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Agroforestry versus agrivoltaic: spectral composition of transmitted radiation and implications for understory crops

**Rosati Adolfo · Proctor Kyle · Dazaea Azad ·
Graham Maggie · Ates Serkan ·
Haley M. Kirschten · Chad W. Higgins**

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Abstract In both agroforestry and agrivoltaics, crops are cultivated under the shade of a top story layer of trees and photovoltaic (PV) panels, respectively. However, the quality (i.e. spectral composition) of the transmitted radiation might differ between the two systems. Tree canopies are green and absorb different spectra selectively, while panels are black and thus should not alter the spectral composition of transmitted radiation. Consequently, plant growth and yield may differ depending on the spectral composition of light. In this study, the spectral composition of transmitted radiation (at ground level) was measured with a spectrometer along transects between adjacent rows of trees and PV panels. The transects crossed both sunlit and shaded areas. The radiation transmitted in sunlit areas was nearly identical, qualitatively and quantitatively, to the incident radiation above both systems. In the shaded areas, transmission was strongly reduced, as expected, and the spectral composition changed. Under tree canopies the percentage of green (G) and red (R) radiation decreased, while the percentage of blue (B) and violet (V) remained similar to the sunlit areas, and far-red (FR) increased sharply. Under the PV panels, both R and FR decreased, G remained similar, while B and V increased gradually from the edge of the shade towards the center of the shaded area. This changed the ratios between different spectra. For instance, the R:FR ratio under the panels varied with the position but remained close to the incoming radiation value (1.35), while under the trees it decreased to 0.35. The R:FR ratio decreased in close correlation ($R^2 = 0.98$) with the fraction of transmitted radiation, under the trees, but not under the panels. The B:R ratio increased in the shade in both systems, but more so in the panel system. G:R and B:G ratios also changed between and within systems, but less dramatically, while the B:FR ratio decreased at decreasing transmittance under the trees, but increased under the panels. The results indicate that even when transmitted

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R. Adolfo (✉)
Research Centre for Olive, Fruit and Citrus Crops, Council for Agricultural Research and Economics (CREA), Via Nursina 2, 06049 Spoleto, PG, Italy
e-mail: adolfo.rosati@crea.gov.it

P. Kyle
Water Resources Engineering, Oregon State University, Corvallis, OR 97331, USA

P. Kyle · G. Maggie · C. W. Higgins
Biological and Ecological Engineering, Oregon State University, Corvallis, OR 97331, USA

D. Azad
Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331, USA

A. Serkan · H. M. Kirschten
Animal and Rangeland Sciences, Oregon State University, Corvallis, OR 97331, USA

radiation quantity is similar, radiation quality in the shaded areas may differ substantially between agroforestry and agrivoltaic systems. The higher R:FR and B fraction under PV panels shade may fail to induce shade adaptation responses in plants, unless low radiation level signals prevail over radiation quality signals in inducing such response.

Keywords Alley cropping · Light · Photovoltaic panels · Shade

Introduction

Agroforestry and agrivoltaics are both agricultural systems in which understory crops are cultivated under the shade of a top story layer, and thus light is usually the most limiting factor for understory plant growth (Dupraz et al. 2011). Optimization of both systems requires knowledge and understanding of crop shade adaptation and response to light quantity and quality. Light, or more precisely electromagnetic radiation, is not only quantitatively important, but also qualitatively important for photosynthesis. Plants perceive different radiation spectra through different pigments absorbing and reacting to radiation of different wavelength, in turn affecting plant development (photomorphogenesis) and behavior (Robson et al. 2015; Tan et al. 2022), including regulation of photosynthesis, production of secondary metabolites, as well as photoperiodicity and phototropism (Hamdani et al. 2019; Muneer et al. 2014; Hernández and Kubota 2016; Carvalho and Folta 2014).

Under the shade of plant canopies, the transmitted radiation becomes impoverished in the wavebands most absorbed by green tissues (red, R, and blue, B) and enriched in the others (green, G, and far red, FR), thus changing ratios between the different spectral components (Hendricks and Borthwick 1963; Wang et al. 2015, 2020). The red/far-red ratio (R:FR), for example, decreases with increasing canopy shade in forests and dense canopies (De Castro 2000; Kurepin et al. 2006; Casal 2013; Park and Runkle 2017), because R radiation is absorbed much more than FR (Woolley 1971; Kasperbauer 1987; Ruberti et al. 2012). This induces morphological and physiological responses in shaded plants, affecting their growth, radiation interception and use-efficiency, and chemical composition, i.e. product quality (Demotes-Mainard et al. 2016; Tan et al. 2022). For instance, low R:FR, sensed by phytochromes, stimulates the so-called shade adaptation syndrome (SAS) or shade avoidance response, increasing internode and petiole length and plant height in many species (Ballaré et al. 1987; Lund et al. 2007; Kurepin et al. 2010; Gommers et al. 2013).

Despite the importance of radiation quality on plant performance, almost all agroforestry studies have provided only quantitative assessments of the radiation transmitted through the tree canopy and available to understory crops. Very few studies have assessed at least some aspects of the radiation spectral composition (e.g., De A. Sá et al. 1999). Drawing from non-agroforestry studies (cited above) on the variations in radiation spectral composition as the radiation passes through a green canopy, it can be hypothesized that these variations occur also in agroforestry environments, at least in the shaded areas below the trees. However, agroforestry systems most often have discontinuous top-story canopies with large gaps, and there is no detailed information on the extent of changes in transmitted radiation composition, their spatial distribution, and their effects on understory plant growth and quality.

While several studies have quantitatively assessed radiation transmission under photovoltaic (PV) panels in agrivoltaic systems (Dupraz et al. 2011; Dinesh and Pearce 2016; Chamara and Beneragama 2020; Touil et al. 2021), there is no information on radiation quality (i.e., spectral composition). Most photovoltaic panels are black; therefore, we hypothesize that, unlike green canopies, black panels are neutral absorbers-reflectors which reduce transmitted radiation without substantially altering its spectral composition. It should be clarified that black PV panels do not transmit solar radiation as leaves do, therefore the radiation reaching the ground (i.e. transmitted radiation) in the agrivoltaic system consists of radiation that passes between panels and radiation reflected by the panels. In the agroforestry system, leaves additionally transmit some solar radiation, scattering it in the process.

Given the large gap in knowledge on the quality of transmitted radiation in agroforestry and agrivoltaic systems, and the possible impact on understory crop performance, the objectives of this study were to assess the quantity and quality (i.e., spectral composition) of the radiation (380–780 nm) transmitted along transects between rows of ground-mounted PV panels and willow (*Salix* sp.) trees. Given that agrivoltaic systems are still predominantly represented by ground-mounted PV systems originally designed as pure photovoltaic systems, under which crops or forages are grown, we chose a typical ground-mounted system with the most common PV panel arrangement in the area of study. Similarly, as alley cropping agroforestry is most commonly practiced in alleys between wide-spaced rows of trees, oriented north–south, we chose to investigate spectral quality under one such system. Although we assessed both the quantity and quality of transmitted radiation, the main objective of this paper was not quantitative, as the quantity of transmitted radiation depends largely on the spacing and size of trees and PV panels. Qualitative changes in the spectral composition of transmitted radiation between shaded and sunlit positions are more likely representative of other systems designs, and thus were the main focus of this study.

Materials and methods

Location

The research was conducted at the Vegetable Farm Solar Array, located at the Oregon State University Extension Station in Corvallis, Oregon (Latitude: 44.57; longitude: − 123.24). The solar array system was established in 2015, with rows of continuous PV panels, oriented East–West and 6.30 m apart, and with panels ground projection covering about 53% of the space (i.e., 47% of the alley space between rows of panels was not vertically covered by panels). The panels are monofacial and are tilted south at an 18° angle with their lowest edge about 1 m above the ground.

Willow trees were planted in rows about 14.45 m apart, oriented North–South, and formed a continuous and uniform canopy along the tree row, about 7 m tall and 7 m wide, with a gap of about 7.45 m between rows.

Measurements

The radiation transmitted at ground level, thus potentially available for understory crops, was measured along a transect between two adjacent rows of PV panels, and along a transect between two adjacent rows of willow trees (Fig. 1). In the panels transect, measurements were taken at about 22.5 cm steps along the transects, from one row of posts supporting the PV panel array to 22.5 cm before the next row (starting from the South to the North, Fig. 2). In the tree transect, measurements were taken at about 50 cm steps, from one row of trees to 50 cm before the next, starting from the East to the West. Thus, 28 measurements were taken between rows of panels and 29 measurements between rows of trees, at each measurement session. The radiation incident above the panels and trees (full-sun control) was measured immediately before each transect measurement, in the open field adjacent to both sites.

Measurements were taken at different times and days during the year, in order to represent different possible situations in terms of solar elevation and weather conditions. Date and time of day of measurements are reported in the figures and supplementary figures. Data were taken using a spectrometer (LI-180, LI-COR, Lincoln, NE, USA), measuring radiation in the 380–780 nm waveband, and its composition: violet (V: 380–400 nm), blue (B: 400–500 nm), green (G: 500–600 nm), red (R: 600–700 nm), and far-red (FR: 700–780 nm). The instrument measures the incoming radiation from a hemisphere (180° view) and is equipped with a high-quality cosine diffusers with a cosine correction nearly identical to the theoretical angular response for cosine correction. Measurements were taken holding the spectrometer

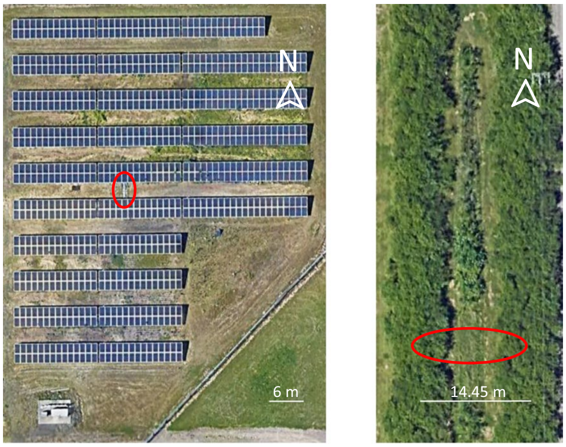


Fig. 1 Aerial view of the photovoltaic site (left), and of the willow site (right), with indication of the measurement sites

Fig. 2 Transect under photovoltaic panels. The figure shows the 28 measuring points along the transect, between two rows of photovoltaic panels. The points were marked on the ground, to allow measuring exactly in the same place at every measuring time

5 cm above ground to avoid possible shading of the sensor by the grass cover, and parallel to the flat ground, thus pointing the sensor vertically toward the sky. The operator held the instrument while squatting down on the opposite side of the sun (i.e. from North-east to Northwest, depending on time of day), to avoid not just shading it, but also affecting the diffuse radiation reading.

Additional measurements were made in some of the same points in the PV transect, by orienting the instrument 60° and 30° south, vertical, and 30° and 60° north, to investigate spectral changes with different sensor orientation. The radiation reflected by the top side of the PV panels was also measured by holding the instrument over the center of a panel, at about 20 cm from the panel surface, pointing perpendicularly towards the panel. Each reading was compared to the incident radiation measured immediately before each reflection measurement.

Results

The amount of transmitted radiation varied greatly along the transects between PV panels or tree rows, with higher values (close to the values of incoming radiation) in the sunlit areas, and much lower (and variable) values in the shaded areas (Fig. 3). Predictably, the transition between sunlit and shaded areas was sudden for the PV panel arrays (since they are not porous to light, they either block the direct radiation or they do not), while it was more gradual for the tree canopy (because canopies are more porous to light at the edge of the canopy, due to lower canopy thickness at the edge). The patterns were similar for all wavelength bands considered, but not identical, so that the relative composition of the radiation changed along the transects (Fig. 4). The sunlit areas (i.e., the points in each transect with the highest values of transmitted radiation in Fig. 3), had nearly the same spectral composition as the incident radiation above the canopy and panels (the individual point between the two transects in Figs. 3, 4 and 5). In the shaded areas, the radiation composition was altered. Under the PV panels, B and V increased while R and FR decreased. These variations in relative composition increased gradually from the sunlit area to the center of the shaded area. In the tree transect, the most notable variation was the gradual increase of FR, moving from the sunlit area into deepest shade. The increase in FR was compensated by a decrease in R and G radiation, while B remained about the same overall, and V tended to increase. R and FR were always close to parallel in the PV panel transect (Fig. 4), so that the R:FR had small variations, remaining always between 1.1 and 1.55, with an average value nearly identical to the 1.35 value in full sun (Fig. 5). However, in the tree transect, when moving from the sunlit area to the increasingly deeper shade, R decreased while FR increased dramatically (Fig. 4), so the R:FR decreased even more dramatically, down to 0.35 (Fig. 5). The results were nearly identical for the many other measuring times (Fig. S1 for the PV system and Fig. S2 for the tree system). The exceptions were that, in the PV system (Fig. S1), during overcast times such as on February 2nd 2022 and March 17th 2022 (as can be seen by the low values of incident radiation in the graphs), the variations described

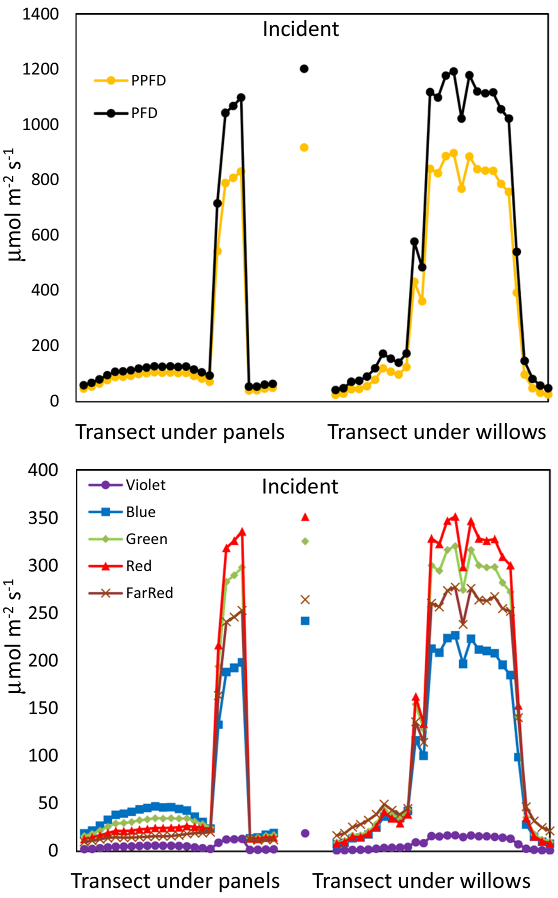


Fig. 3 Top: Photosynthetic (400–700 nm) and total (380–780 nm) photon flux densities (PPFD and PFD, respectively). Bottom: photon flux densities of the different spectra (violet, 380–400 nm; blue, 400–500 nm; green, 500–600 nm; red, 600–700; far-red, 700–780). Points in the graph, starting from left to right, are individual measurements at different positions along the transect, starting from under the panel row (position 1 in Fig. 2), and up to 25 cm before the same position under the next row (position 28 in Fig. 2), and starting from under the east row of trees, up to 50 cm before the west row. The individual points at the center of the graphs, between the two transects, are for the radiation incident above the panels and trees (full-sun control) and are the average of three measurements, taken before, after and between the two transect measurements)

above were minimal, and the spectral composition was almost constant across the transect. Additionally, while the R:FR in the shaded areas tended to remain close to the full-sun value from November to March, it tended to decrease from April to August, though not as much as in the shaded areas under the trees (Fig. S1).

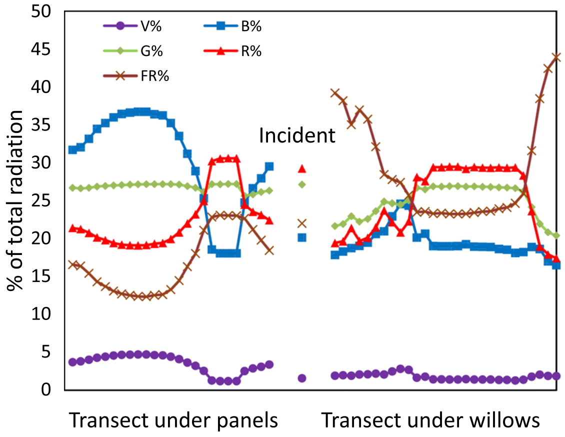


Fig. 4 Percentage of total radiation for the five different spectra. Points are individual measurements as in Fig. 1

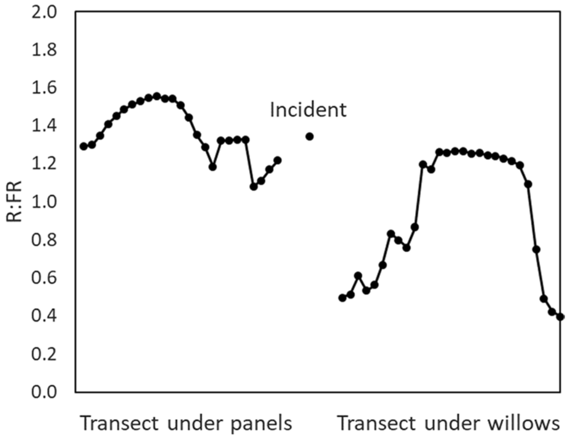


Fig. 5 Red far-red ratio (R:FR). Points are individual measurements as in Fig. 1

To investigate whether the changes in the relative composition of radiation were due to selective absorbance by the canopy as the radiation passes through it, the relative values measured at each point were plotted against the overall transmittance of the photosynthetically active radiation (PAR) at that point, i.e. PAR transmitted at that point/PAR incident above the panels and trees (Fig. 6). The percentage of V radiation (top graph in Fig. 6) tended to increase slightly moving from sunlit areas (or incident radiation) to canopy-shaded areas (i.e. at decreasing transmittance), while it increased much more sharply, from 1.6 to values ranging between 2.5 and 4.7 under

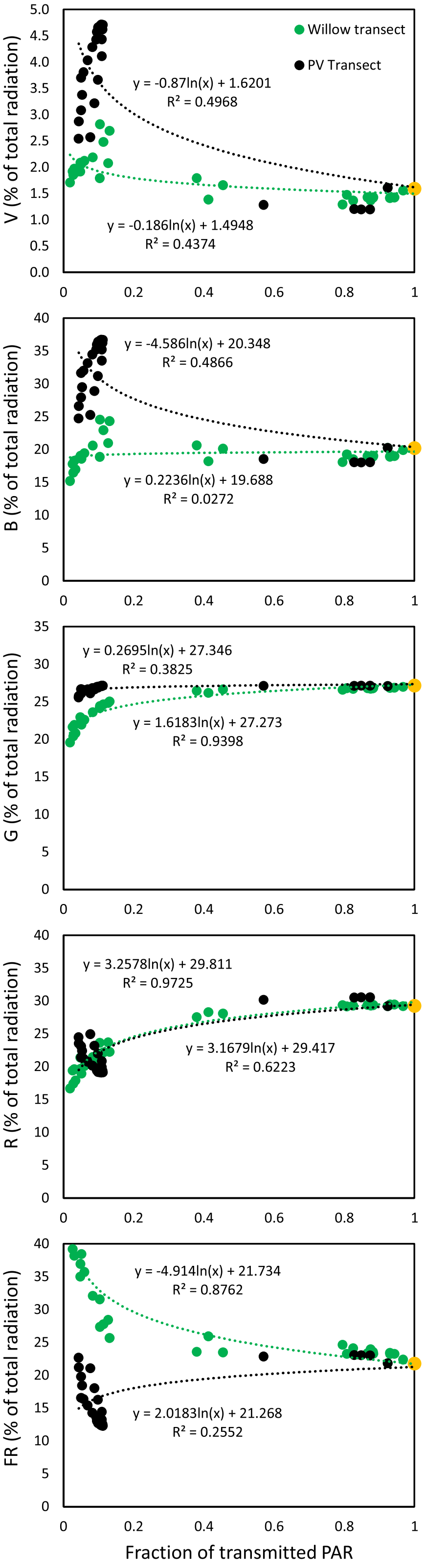


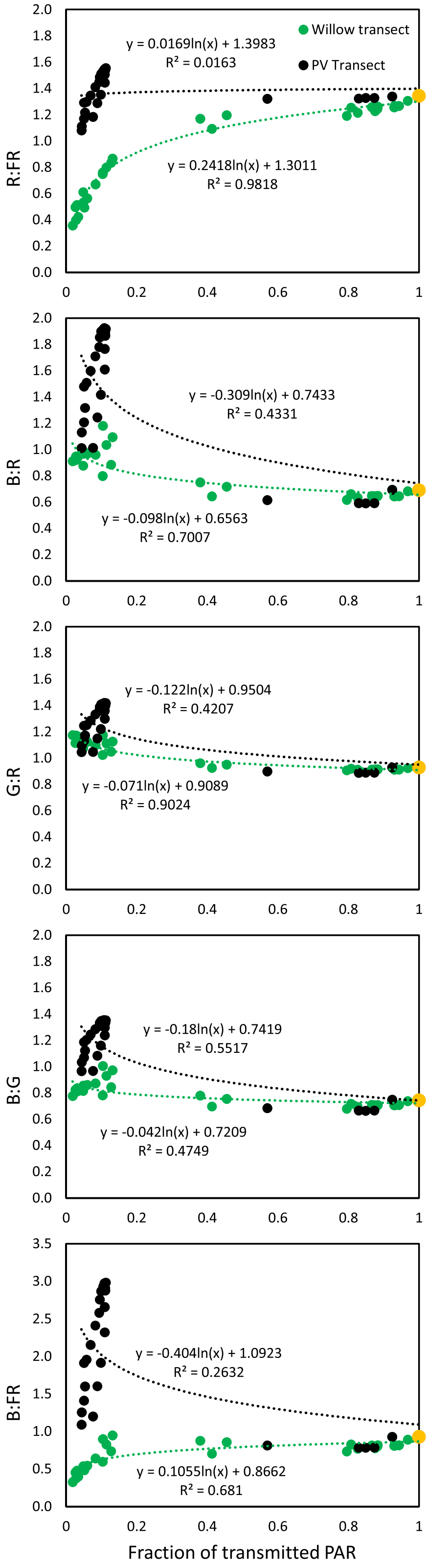
Fig. 6 Relationship between the percentage composition of ▶ the radiation of the different spectra (violet: V; blue: B; green: G; red: R; far red: FR), and the fraction of transmitted radiation under the trees or PV panels. The yellow and larger symbols are for the incident radiation (full-sun control)

the PV panels. The percentage of B (second graphs from top in Fig. 6) remained similar across the transect under trees, while it went up from 20% (sunlit areas + incident radiation) to 25–37% under the panels. The percentage of G decreased from 27 to 20% as radiation was filtered through the tree canopy, while it was virtually unaffected under the panels. The percentage of R decreased under the shade for both systems, from 29 to 20–21%. However, the decrease was much more strongly related ($R^2 = 0.97$) to the transmittance under tree canopies, while in the panels transect there was a large difference between sunlit areas and shade, but within the shaded area there was no relation with transmittance. The percentage of FR increased dramatically under the trees, and in close relation ($R^2 = 0.88$) with decreasing transmittance, while it decreased under panels, although with large variations unrelated to transmittance within the shaded area.

The different patterns of change for the different components of the radiation transmitted gave rise to different ratios between components (Fig. 7). The R:FR varied relatively little in the panels transect, although with some variations unrelated to transmission within the shaded area, while under the trees the R:FR decreased strongly and in close relation ($R^2 = 0.98$) with transmittance values. The B:R ratio increased from sunlit area to shade in both systems, though with higher values under the panels. The G:R ratio also increased from sunlit area to shade in both systems, but in a similar manner for both systems. The B:G ratio, instead, increased from sunlit area to shade in both systems, but more so under the panels. The B:FR ratio increased under the panels, although with large variations unrelated to transmission within the shaded area, while under the trees the B:FR ratio decreased strongly and in closer relation ($R^2 = 0.68$) with transmittance values.

Orienting the instrument at different angles (from 60° south to 60° north), gave large variations in the readings (Fig. 8). In the shaded positions on the south side of the transect (i.e. the first three series of 5 points from the left), the radiation detected by

Fig. 7 Relationship between different spectra ratios (red/far-red: R:FR; red/blue: R:B; red/green: R:G; blue/green: B:G; blue/far-red: B:FR), and the fraction of transmitted radiation under the trees or PV panels. The yellow and larger symbols are for the incident radiation (full-sun control) ▶

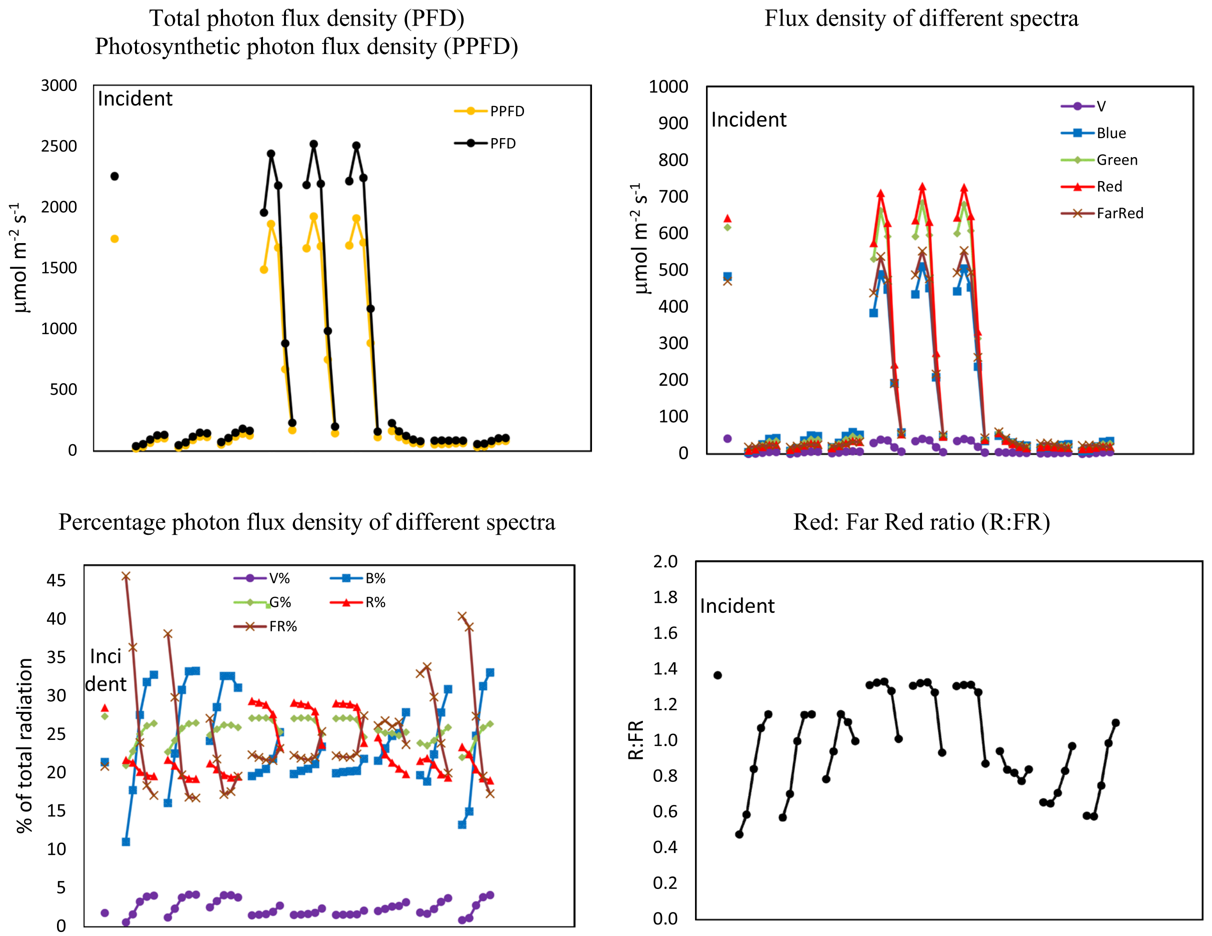


the instrument increased when moving it from the southernmost to the northernmost orientation for all wave bands (PFD, PPFD, V, B, G, R and FR), but not for the shaded positions in the north side of the transect. In the sunlit central positions (i.e. the middle three series in the graphs), radiation increased from 60° to 30° south, then decreased. For both the shaded positions in the south and north side of the transect, radiation composition (i.e. % of total radiation) was heavily affected by orientation (bottom left graph in Fig. 8). From the southernmost to the northernmost sensor orientation, G (moderately) and B (dramatically) increased, while R (moderately) and FR (dramatically) decreased. For the sunlit (central) positions, B and R had similar response (B increased and R decreased), though much less dramatically, while G and FR varied less. The R:FR tended to increase with orientation from South to North in all shaded areas, while it was little affected in the sunlit areas, except for decreasing at the northernmost orientation. Results were nearly identical for the other measuring times (Figs. S3 and S4). The exception was that, on April 25th (Fig. S4), an overcast day (as can be deduced from the low incident radiation), in the shaded positions R generally increased somewhat, instead of decreasing, and B and FR still increased and decreased, respectively, but to a lower extent when sensor orientation moved from vertical to northern orientations.

The radiation reflected by the panels, although much lower than the incident radiation, did not change its percentage composition noticeably, nor the R:FR (Fig. 9).

Discussion

We hypothesized that the radiation transmitted through the tree canopies, and available for understory crops in agroforestry systems would change its spectral composition, at least in the shaded areas, reflecting the selective absorbance of different wavelengths by green canopies. The results suggest that



Total photon flux density (PFD)
Photosynthetic photon flux density (PPFD)

Flux density of different spectra

Percentage photon flux density of different spectra

Red: Far Red ratio (R:FR)

Fig. 8 Photosynthetic (400–700 nm) and total (380–780 nm) photon flux densities (PPFD and PFD, respectively), photon flux densities of the different spectra, percentage of total radiation for the five different spectra and Red Far-Red ratio (R:FR). The first measurement to the left is for incoming radiation. Moving to the right, each series of 5 points is for measurements made holding the sensor 60° south, 30° south vertical, 30° north, 60° north. From left to right, each series of 5 measurements was take at different positions in the PV panel transect, corresponding to positions 2, 5, 8, 11, 15, 18, 21, 24, 27, as shown in Fig. 2. Data in this figure are for 22 April 2022 at 10.42 h

this is mostly the case: under tree shade, FR radiation was transmitted through the tree canopy to a much greater extent than all other spectra, thus increasing the relative FR composition of the transmitted radiation and reducing the relative composition of most other spectra (Figs. 4 and S2). However, this was the case only for the shaded area, and the changes in spectral composition increased with increasing shade (Fig. 6), confirming that the more canopy the radiation penetrates, the more the transmitted radiation is affected by the selective absorption of the different spectra. In the sunlit areas, however, the relative composition of the transmitted radiation was nearly identical to that of the incoming radiation (Figs. 4 and S2). Given that exposure to direct sunlight, in absolute terms, contributes much more radiation interception than exposure to shade, the overall impact of the spectral changes in the shade might be small when understory crops are placed at positions in the tree alleys that receive direct sunlight for even a relatively short part of the day. However, it is possible that spending considerable amounts of time under altered spectral composition in the shade might affect plant response to radiation, despite a possibly small absolute contribution of this radiation to the total radiation interception. In fact, small amounts of radiation of

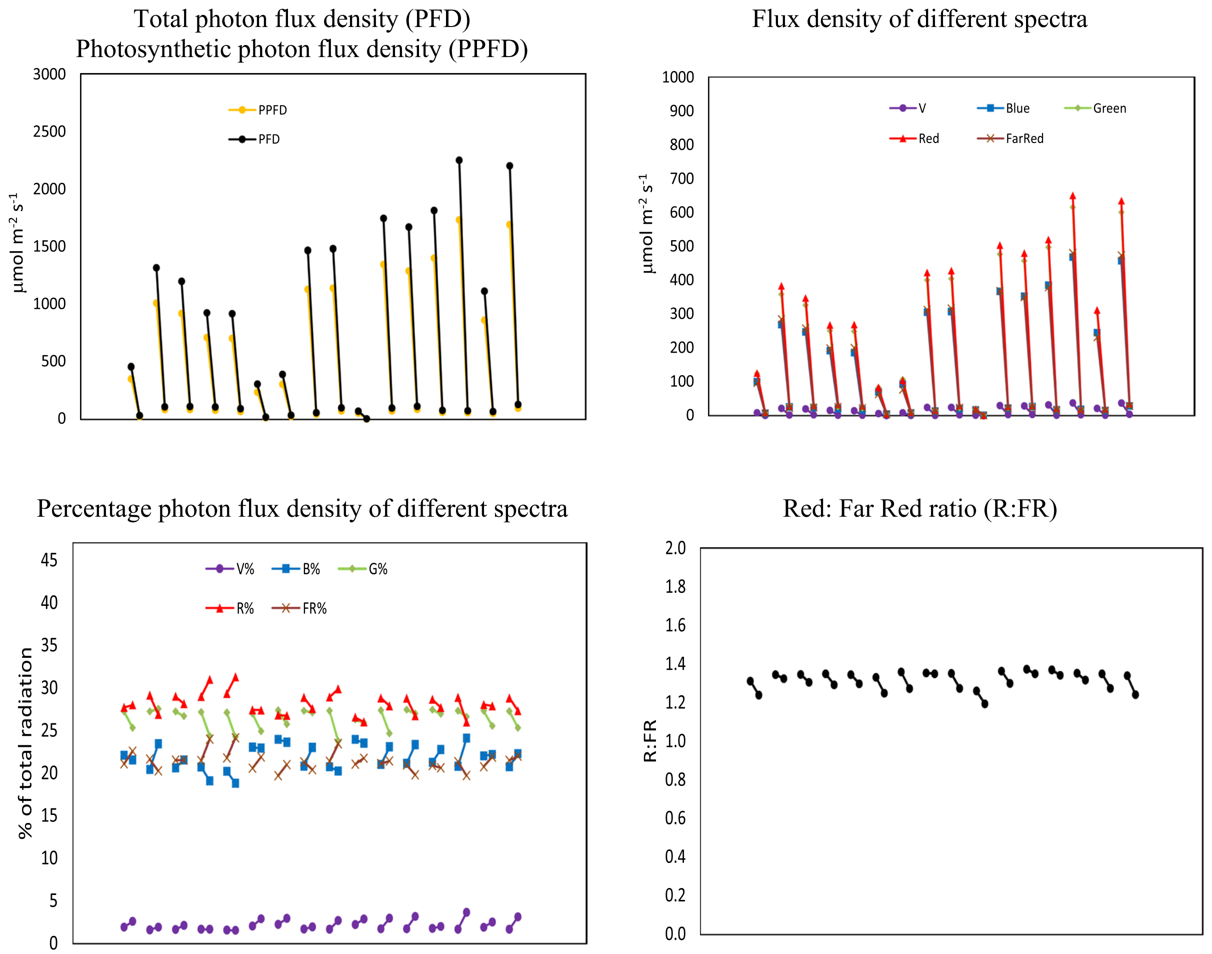


Fig. 9 Photosynthetic (400–700 nm) and total (380–780 nm) photon flux densities (PPFD and PFD, respectively), photon flux densities of the different spectra, percentage of total radiation for the five different spectra and Red Far-Red ratio (R:FR). In each series of 2 points, the first measurement (left points) is for incoming radiation above the panels, while the second measurement is for radiation reflected by the PV panels. Measurements are from the year 2022. Moving from left to right, the series are for 14 January at 11.23 h, 25 January at 12.53 h, 25 January at 12.54 h, 28 January at 14.07 h, 28 January at 14.32 h, 2 February at 9.24 h, 2 February at 12.05 h, 12 February at 11.50 h, 12 February at 12.20 h, 27 February at 16.28 h, 6 March at 10.36 h, 10 March at 10.16 h, 10 March at 11.29 h, 14 March at 10.51 h, 17 March at 10.10 h, 25 March at 10.39 h

certain wavelength, applied over only a few minutes, can have strong effects (Craig and Runkle 2016; Chia and Kubota 2010; Yang et al. 2012; Chinchilla et al. 2018).

Typically, green canopies absorb preferentially both R and B radiation, while G and FR radiation are reflected/transmitted to a greater extent (Hendricks and Borthwick 1963; Wang et al. 2015, 2020). In the shaded parts of the transects between tree rows, we also found that G radiation decreased less than R, relative to the sunlit areas and the incoming radiation (Figs. 4 and S2). However, the B component of the transmitted radiation was overall similar between sunlit and shaded areas. The possible explanation for this is discussed further down.

We further hypothesized that, being black instead of green, PV panels are neutral absorbers-reflectors, thus reducing transmitted radiation without substantially altering its spectral composition. This was the case for reflected radiation from the panels, which did not differ qualitatively from the incident radiation (Fig. 9). The spectral composition of the transmitted radiation was instead altered, but in a very different way than for the green canopy of the willow trees.

Compared to the sunlit areas and incoming radiation, in the PV panels' shade the transmitted radiation had relatively higher B and V and lower R and FR fractions, while G remained about the same (Figs. 2 and S1). These changes were gradual, moving from the sunlit area into the shade, reaching large variations, with B increasing from 18 to 20% in sunlit areas-incoming radiation, to 37% in the middle of the panel shade, and V increasing from 1–2 to 5% (Fig. 2). R decreased from 29–30 to 19%, and FR from 22–23 to 12%. Similar results were obtained in all other clear-sky conditions (Fig. S1). The graduality of the changes was surprising as the PV panels pose a uniform virtually non-transparent obstacle to the radiation, unlike canopies which can be crossed by the radiation at different places with different canopy depths and, thus, different radiation extinction levels. Therefore, the different radiation composition at different shaded positions under the panels is likely related to the different sources of diffuse radiation reaching those positions. In fact, the positions under the panels have different views of the sky and of the bottom side of the panels. Radiation from the sky is richer in B (due to Rayleigh scattering, Dye 2004) while the bottom side of the panel is white and thus should reflect all wavebands equally. The higher levels of B in the central parts of the shaded area (Figs. 2 and S1), corresponded to positions in the north side of the panels (i.e. south side of the alley), that had a larger view of the sky (but not of the sun) and a smaller view of the panels. This would also explain why, in the tree transects, B radiation did not decrease as R radiation: while R radiation was selectively absorbed and thus decreased under the canopy shade, the B radiation was selectively absorbed as well, but the decrease was compensated by the greater levels of B coming from the sky. This is different than in uniform canopy covers, like forests or crop canopies, where direct sunlight and diffuse light from the sky are both increasingly blocked at increasing canopy depth. In alley cropping (both with PV panels and trees), while the sun is blocked in the shaded areas, the gaps between tree or panel rows still allow high levels of diffuse radiation from the sky to reach the ground, increasing (or compensating the decrease of) B radiation. This interpretation is supported by the fact that orienting the spectrometer towards the north increased the blue radiation (Figs. 8, S3 and S4). Orienting the spectrometer towards the north increases the view of the sky and decreases the view of the panels (given that the panels are tilted south). When the sky is clear, the radiation from the sky has greater B fraction due to Rayleigh scattering (Dye 2004). The effect is evident in all positions in the PV transect, but more evident in the shaded positions where only diffuse radiation reaches the sensor. In the sunlit positions, the diffuse radiation represents a small part of the total radiation, dominated by the direct radiation, which has a more constant composition (with lower B).

The increase in B and V radiation, and the decrease in R and FR, in the PV panels shade, implied altered ratios among spectral components (Fig. 7). The decrease of both R and FR in a similar fashion resulted in a small variation of the R:FR ratio, and this small variation was not related to the radiation transmittance, unlike under tree canopies where this ratio was dramatically reduced, and in close relation with transmission (top graph in Fig. 7). The increase in B and decrease in R altered the R:B ratio, more so than under the tree canopy (second graph from top in Fig. 7). Therefore, the main difference in the relative composition of the radiation transmitted under PV panels vs. under the green tree canopy, compared to full-sun, was increased B (and V) but similar R:FR under panels, and increased FR and much lower R:FR under the tree canopy. In the following paragraphs we will discuss possible effects of such variation on photomorphogenesis and crop quality.

Although B radiation, when applied alone in the short term, is less efficient for photosynthesis than R radiation (Hoover 1937; McCree 1972a, b; Inada 1976), some B radiation is apparently necessary for photosynthesis (Goins et al. 1997; Yorio et al. 2001) and increasing the B fraction increases photosynthetic capacity in several species (reviewed in Bugbee 2016), possibly through increased leaf thickness (Terfa et al. 2013). However, increasing the B fraction usually inhibits cell division and expansion, and reduces leaf area (Dougher and Bugbee 2004), resulting in reduced light capture and, ultimately, reduced whole-plant photosynthesis and growth (Bugbee 2016). Additionally, in whole canopies, B radiation is used less efficiently not only than R, but also than G radiation, which penetrates deeper into the canopy and improves photosynthesis of lower leaf and canopy layers (Terashima et al. 2009; Brodersen and Vogelmann2010; Liu and van Iersel 2021). All of this might reduce radiation use efficiency and plant growth, and affect photomorphogenesis, in the B-enriched shade of PV panels. However, reduced radiation interception might be more limiting to growth in non-dense canopies and widely spaced plants, as in most experiments cited above, while in dense canopies radiation interception is close to 100% and, thus, little affected by small changes in leaf area. Increasing B radiation often increases the production of different secondary metabolites in plants (Landi et al. 2020; Paradiso and Proietti 2022), which may affect both product quality (Carvalho et al. 2011) and plant resistance to abiotic and biotic stresses (Vänninen et al. 2010; Ouzounis et al. 2014). Therefore, under the B-rich shade of PV panels, plant chemical composition and product quality may change, at equal shade intensity, compared to plants grown in agroforestry systems. However, there may be interactions between radiation composition (e.g., B fraction) and total radiation levels (low in shade) (Paradiso and Proietti 2022). For instance, stem elongation and leaf expansion (shade avoidance mechanisms), are often closely correlated with the blue fraction, but in other cases photomorphogenetic responses correlated better with absolute B radiation levels (Snowden et al. 2016; Dougher and Bugbee 2001; Wheeler et al. 1991; Cope and Bugbee 2013). In other cases, total radiation overrides the effects of radiation quality (Kusuma et al. 2021).

In many shade-avoiding species, low R:FR, sensed by phytochromes, stimulates internode and petiole length, and plant height (Ballaré et al. 1987; Lund et al. 2007; Kurepin et al. 2010; Hitz et al. 2019), reduces branching, tillering, leaf to stem ratio and root to shoot ratio, and stimulates earlier flowering (Morgan and Smith 1979; Kasperbauer 1987; Halliday et al. 1994; Smith and Whitelam 1997; Casal 2012). In shade-avoiding crop species planted in monocultures, these shade-avoidance responses can reduce crop yield (Morgan et al. 2002; Carriedo et al. 2016; Demotes-Mainard et al. 2016; Wille et al. 2017). On the other hand, shade-tolerant species respond to lower R:FR ratio with thinner but more expanded leaves to increase light capture (Gommers et al. 2013). Supplemental FR radiation has been used to induce shade responses and increase leaf area in leafy greens and other crops, increasing their growth via increased light interception (Stutte et al. 2009; Park and Runkle 2017; Kalaitzoglou et al. 2019). Therefore, under the same shade intensity, shade-avoiding species might not develop the shade avoidance syndrome under PV panels, because the R:FR ratio is not reduced, unlike under green canopy shade. This might increase their yield (Dreccer et al. 2022). On the contrary, shade-adapted species might not adapt to shade (a negative feature) under PV panels. They may instead develop even thicker and smaller leaves, due to increase B radiation. In other words, the PV panel shade may trick the plant twofold: by not reducing the R:FR ratio as occurs under canopy shade, and by increasing the proportion of B radiation even above that of full sunlight. Both situations should signal a non-shade condition to the plant.

However, as mentioned above, there may be interactions between radiation quality and quantity, and it is possible, and perhaps likely, that the low overall radiation in the PV panel shade might override possible effects of increased B and lower R:FR, allowing plants to still sense and respond to shade. Future studies growing different plant types (i.e., shade tolerant and shade avoiding), under the two kinds of shade studied here, will allow for more clarity on the combined effects of the strong variations in radiation quality and quantity, between and within agroforestry and agrivoltaic systems. If changes in radiation quality will prove to affect qualitative and quantitative understory crop performance, future agroforestry crop models might have to incorporate radiation quality aspects, considering selective absorbance of different spectra by green canopies and different spectral composition of the different radiation sources (i.e. diffuse vs. direct) and orientation.

Finally, it should be emphasized that in this study we measured a limited radiation spectrum (i.e. 380–780 nm), while it would be useful to investigate the whole spectrum of the radiation, as changes in radiation spectra outside of the range here considered can also have significant effects on plant behavior.

Conclusions

Despite the importance of radiation spectral quality for plant development and crop quality, very few studies have explored radiation quality in agroforestry systems and no studies are available for agrivoltaic systems. In this study, we assessed the spatial variation in the quality and quantity of the radiation transmitted at ground level along transects across rows of trees or PV panels. Transmitted radiation quality changed both between sunlit and shaded areas, and between systems. In sunlit areas of both systems, the spectral composition was nearly identical to that of the incoming radiation. This means that, as long as plants (crops) are sunlit for a significant time during the day, they will experience a light quality similar to open field crops, given that this time will contribute quantitatively much more to the plant's daily budget of intercepted radiation. Nonetheless, at least for some photomophogenetic traits, it is also possible that a long exposure to altered radiation spectra in the shade will exert some significant effects, despite the modest contribution to the daily radiation budget.

The shade in agroforestry systems had similar spectral composition as in naturally shaded environments (i.e., lower R and R:FR), therefore heavily shaded plants (i.e. not sunlit for a significant time) will behave as expected for shaded plants in naturally shaded environments. The same cannot be said for understory crops in agrivoltaic systems, as the shade under the PV panels is quite different from that of natural environments. R and FR are both lower than for sunlit areas or for the incoming radiation, and the R:FR ratio, although somewhat variable, does not vary as much as for natural (canopy) shade and remains at values similar to those in sunlit areas. These conditions could potentially fail to induce shade responses in the understory plants, even if constantly shaded. This failure could be further enhanced by the higher B fraction in the PV panels shade, which can counter the effects of FR radiation. This could lead to a substantially different performance of understory crops under the two systems, in terms of plant morphology and physiology, affecting plant growth and yield, and product quality, even at similar transmitted radiation levels. While this is very intriguing, it remains possible that very low irradiance conditions will prevail over the spectral changes, reducing such possible differences. Future studies will have to investigate whether differences in the spectral composition of transmitted radiation between alley cropping agroforestry and agrivoltaic systems will have significant effects on crop growth and quality. Meanwhile, the present results shed some light on radiation quality differences between agroforestry and agrivoltaic systems and highlight the importance of assessing spectral quality when designing and optimizing such systems.

Author contributions RA, GM, AS, HC planned the experiment. All authors, set up field equipment and collected data. RA wrote the manuscript. All authors reviewed the manuscript.

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Declarations

Conflict of interest The authors declare that they have neither financial nor non-financial conflicts of interest relevant for the content of the article.

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