response below the 0.6 absorbance value recommend by the manufacturer, and may be more suitable if longer term integration of canopy light conditions is required. For the R-3D films deployed within the canopy, fading below the minimum absorbance value occurred in about 10 days when weather conditions included a number of overcast days. The rate of fading was faster in periods of full sunshine, suggesting that the R-3D films may be better suited to shorter deployments of 5-10 days and then removed as a group before the absorbance of the most exposed films falls below 0.6 absorbance units. The reason for the slight increase in film absorbance on some occasions was not identified. However, as the stated accuracy of portable spectrophotometer is ± 0.05, and up to ± 0.1 absorbance units under some conditions, this apparent absorbance rise may reflect a slight difference in the zero point recorded with the blank film at each date.

While we found a better fit with a simple linear regression for the R-3D films, the calibrations provided by the manufacturer produced radiation values in accordance with our results, and could be used for converting the change in film absorbance to cumulative radiation where radiation data is not available. Regular checks are needed to prevent the most exposed films fading below the recommended 0.6 absorbance units, but in practice this can be difficult to avoid when many films are deployed in the field. For more general applications, using values down to 0.5 absorbance units would not greatly impact on the interpretation based on our findings, and including some lower points in the calibration allows the linearity below 0.6 to be checked. As the portable spectrophotometer will still provide an absorbance value down to 0.5, it also provides some leeway for using films that have faded further than intended. The proximity of a weather station made calibrating a relatively straightforward process in the present study, and if higher accuracy is required for research purposes, corrects for local weather conditions and also provides the option to include films with lower absorbance values in the calibration.

As a final point regarding future studies, the nearly equal contribution of wavelengths above and below 400 nm to film fading suggests more information about light conditions between sites could also be obtained with partial screening of the film with UV-filtering plastic. Films could also be placed against an opaque surface to screen reflected radiation and provide a directional measure of radiation. Although our calibrations were made above a similar ground cover and at a similar height to the films in the vineyards, pyranometers are screened from reflected radiation below the horizon so measured values with non-screened films may differ slightly depending on the amount of radiation reflected from the vineyard floor.

Conclusion

Overall, the light sensitive films used here appear to provide a reliable approach for estimating and evaluating cumulative light exposure within the fruiting zone of grapevine canopies. The films can provide an absolute measure of global solar radiation received over the deployment period, or this value can be expressed as a percentage of total above canopy radiation if a more standardized value is required. For research applications the films provide an option for large numbers of spatial light measurements, and we suggest the best approach is to deploy a full set of films and then retrieve them all as the most exposed film approaches an absorbance threshold defined by the lower range of the calibrations. The manufacturer recommends a value of 0.6 for this absorbance threshold, but for the R-3D films we used for most of this study, values down to 0.5 did not deviate substantially from the linear relationship with total radiation. For industry applications, the films could be suited for survey type assessments across vineyards, and provide a method of linking a fruit composition to a longer term measure of the canopy light environment. Although limited to just a few simple comparisons here, we did not find a large difference between radiation calculated with the locally produced calibration and the summer calibration provided by the manufacturer, and suggest the latter could still be used in the absence of local radiation data.

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