Gurrea-Ysasi, G.; Blanca Giménez, V.; Fita Fernández, IC.; Fita, A.; Prohens Tomás, J.; Rodríguez Burruezo, A. (2018). Spectral comparison of diffuse PAR irradiance under different tree and shrub shading conditions and in cloudy days. Journal of Photochemistry and Photobiology B Biology. 189:274-282. https://doi.org/10.1016/j.jphotobiol.2018.10.023

Manuscript Details

Manuscript number	JPHOTOBIOL_2018_633
Title	Spectral comparison of diffuse PAR Irradiance under different tree and shrub shading conditions and in cloudy days
Article type	Full length article

Abstract

Spectral Solar Photosintetically Photon Flux Density (PPFD) (380 to 780 nm) reaching the surface of a plant in different lighting conditions has been analyzed in order to better understand the different photosynthetic performance of plants depending on their spatial situation and the vegetation surrounding. A comparison between the shadow of several trees in a sunny day and the case of a cloudy day in an open space has been studied. Three isolated trees (a palm tree, an olive tree and a shrub oleander) and a tipuana grove have been studied. The study has been developed in Valencia (Spain) during January and February 2017. A portable Asensetek Standard ALP-01 spectrometer with a measurement wavelength range of 380 to 780 nm, has been used. Conditions with higher PPFD received are found to be, apart from those of a sunny day, those for cloudy day (with a spectral maximum in the Green region of the spectrum), and those for individual trees and shrub shadows in a sunny day (with a spectral maximum in the Blue region). The case in which less amount of PPFD is received is that under the shadow of tipuana grove (with a spectral maximum in the Infrared region of the spectrum). In fact the order of magnitude in which the PPFD in a cloudy day exceeds the PPFD under the tipuana grove shade is up to 20.

Keywords	spectral irradiance, photosynthesis, shadows, clouds, PPFD

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HIGHLIGHTS

- Different light conditions affect photosynthesis plants performance.
- Cloudy day is compared with shadows in sunny day.
- Shadow under isolated trees is compared with grove one.

Spectral comparison of diffuse PAR Irradiance under different tree and shrub shading conditions and in cloudy days

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ABSTRACT

Spectral Solar Photosintetically Photon Flux Density (PPFD) (380 to 780 nm) reaching the surface of a plant in different lighting conditions has been analyzed in order to better understand the different photosynthetic performance of plants depending on their spatial situation and the vegetation surrounding.

A comparison between the shadow of several trees in a sunny day and the case of a cloudy day in an open space has been studied. Three isolated trees (a palm tree, an olive tree and a shrub oleander) and a tipuana grove have been studied.

The study has been developed in Valencia (Spain) during January and February 2017. A portable Asensetek Standard ALP-01 spectrometer with a measurement wavelength range of 380 to 780 nm, has been used. Conditions with higher PPFD received are found to be, apart from those of a sunny day, those for cloudy day (with a spectral maximum in the Green region of the spectrum), and those for individual trees and shrub shadows in a sunny day (with a spectral maximum in the Blue region). The case in which less amount of PPFD is received is that under the shadow of tipuana grove (with a spectral maximum in the Infrared region of the spectrum). In fact the order of magnitude in which the PPFD in a cloudy day exceeds the PPFD under the tipuana grove shade is up to 20.

Keywords: spectral irradiance, photosynthesis, shadows, clouds, PPFD.

INTRODUCTION

Light is of great importance for the development of most living organisms. The beneficial effects of solar radiation on people and plants are well known [1-3] and sunlight is the most important physical factor for photosynthesis by plants [4]. However, humans and plants perceive light differently. While humans are more sensitive to the green area of the visible light spectrum (497 to 570 nm), compared to the red (600 to 700 nm) and blue (400 to 499 nm) spectrum areas, which is known as the photopic response curve [5], the plants use the part of the spectrum between 400 and 700 nm to transform the energy of the sun into chemical energy through photosynthesis. This part of the spectrum is known as Photosynthetically Active Radiation (PAR) and represents approximately 45% of the total Global Solar Radiation [6].

For that reason, when measuring light, different magnitudes are used in the case of humans and plants. In this way, lux are used as the usual unit of illuminance for humans, but if lux were used for plants there would be an underestimation of the blue and red area of the spectrum, since the human eye does not efficiently perceive the light in these regions of the spectrum. However, plants, using their foliar pigments such as chlorophylls, xanthophylls, carotenoids and anthocyans, are very efficient in the use of blue and red regions for photosynthesis [7].

Thus, the quantity used to measure the amount of light that is received by plants is the Photosynthetic Photon Flux Density (PPFD), defined as the amount of PAR radiation that reaches the plant or, more precisely, the number of photosynthetically active photons that reach a given surface every second [8-11]. Therefore, the unit of measurement is $\mu mol / m^2 \cdot s$.

It is a proven fact that the total absence of sunlight completely inhibits the plants from performing the photosynthetic process [12]. Also, the plants, or parts of the plant, that

are under the shade, in a sunny day, receive a lower amount of irradiance reaching the surface of its leaves. This results in a global decrease of the photosynthesis efficiency of shaded plants. On the other hand, many species have evolved by increasing their photosynthetic efficiency in order to optimize the low amounts of light captured by their photosynthetic tissues [13].

Furthermore, when the sky is covered with clouds, photosynthesis is affected [14, 15]. In those days, all the radiation that reaches the surface is diffuse radiation. However, the effect of clouds on photosynthesis is not as clear as the case of total absence of sunlight that can occur at night. Although, in general, the presence of clouds decreases the productivity of plants due to the reduction of total irradiance [16], it has also been shown, in different studies, that the solar radiation of cloudy days also allows photosynthesis. In fact, in certain cases, the efficiency of this process is greater than in clear day conditions [17].

However, the mechanism by which the efficiency of the photosynthetic process is increased on cloudy days is not fully understood [15]. It may be caused by the combination of the action of plants and the intrinsic characteristics of diffuse radiation on a cloudy day [18]. In this respect, there are several studies that hypothesize on the biological action of plants for the explanation of this phenomenon [19-22].

Several parameters are studied to evaluate the effects of solar diffuse radiation on plant photosynthesis. Among the most revealing parameters, the Photosynthetic Photon Flux Density (PPFD), the B / R ratio (being B, the amount of radiation from blue region of the spectrum and R the amount of region from the red one), and the R / IR ratio (being IR de amount of radiation from infrared part of the spectrum), are specially relevant in order to study which part of the spectrum is absorbed by plants under different conditions. With respect to the B / R parameter, different studies show that the ratio

between B and R varies between 0.5 (for direct radiation) and 0.95 for diffuse radiation [23]. In general, it has been observed that, once the sun passes through the tree canopy, the spectral region of G (green region) and IR is transmitted or reflected, whereas the region of B and R is mostly absorbed [24, 25], and these regions are therefore the most important for the correct photosynthesis efficiency [26, 27].

The objective of the present study is to compare the spectral component of diffuse radiation in different conditions, including both the case of a completely cloudy day, and also various cases of tree shades in clear sky conditions. In addition, in the case of shadows in clear day conditions, isolated trees (specifically a palm tree, an olive tree and a shrub oleander) have been compared with the case of a tipuana grove. Analyzing the differences in the spectral characteristics of the diffuse irradiance under different shade conditions can contribute to understand the photosynthetic performance of plants in different light conditions.

MATERIALS AND METHODS

Measurement conditions

In this study, measurements have been made in the campus of the Universitat Politècnica de València, placed in the city of Valencia (39°28'N, 0°22'W.). Measures for sunny days were made on 25th January and 14th February 2017. Three measures were taken each day: one at 10 h, another at 13 h and a third at 16 h (local time). The measurements for sunny days were always carried out under totally clear sky conditions.

<Table 1>

Measures for cloudy days were made on 24th January and 3rd February 2017. Three measures were taken each day at the same hours than for sunny days: 10 h, 13 h and 16 h (local time). Measurements were made in open space (not under a tree) and in totally cloudy sky conditions (sun completely covered by clouds). The meteorological conditions are shown in the Table 1.

Shading conditions. Trees description

To characterize the diffuse irradiance received in different shade conditions, on a sunny day, measurements have been made in the shadow cast by two isolated trees, a shrub and under the shade of a group of trees (grove). In particular, the individual trees and shrub under study were: a palm tree (*Phoenix canariensis*), an olive tree (*Oleaeuropaea*), and an oleander shrub (*Nerium oleander*). The grove consisted of a group of tipuana (*Tipuanatipu*) trees (Figure 1).

The species mentioned encompass a range of plant sizes and canopy sizes and structures, and they are very common for ornamental and/or shading purposes in Mediterranean gardens [28]. P. canariensis palm, original from the Canary islands, has adapted very well to Mediterranean conditions and exhibits a similar performance to the date palm (P. datilifera). Furthermore, olive tree and oleander are very representative of the native Mediterranean flora. Finally, tipa is original from South America but its fast growth and covering canopy has spread its use in gardens and carparks [29].

<Figure 1>

Equipment

A portable Asensetek Standard ALP-01 spectrometer (Asensetek, New Taipei City, Taiwan), with a measurement wavelength range of 380 to 780 nm, has been used. The range of illuminance is from 5 to 50000 lux, reliable chromaticity from 50 to 50000 lux, optical resolution of 8 nm, repeatability (2σ) for x, and <0.0005, integration time from 6 ms to 16 s and a storage range temperature from -10 to 45 °C. The spectrometer is calibrated at Asesentek Laboratories in New Taipei City, Taiwan with an uncertainty for measurement of ± 3%. [30].

All measurements, i.e. full sun, cloudy conditions, and the four plant shades, were recorded by placing the spectrometer at 1.5 m above the ground in horizontal position and in open space. Moreover, in the case of plant shades, the spectrometer was placed in the middle of the shadow provided by the canopies.

Light Parameters

For diffuse radiation characterization, the Photosynthetic Photon Flux Density (PPFD) has been measured. The PPFD corresponds to the number of photons that affect per unit area and per unit time. PPFD in a particular region of the spectrum is measured as $\mu mol \cdot m^{-2} \cdot s^{-1}$, where1mol = $6.023 \cdot 10^{23}$photons. For example, solar radiation reaching the ground surface at ground level on a clear day, has a PPFD value of approximately 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [17].

The following integrals have been considered for calculating PPFD (μmol / m²s) in each one of the PAR radiation spectrum:

$$PPFD_{IR} = \int_{701}^{780} PPFD(\lambda) d\lambda \quad (1) \qquad PPFD_{R} = \int_{600}^{700} PPFD(\lambda) d\lambda \quad (2)$$

169 $PPFD_G = \int_{500}^{599} PPFD(\lambda)d\lambda$ (3) $PPFD_B = \int_{400}^{499} PPFD(\lambda)d\lambda$ (4)

170 $PPFD_{UV} = \int_{380}^{399} PPFD(\lambda)d\lambda$ (5) $PPFD_{TOTAL} = \int_{380}^{780} PPFD(\lambda)d\lambda$ (6)

171 being IR, the infrared region, R, the red region, G the green region, B, the blue region
172 and UV the ultraviolet region.

173 In addition, the R/B and R/IR ratios have been calculated as:

174 $$R/B = \frac{PPFD_R}{PPFD_B} \quad (7)$$

175 $$R/IR = \frac{PPFD_R}{PPFD_{IR}} \quad (8)$$

176 We also define the PPFD Ratio between the shade and the sun (ER) as

177 $$ER = \frac{PPFD_{shadow}}{PPFD_{sun}} \quad (9)$$

178

179 being $PPFD_{shadow}$ and $PPFD_{sun}$ the values of the PPFD received under the trees shadow
180 or in full sun, respectively.

181

182 **RESULTS**

183 **Comparison of PPFD received in full sun and under different shade conditions**

184 As it was expected, the amount of PPFD received in full sun is much higher than that
185 received on a cloudy day and in the different shade conditions of the palm or olive trees,
186 oleander shrub or tipuana grove (Figure 2). This difference is much larger both at 10 h
187 and at 13 h than at 16h, in which these differences, although still maintained, are not so
188 pronounced.

189 <Figure 2>

190

191 When comparing different measurement hours, it can be observed that the maximum
192 values of PPFD, both at full sun and in the different shadows, occurs at 13h, reaching a
193 range of values [min, max], in decreasing order, of [0.94, 3.90] $\mu mol \cdot m^{-2} \cdot s^{-1}$ for full sun,
194 [0.40, 1.14] for cloudy day, [0.29, 0.63] for the palm tree shade, [0.11, 0.37] for the
195 oleander shrub shade, [0.09, 0.28] for the olive tree shade, and [0.05, 0.42] for the grove
196 shade.

197 Therefore, from the shadow situations analyzed, it is in the shadow position produced
198 on a cloudy day as a consequence of the clouds, where a greater amount of PPFD is
199 received at the surface, generally surpassing the shadow of individual palm (in a factor
200 of 1.8) or olive trees (in a factor of 4), oleander shrub (in a factor of 3) or tipuana grove
201 (in a factor of 2.7) on a sunny day. This means that a plant on a cloudy day (and in open
202 space) may have even more PPFD to perform its photosynthesis functions properly,
203 than on a completely clear day if that plant is in the shade of another tree.

204 However, it is remarkable, as seen in Figure 2, that, in the measure corresponding to
205 16h, the differences between the sun and the different shadows is not so accused and
206 indeed, according to the area of the spectrum, it becomes insignificant. The range [min,
207 max] of PPFD values received at 16h are, in decreasing order, [0.32, 1.30] for the full
208 sun, [0.20, 0.81] for the palm tree shade, [0.22, 0.53] for the olive tree shade, [0.17,
209 0.46] for the cloudy day, [0.19, 0.047] for the oleander shrub shade, and [0.06, 0.32] for
210 the tipuana grove shade.

211

212

213 **Comparison of PPFD received in each spectral region**

214 In the following section, the integrated value of PPFD received in each particular
215 spectrum region is compared. Taking a look at Table 2, the spectral PPFD received in
216 the full sun in the different specific regions of the spectrum reveals that the maximum
217 value is given at Red region (slightly higher than the case of Green region) with a value
218 at 13h of 358.24 ± 78.12 $\mu mol \cdot m^{-2} \cdot s^{-1}$. And the lower value is given at UV region at
219 16h with a value of 8.24 ± 1.84 $\mu mol \cdot m^{-2} \cdot s^{-1}$

220 <Table 2>

221 For the case of the shadow of a cloudy day (Table 3), it is observed that the integrated
222 value of PPFD received, reaches its maximum value, regardless of the time of
223 measurement, in the Green zone of the spectrum, with a maximum value of 107.87 ±
224 47.31 $\mu mol \cdot m^{-2} \cdot s^{-1}$ registered at 13h which turns to be lower than the value in full sun in
225 a factor of 3.32. In contrast, the minimum values are given, regardless of the time of
226 measurement, in the Ultraviolet zone, with an absolute minimum value of 4.28 ± 0.40
227 $\mu mol \cdot m^{-2} \cdot s^{-1}$ measured at 16h.

228 <Table 3>

229 When considering integrated values of PPFD measured for individual palm, olive tree
230 and the oleander shrub (Tables 4, 5 and 6), it can be concluded that, except in the case
231 of the palm tree at 16h, in all the cases, and for any measurement time, the maximum
232 values of PPFD received are given in the Blue zone of the spectrum. Specifically,
233 maximum values of 42.12 ± 19.97 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 47.49 ± 19.91 $\mu mol \cdot m^{-2} \cdot s^{-1}$ are
234 obtained for oleander shrub and olive respectively, and in both cases at 16h. These
235 values are lower than that received in full sun in a factor of 8.5 and 7.54 respectively.

The minimum values are again obtained in the Ultraviolet zone of the spectrum, with minimum values of 4.78 ± 1.28 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (at 16h), 5.04 ± 0.78 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (at 16h) and 3.14 ± 19.91 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (at 13h) for shrub, palm and olive respectively.

<Table 4>

<Table 5>

<Table 6>

In the case of the tipuana grove shade, the maximum values of PPFD received do not occur in the Green region (as in cloudy days) or in the Blue one (as in the case of individual trees), but in this case it occurs in the Infrared area, reaching a maximum value of 22.55 ± 3.42 $\mu mol \cdot m^{-2} \cdot s^{-1}$ recorded at 13h (Table 7) which is lower than the value received in full sun in a factor of 15.8. In contrast, minimum values of PPFD occur in the Ultraviolet zone, as in all other cases under study, with a minimum value of 0.95 ± 0.04 $\mu mol \cdot m^{-2} \cdot s^{-1}$ recorded at 10h.

<Table 7>

Analysis of ER Ratio

In order to compare the amount of PPFD reaching the plant, in the different shadow conditions, with respect to the case of full sun, and for each specific region of the PAR radiation spectrum, the ER in the different conditions and in the different hours has been analyzed. In addition, the value of the mean solar zenith angle for the measurement days is also shown at 10h, 13h and 16h.

It can be observed (Figure 3) that in the UV zone is where higher values of the ER are obtained, which implies that there is a lower filtering of the PPFD received in the shadows with respect to that received in the sun. It is also the region of the spectrum in which there are smaller differences between ER values measured at 10h and 13h and those measured at 16h.

<Figure 3>

Although, as mentioned, ER values are high, it is also true that the PPFD received in the UV region has the lowest values in relation to the other regions of the spectrum. In this region, the highest PPFD filtering occurs in shade conditions under tipuana grove (ER value of 0.05 at 13h), while the lowest PPFD filtering effect occurs under shadow conditions of one cloudy day (with a maximum ER value of 0.52 at 16h). This trend changes in the values measured at 16h (when the average solar zenith angle is close to 70 °) being the olive tree shade the one that filters the least amount of PPFD, with a value of ER > 0.6.

In the case of the Blue region of the spectrum, it can be observed that, in general, there is a higher filtering effect than in the UV zone (with lower ER values in all cases) and also the difference between the values measured at 10h and 13h begins to differ significantly from those measured at 16h. For both 10h and 13h, the higher filtering effect (lower ER value) occurs in shade conditions under the tipuana grove, reaching a minimum of 0.03 at 13h. In contrast, the lowest filtrate value is observed to occur in cloudy day conditions, as it was in the case of UV zone. At 16h, the situation is somewhat different, since, although the shadow of tipuana grove is maintained as the condition in which there is a greater filtering, at this time is the shadow of the palm tree, followed by the olive tree, which produce a lower filtering effect, reaching, in the case of the palm, an ER value of 0.81.

In the Green region of the spectrum, except for 16h, where ER values are very similar to the Blue region, the PPFD filtering effect continues to increase. In fact, with the exception of cloudy day case, the ER is always less than 0.2. It is also possible to observe how the effect of the oleander shrub and olive tree in this region of the spectrum is very similar in terms of PPFD filtering effect (at 13h the ER values are 0.04 and 0.06, respectively). Regarding the maximum values of filtering (lower ER), they occur in the case of tipuana grove shade (0.02 at 13h), while the lowest filtering effect (higher RE values) is for cloudy day at 10h and at 13h, while at 16h that minimum filtering value occurs under the shade of the palm tree (which even registers an ER> 1).

The Red region of the spectrum is where a greater PPFD filtering effect occurs in general for all cases. It is also the spectral region in which there is a greater difference between the ER measured at 10h or at 13h and the one recorded at 16h. In fact, for example, in the case of the palm tree, the ER at 16h is higher in a factor of 4.3 with respect to the palm tree at 13h. There is a greater filtering effect in the case of tipuana grove shade, which, in this region of the spectrum, reaches its absolute minimum ER value, with a value of 0.017. On the other hand, the lowest filtrating effect, at 10h and 13h, is for cloudy day shade, while at 16h, as in the Blue and Green regions, the lower value is for palm tree shade.

The trend in the Infrared region of the spectrum is very similar to what occurs in the Red zone, except that, in this case, unlike the other regions, at 10h and 13h, the highest value of filtrating effect occurs for the oleander shrub shade, instead of the tipuana grove shade.

Comparison between PPFD cloudy day / PPFD tree shadow

In order to analyze, in a quantitative way, the difference in the PPFD received in a cloudy day (in an open space) with respect to the rest of tree shadows in a sunny day,

the ratio between the amount of PPFD received in a cloudy day with respect to the amount of PPFD received in the shadow of the different types of tree studied has been represented. In addition, measurements were compared at 10h, 13h and 16h (Figure 4).

<Figure 4>

From the values of this ratio, it can be concluded that the PPFD received on a cloudy day (open space) exceeded that received in the shade of a tree on a sunny day. In particular, it can be observed that the greatest difference is given, for any time of the day, between cloudy and shady tipuana grove conditions. In fact, the ratio between PPFD in cloudy day and under tipuana grove reaches, at 13h, a maximum value of 20.6. In contrast, for the individual trees, that maximum value of the ratio is 2.11, 9.01 and 10.46 for palm tree, oleander shrub and olive tree, respectively. That means that the PPFD received on a cloudy day at 13h can be 21 times higher than that received in the shadow of a tipuana grove on sunny day, and the PPFD received at that time under tipuana grove shade can be 9.76, 2.28 and 1.96 times lower than that received under the shade of the palm tree, oleander shrub, and olive tree respectively. At 16h, the ratio between PPFD in cloudy day and PPFD under tipuana grove shade, is not so high, reaching a maximum of 3.33.

For the three individual trees under study (shrub, palm and olive), it can be seen, from Figure 4, that, at 10h and at 13h, the greatest difference with the cloudy day occurs under the olive tree shade, while in the case of the palm tree the differences are significantly reduced, even in some cases the PPFD received in this case is higher in comparison with the cloudy day. In particular, it can be observed that, at 13h, the ratio between cloudy days and olive tree shade varies between 3.00 and 10.46, while for the palm tree these values range from 1.38 to 2.11. At 16h the ratio for the palm tree

reaches values <1 ([0.55; 0.86]) which reflects that, at this time of day, the PPFD received in the shade of the palm tree is higher than that received on a cloudy day.

It can be observed that, for any time of day, the maximum differences between PPFD received in cloudy day with respect to the rest of the shadow conditions, occurs in the Red region of the spectrum, while the minimum difference occurs in the Infrared zone. Moreover, in this particular region of the spectrum, it is observed that there is no clear relationship between the PPFD received in cloudy day with respect to the other shadows, since at 10h and 13h, in this region, the ratio is higher in the case of the shrub, and olive than in the case of tipuana grove, whereas at 16h it is again greater for the case of tipuana grove than for the rest of individual trees.

Comparison of the R / I parameter

As mentioned in the previous section, the parameter R / I, may give an idea about the spectral irradiance shape. Therefore it is important to analyze and compare it in the different cases. As it can be seen from Table 9, except under tipuana grove shade, this value is always higher than one, reflecting a minimum for the irradiance in infrared region. In the case of tipuana grove shade, this value ranges from 0.28 to 0.61 according to the time of day, showing that, for these shade conditions, there is a greater amount of irradiance in the Infrared zone.

Comparison of the B / R parameter

With respect to the irradiance distributed between the Blue band and the Red band of the spectrum, it can be observed in Table 8 that, for all cases of tree shade (both individual trees and tipuana grove), the parameter B/R is higher than one. In particular, it reaches values of [1.30, 2.47] for the oleander shrub, from [0.76, 1.34] for the palm

357 tree, [1.22; 1.50] for the tipuana grove, and [1.34; 1.85] for the olive tree. These values
358 show the possible decreasing shape of the spectral irradiance curve with a maximum in
359 the Blue region and a minimum in the Red one.

360 However, in the case of the cloudy day, it can be seen that the values of the B / R
361 parameter are almost equal to one (ranging from [0.94; 1.01]), which shows that the
362 spectral irradiance, in this particular case, may be flatter, with not many difference
363 between the Blue zone and the Red zone of the spectrum.

364 <Table 8>

365

366 **DISCUSSION**

367 It is well known the influence of light quality on plants, particularly in their growth and
368 photosynthesis performance [31, 32]. There are studies on the influence of natural light
369 and artificial light on the growth of various species under direct lighting conditions
370 (sunny day or lamps in maximum intensity) [33, 34]. However, there are not so many
371 studies concerning the spectral quality of diffuse light (received in shady or sunless
372 conditions).

373 The present study is based on the analysis of incident radiation on the surface in
374 different shade conditions, including the shadow produced by a palm, an olive, an
375 oleander shrub and a tipuana grove in a sunny day, and comparing it with the diffuse
376 irradiance coming from a cloudy day in an open space. The goal is to compare the
377 quality of diffuse light in different conditions.

378 The PPFD in $\mu mol \cdot m^{-2} \cdot s^{-1}$, both at full sun and under different shade conditions, the
379 PPFD R ratio (between cloudy day and tree shadows) and the B / R and R/IR ratios
380 have been analyzed.

Regarding the value of PPFD received, it has been verified that conditions in which more quantity of $\mu mol \cdot m^{-2} \cdot s^{-1}$ are received are, after those of a sunny day, those for cloudy day, and those for individual trees and shrub shadows in a sunny day. The case in which less amount of PPFD is received is that under the shadow of tipuana grove. The spectral analysis reveals that the maximum values of PPFD are received in the green region for the cloudy day, in the blue region under individual trees shade, and in the infrared region under the tipuana grove. From these results it can be concluded that one of the differences between the cloudy day and the shade of the trees is the different region of the spectrum that reaches the surface in each case. In the case of trees, there is less absorption (and consequent reflection) of the green area of the spectrum (hence the green color of leaves), whereas in the case of cloudy day, the maximum PPFD is received in this region. For the tipuana grove, the particular arrangement of trees, covering the sun, both zenith and laterally, produces a great absorption of most of the spectrum, except the infrared zone, which has a very relevant presence in these shady conditions.

To analyze the filtering effect produced by the presence of trees or clouds, it has been calculated the ER, defined as PPFD ratio between $PPFD_{shadow}/PPFD_{sun}$. The trend of this ratio remains constant over most of the PAR radiation spectrum, so that, in the UV zone as well as in the Blue, Green and Red areas, the maximum filtering value of the incident direct radiation (which corresponds to a lower value of ER) occurs for the tipuana grove, while the minimum value is for the cloudy day. From all regions of the spectrum mentioned above, it has been found that in the Red one, the filtering effect is higher, reaching a value of 0.017 for the tipuana grove. Only in the infrared region, there is a change of that tendency. In that region of the spectrum, the highest value of the filtrating effect has been obtained for shrub shade, while the minimum value has

406 also been obtained for the cloudy day. The reason why the shade of trees exert a greater
407 filtering of incident radiation than clouds on a cloudy day can be that clouds, even
408 though they reduce the amount of global solar radiation (just the trees do), however,
409 they also increase the relative proportion of diffuse radiation reaching the surface
410 compared to the trees. As a result, a plant placed near the ground on a cloudy day will
411 receive more radiation than the same plant placed in the shade of a tree on a sunny day.

412 These results are measured at midday. However at 16h, the trends discussed in the
413 previous paragraph vary. Although the greatest filtering effect at that time is still the one
414 produced by the tipuana grove, the least filtering effect is no longer for cloudy day, but
415 occurs in the case of the palm and olive. At 16h the solar zenith reaches values close to
416 70 °, so that the sun's rays strike very oblique on the earth's surface. In these conditions,
417 we can conclude that the cloudy day does have a greater effect of filtering than the case
418 of the shadow of individual trees, in which similar amount of radiation as in the case of
419 full sun is received.

420 As mentioned in the previous paragraphs, it has been observed that a greater amount of
421 PPFD is received in a cloudy day with respect to other shade conditions (both individual
422 trees and tipuana grove cases). To quantify these differences $PPFD_{cloudy\ day}/PPFD_{shadows}$
423 has been analyzed.

424 It has been obtained that the order of magnitude in which the PPFD in a cloudy day
425 exceeds the PPFD under the tipuana grove shade is up to 20, whereas, regarding the
426 shadow of the individual trees, that value reaches 2, 9 and 10 for palm, shrub and olive
427 respectively. In this sense, it is clear the influence of canopy density of each individual
428 tree, being the olive denser, followed by the shrub and finally the palm tree, which is the
429 one with a lower canopy density. This lower density may be the reason why, as

discussed in the previous paragraph, the effect of filtering on the incident radiation is also lower.

Finally, with the objective of characterizing the Irradiance curve shape in all the cases studied, the value of R / IR and B / R parameters has been obtained.

For both, the R / IR and the B / R parameter, and with the exception of the tipuana grove case, values are always higher than unit, from which we can conclude that, in the spectral curves, in all cases, there will be a greater weight of the R zone in front of the IR and, also, of the zone B with respect to the R. that is the reason why the curves, in general, will probably show maximum values in the B zone and minimum values in IR zone. The exception is the case of the tipuana grove that shows an R / IR parameter less than unity, which implies that its spectral curve has a peak in the IR area.

For future works it should be interesting to add some measurements in other times of the year in order to compare the effects observed in this study. Additionally, a more complete set of tree species would be included (with different canopy densities, different height…)

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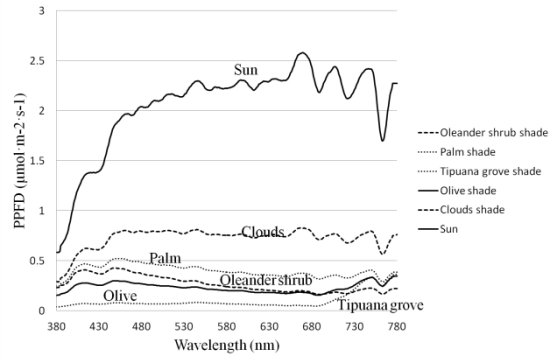
Figure captions

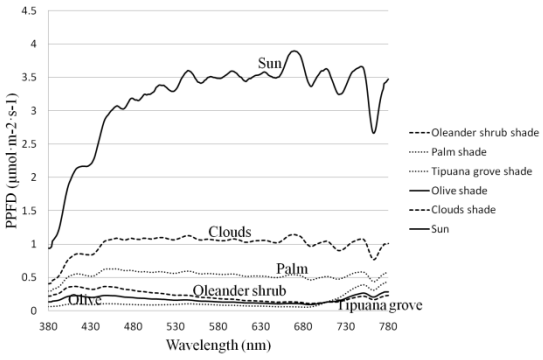
Figure 1. Palm tree (above left), olive tree (above right), oleander shrub (below left), and tipuana grove (below right) used for the present study.

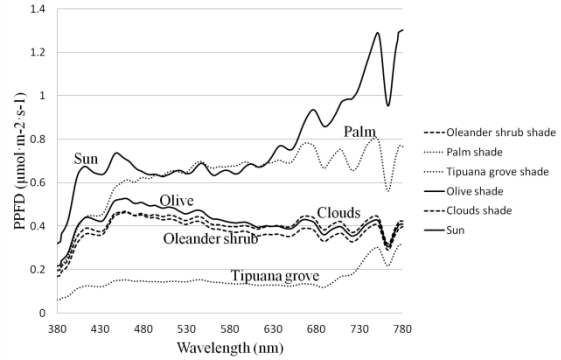
Figure 2. PPFD received under different conditions. left: at 10h; right: at 13h; bottom: at 16h.

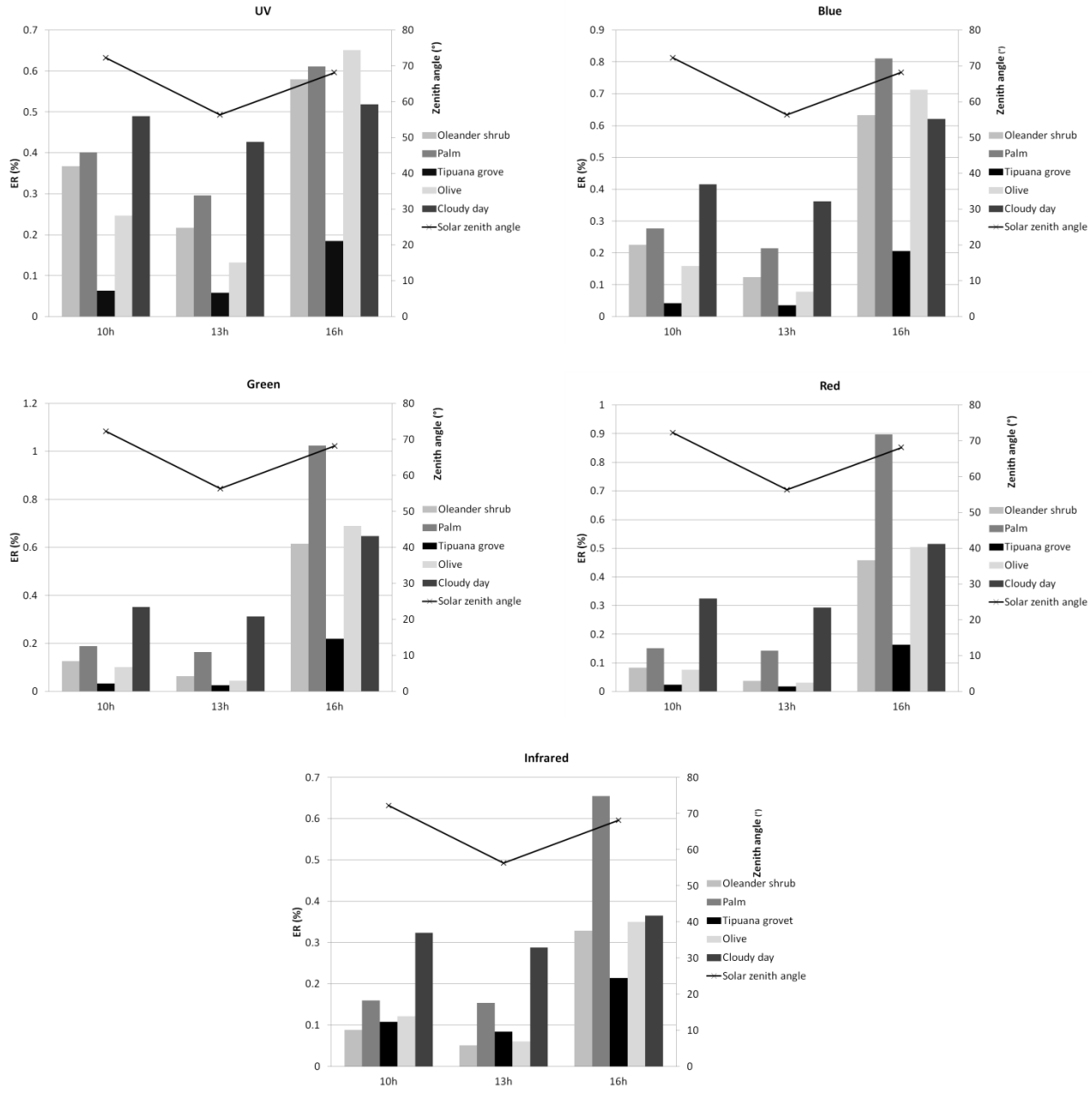
Figure 3. ER for every spectral region.

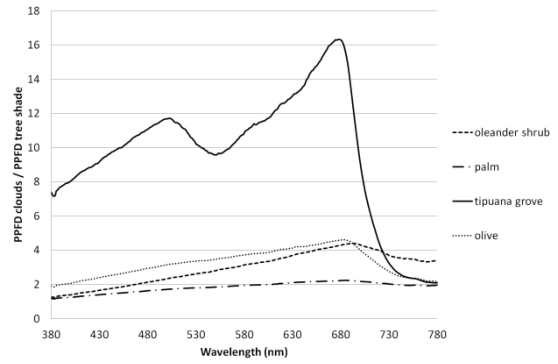
Figure 4. PPFD cloudy day / PPFD tree shadow. Left:at 10h; right: at 13h; bottom:at 16h

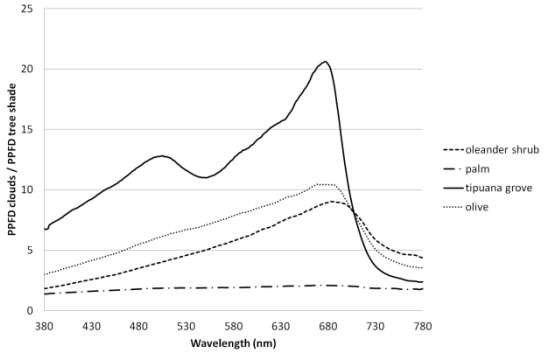

PPFD (µmol·m-2·s-1)
Wavelength (nm)
Sun
Clouds
Palm
Oleander shrub
Olive
Tipuana grove
Oleander shrub shade
Palm shade
Tipuana grove shade
Olive shade
Clouds shade
Sun


PPFD (µmol·m-2·s-1)
Wavelength (nm)
Sun
Clouds
Palm
Oleander shrub
Olive
Tipuana grove
Oleander shrub shade
Palm shade
Tipuana grove shade
Olive shade
Clouds shade
Sun


PPFD (µmol·m-2·s-1)
Wavelength (nm)
Palm
Sun
Olive
Clouds
Oleander shrub
Tipuana grove
Oleander shrub shade
Palm shade
Tipuana grove shade
Olive shade
Clouds shade
Sun


UV
ER (%)
Zenith angle (°)
10h
13h
16h
Oleander shrub
Palm
Tipuana grove
Olive
Cloudy day
Solar zenith angle
Blue
Green
Red
Infrared
Tipuana grovet


PPFD clouds / PPFD tree shade
Wavelength (nm)
oleander shrub
palm
tipuana grove
olive


PPFD clouds / PPFD tree shade
Wavelength (nm)
oleander shrub
palm
tipuana grove
olive

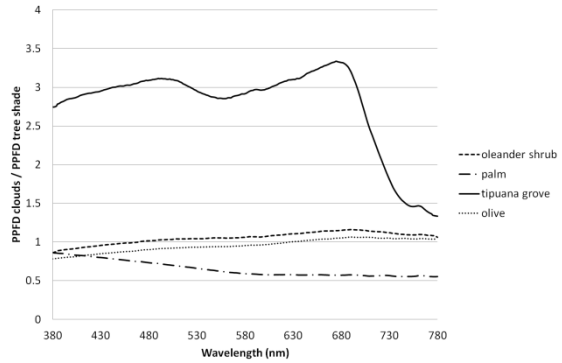

PPFD clouds / PPFD tree shade
Wavelength (nm)
oleander shrub
palm
tipuana grove
olive

Table 1. Climate conditions and solar zenith angle at the time of measurements.

Date	Average air temperature (ºC, min-max)	RelativeHumidity (%)	Average Solar ZenithAngle (°)		
			10h	13h	16h
Sunny conditions					
25/01/17	10.6 (4.8-16.4)	54.0	73.8	58.4	70.0
14/02/17	13.8 (9.1-18.4)	66.0	69.3	52.4	64.7
Cloudy conditions					
24/01/17	11.0 (6.8-15.2)	59.0	73.9	58.6	70.2
03/02/17	16.0 (12.6-19.4)	58.0	72.0	55.9	67.7

Table 2. Spectral PPFD received under the full sun

	Sun		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	627.58±29.66	972.82±217.19	210.85±43.13
PPFD IR (µmol/m²s)	177.53±4.07	269.01±57.19	87.25±28.02
PPFD R (µmol/m²s)	234.14±9.64	358.24±78.12	78.99±8.82
PPFD G (µmol/m²s)	221.34±10.27	345.13±77.72	65.24±25.68
PPFD B (µmol/m²s)	172.08±9.77	269.46±61.35	66.62±8.63
PPFD UV (µmol/m²s)	14.90±0.88	23.76±5.37	8.24±1.84

Table 3. Spectral PPFD received in a cloudy day.

	Cloudy day		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	225.19±43.99	310.40±133.03	124.20±11.59
PPFD IR (µmol/m²s)	57.4±14.76	77.38±36.87	31.90±5.65
PPFD R (µmol/m²s)	75.99±18.13	105.11±49.41	40.68±7.25
PPFD G (µmol/m²s)	77.78±16.26	107.87±47.31	42.20±4.26
PPFD B (µmol/m²s)	71.42±9.60	97.41±36.30	41.33±0.06
PPFD UV (µmol/m²s)	7.29±0.57	10.15±3.03	4.28±0.40

Table 4. Spectral PPFD received under the palm tree shade

	Palm tree shade		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	124.82±6.86	165.77±26.65	191.77±46.58
PPFD IR (µmol/m²s)	28.40±0.60	41.47±9.17	57.15±15.77
PPFD R (µmol/m²s)	35.39±1.41	51.31±11.21	70.94±17.76
PPFD G (µmol/m²s)	41.85±2.57	56.74±9.65	66.85±16.56
PPFD B (µmol/m²s)	47.59±2.90	57.72±5.80	53.98±12.27
PPFD UV (µmol/m²s)	5.98±0.35	7.04±0.38	5.04±0.78

Table 5. Spectral PPFD received under the olive tree shade

	Olive tree shade		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	67.41±19.18	47.23±15.56	132.30±87.33
PPFD IR (µmol/m²s)	21.54±5.44	16.27±0.06	30.51±29.67
PPFD R (µmol/m²s)	17.84±6.72	11.03±2.76	39.87±36.20
PPFD G (µmol/m²s)	22.29±6.67	15.24±4.82	44.93±31.20
PPFD B (µmol/m²s)	27.28±5.79	20.96±7.98	47.49±19.91
PPFD UV (µmol/m²s)	3.68±0.54	3.14±1.26	5.37±1.07

Table 6. Spectral PPFD received under the oleander shrub shade

	Oleander shrub shade		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	86.26±21.47	68.54±15.62	118.45±80.87
PPFD IR (µmol/m²s)	15.67±3.95	13.83±0.56	28.71±26.06
PPFD R (µmol/m²s)	19.53±6.70	13.44±3.15	36.19±32.24
PPFD G (µmol/m²s)	27.95±7.36	21.77±4.95	40.14±28.65
PPFD B (µmol/m²s)	38.80±7.40	33.34±7.53	42.12±19.97
PPFD UV (µmol/m²s)	5.47±0.71	5.15±1.05	4.78±1.28

Table 7. Spectral PPFD received under the Tipuana grove shade

	Tipuana grove shade		
	10h	**13h**	**16h**
PPFD TOTAL (µmol/m²s)	20.13±1.80	24.82±6.14	40.93±31.02
PPFD IR (µmol/m²s)	19.19±3.09	22.55±3.42	18.71±12.85
PPFD R (µmol/m²s)	5.59±0.61	6.34±1.70	12.89±12.16
PPFD G (µmol/m²s)	7.37±0.71	8.98±2.18	14.32±11.07
PPFD B (µmol/m²s)	7.16±0.47	9.49±2.26	13.73±7.81
PPFD UV (µmol/m²s)	0.95±0.04	1.39±0.34	1.52±0.59

Table8. R/I and B/R ratios in the different cases of study

	Day time		
	10:00 h	13:00 h	16:00 h
Sun exposure			
R/IR	1.32±0.03	1.34±0.01	0.97±0.41
B/R	0.73±0.01	0.75±0.01	0.84±0.02
Clouds			
R/IR	1.33±0.03	1.36±0.01	1.28±0.01
B/R	0.94±0.10	0.94±0.10	1.01±0.19
Palm			
R/IR	1.25±0.08	1.24±0.00	1.25±0.04
B/R	1.34±0.04	1.13±0.14	0.76±0.02
Olive tree			
R/IR	0.82±0.11	0.68±0.17	1.39±0.16
B/R	1.56±0.28	1.85±0.24	1.34±0.98
Tipuana			
R/IR	0.29±0.01	0.28±0.03	0.61±0.23
B/R	1.28±0.05	1.50±0.05	1.22±0.73
Oleander			
R/IR	1.23±0.11	0.98±0.27	1.28±0.04
B/R	2.02±0.08	2.47±0.04	1.30±0.80