Layering contrasting photoselective filters improves the simulation of foliar shade

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Abstract

Background

Neutral density shade cloth is commonly used for simulating foliar shade, in which it reduces light intensity without altering spectral quality. However, foliar shade also alters spectral quality, reducing the ratio of red to far-red (R:FR) light and altering the ratio of blue to green (B:G) light. Unlike shade cloth, photosensitive filters can alter spectral quality, but the filters used have not simulated foliar shade well. We examined the spectral quality of sunlight under color temperature blue (CTB), plus green (PG), and neutral density (ND) filters from LEE Filters, Rosco e-colour+, and Rosco Cinegel brands either alone or layered, hypothesizing that the contrasting qualities of the different filters would improve simulations. As a proof-of-concept, we collected spectral data under foliar shade to compare to data collected under photosensitive filters.

Results

Under foliar shade reductions in the R:FR ratio ranged from 0.11–0.54 (~ 1.18 in full sun), while reductions in the B:G ratio (~ 0.87 in full sun) were as low as 0.53 (deep shade), or were as high as 1.11 (moderate shade). Neutral density filters led to near-neutral reductions in photosynthetically active radiation and reduced the R:FR ratio similar to foliar shade. Color temperature blue filters simulated the increased B:G ratio observed under moderate foliar shade; however, these filters did not reduce the R:FR ratio low enough. On their own, PG filters did not simulate any type of foliar shade. Different brands of the same filter type also had disparate effects on spectral quality. Layered CTB and ND filters improved the accuracy of moderate foliar shade simulations, and layering CTB, PG, and ND filters led to accurate simulations of deep foliar shade.

Conclusions

Layering photosensitive filters with contrasting effects on the spectral quality of sunlight results in more accurate simulations of foliar shade compared to when these filters are used separately. Layered filters can re-create the spectral motifs of moderate and foliar shade, and could be used to simulate shade scenarios found in different cropping systems. Photosensitive filters offer numerous advantages over neutral density shade cloth, and could be a direct replacement for researchers using neutral density shade cloth in their experiments.

Background

Shade is a consistent issue for agronomic crops and horticultural plants, and there has been a considerable amount of research on the fundamental biology of shade responses (1, 2). Results of shade related research have also led to the modification of agronomic practices, such as alterations in plant

density or spacing of row crops (3–5), or the cultivation of varieties that perform better under shade (6). However, shade is still an issue for practitioners across many systems such as turfgrasses and landscape plants as well as in agricultural systems that use intercropping or agroforestry.

The relative lack of improvement in tolerance towards foliar shade can be partially attributed to its complicated nature. Foliar shade, which is defined as shade due to neighboring/overhead leaves, leads to reductions in photosynthetic photon flux (PPF) as well as alterations to the spectral quality of the solar radiation filtered through the foliage (7–9). These alterations in spectral quality include distinct changes in the ratio of red to far-red (R:FR) light and in the ratio of blue to green (B:G) light. Reduction in the R:FR ratio provokes specific changes in plant growth and development, termed shade avoidance responses (or shade avoidance symptoms), resulting from perception and signaling through phytochrome photoreceptors (1, 2, 9). Similarly, the modifications in the B:G ratio can also lead to shade avoidance type responses through blue light sensing cryptochrome photoreceptors (10, 11).

It can be difficult for researchers to examine plant tolerance to altered spectral quality without also dealing with other stresses, such as water-deficit, and simulations are therefore needed to remove these confounding effects. Many researchers use neutral density black shade cloth (shade cloth, black shade cloth, etc.) to apply shade treatments in the field or in greenhouses, but this only reduces PPF and does not alter spectral quality (12, 13). Plants respond differently to altered spectral quality compared to reductions in PPF alone (14–16). Using neutral density black shade cloth may lead to misinterpretation of a plants' tolerance to foliar shade, and expression or post-translational regulation of foliar shade specific genes may not occur under neutral density black shade cloth treatment, limiting the ability to make genetic improvements for tolerance to foliar shade.

Materials that selectively filter sunlight, like leaves, exist and have been used to simulate foliar shade in plant science research (17–24). Photosensitive filters (i.e. photosensitive gels or interference filters) are thin polyester plastic sheets that contain dyes that selectively filter wavelengths of light (25). Filters used in more recent research, such as Peacock blue and Dark green, do not simulate foliar shade well and lead to alterations in spectral quality that are more extreme than what occurs under foliar shade (Table 1, Fig. 1); these filters almost completely remove red light (600–700 nm) to achieve a strong reduction in the R:FR ratio (Fig. 1). Hurdzan and Klein (18) aimed to improve foliar shade simulations through layering a Medium amber Cinemoid filter with a Slate blue Cinemoid filter, and while these authors showed that specific spectral ratios like the R:FR ratio simulated deciduous shade to some degree, they failed to show if this system accurately simulated the entire deciduous shade spectral energy distribution (SED). Simply using filters that have been used in previous research may not be the best choice for those looking to simulate foliar shade more accurately.

Table 1
Attributes of photosselective filters used in previous research

Filter(s) used	R:FR a	PPE b	B:G c	Additional comments	Author(s)
Cinemoid Medium amber (No. 4) + Cinemoid Slate blue (No. 61)	0.75	-	-	Data were collected under sunlight in a greenhouse near solar noon	Hurdzan and Klein, 1975 (18)
Cinemoid Primary green (No. 39)	-	0.03	-	Data were collected in a growth chamber with fluorescent lamps	Hilton et al., 1984 (26)
Green plastic film	0.69–0.83	-	-	Data were collected under sunlight in the field, no mention of time of day	Skálová and Krahulec, 1992 (23)
LEE Filters, Dark green (No. 124)	0.04	0.44	-	Data were collected in a growth chamber with metal halide lamps	Gautier et al., 1999 (15)
LEE Filters, Peacock blue (No. 115)	0.04	0.39	-	Data were collected under sunlight in a greenhouse, no mention of time of day; Under high pressure sodium lamps, R:FR = 0.12, PPE = 0.62	Runkle and Heins, 2001 (22)
LEE Filters, Soft green (No. 322)	0.10	-	-	Data were collected under sunlight in a greenhouse, no mention of time of day	Gautier et al., 2005 (27)
LEE Filters Pale green (No. 138)	0.70	-	-	Data were collected under sunlight in a greenhouse, no mention of time of day	Griffith and Sultan 2005 (17)

^a Red to far-red light ratio

^b Photosynthetic photoequilibria

^c Blue to green light ratio

Filter(s) used	R:FR a	PPE b	B:G c	Additional comments	Author(s)
Rosco, Roscolux Surprise pink (No. 51)	0.58	-	-	Data were collected in a growth chamber with fluorescent and incandescent lamps	Linkosalo and Lechowicz, 2006 (19)
Mitsubishi, blue polyethylene	0.66–0.70	0.67	-	Data were collected under sunlight in a greenhouse near solar noon	Studzinka et al., 2012 and Petrella and Watkins, 2020 (20, 24)
^a Red to far-red light ratio					
^b Photosynthetic photoequilibria					
^c Blue to green light ratio					

We previously evaluated 85 blue, green, or neutral density (ND) filters from two companies, LEE Filters and Rosco, and observed that while many filters are well suited to simulate specific R:FR ratios, only a select number of filters are useful for simulating an entire SED including color temperature blue (CTB) and ND filters (28, 29). However, while the spectral properties of other filters may not be well suited to simulate foliar shade on their own, some filters, including plus green (PG) filters, may improve foliar shade simulations when layered with contrasting filters. Additionally, because shade simulations may take place in greenhouses, common supplemental lighting sources such as high-pressure sodium (HPS) or metal halide (MH) lamps may further effect the spectral quality underneath these filters due to their differences in their spectral output (30). Therefore, our overall objective was to examine if single-, double-, and triple-layered photoselective filters consisting of CTB, PG, or ND filters from LEE Filters and Rosco improved the accuracy of simulating spectral quality of foliar shade under both natural and electric lighting.

Materials And Methods

Description of the photoselective filters evaluated

Filters were chosen based on preliminary results that indicated which filters may improve the accuracy of foliar shade simulations when layered (28, 29). For this study we examined ND, CTB, and PG filters only. For each type of filter, we acquired data from three brands: 1) LEE Filters (Hampshire, UK), 2) Rosco Cinegel (Stamford, CT, USA), and 3) Rosco e-colour+ (Stamford, CT, USA), in which the same filters from different brands were mostly indistinguishable (Fig. 2). These filters are all available in multiple strengths,

ranging from weak to strong effects on spectral quality, and we therefore evaluated multiple strengths of each filter (Fig. 2).

In each case, we evaluated the alteration in spectral quality under a single layer of each filter separately, and when the filters were layered. When layering filters, ND filters were always kept on top, and when evaluating triple-layered filters, they were layered with CTB filters on the bottom, PG in the middle, and ND on top (Fig. 3).

Photoselective filter spectral data collection

Spectral data were collected under photoselective filters in unobstructed, natural sunlight during sunny days in 2020 at the University of Minnesota Turfgrass Research, Outreach, and Education center. Data were collected on 27 May, 30 May, and 12 June 2020 and each day was treated as a replicate for statistical analyses. Data were also collected in greenhouses at the University of Minnesota in the Minnesota Agricultural Experiment Station Plant Growth Facility on 12 June, 13 June, and 14 June 2020 at 22:00 h (when supplemental lighting was the sole light source) with either 400 watt HPS (LU400/H/ECO, General Electric, Boston MA, USA) or 400 watt quartz MH (MVR400/U, General Electric, Boston MA, USA) high-intensity discharge lamps to determine the maximum potential effects of these common sources of supplemental lighting on the spectral effects of the photoselective filters.

A cosine corrected spectroradiometer (Apogee Instruments SS-110, Logan UT, USA) was placed on a box and was leveled approximately 15.24 cm from the surface to collect spectral data. Another box with a ~ 3.0 x 3.0 cm hole was placed over the spectroradiometer. The sensor was positioned under the hole to where it was even with surface of the outside of the box. Sections of photoselective filter (7.62 x 3.81 cm) were then placed over the 3.0 x 3.0 cm hole for the sensor to only be exposed to sunlight filtered through the filter (Additional file 1: Supplemental Figure S1). An automatic integration time was used while taking data, and data were acquired using an average of three scans. Spectral data for each filter were acquired in a random order on each day.

Proof-of-concept: Foliar shade spectral data collection

Spectral data were acquired under foliar shade and in an area of unobstructed full sun (Additional file 1: Supplemental Figure S2) at the University of Minnesota Turfgrass Research, Outreach, and Education center (44°59'42.31"N, 93°11'10.25"W) and the University of Minnesota St. Paul campus (44°59'10.32"N, 93°11'04.05"W) to determine the effectiveness of the photoselective filters to simulate these spectral data.

Data for sites 1 and 5 were acquired in a five row by four column (north-south) grove of sugar maples (*Acer saccharum*) that were approximately 9–12 m in height and on 6 m spacings. Data for site 1 were acquired on the south end of the grove (between rows one and two), and data for site 5 were taken on the north end of the grove (between rows four and five). Data for site 2 were acquired within a mature grove of northern red oaks (*Quercus rubra*) that were approximately 30–37 m in height and of a mixed spacing.

Data for site 3 were acquired on the north edge of a small mixed-species forest that had unevenly spaced young Ohio buckeye trees (*Aesculus glabra*) to the north (9–12 m in height). Data for site 4 were taken on the south side of the same small forest that also had a single, mature, Norway maple (*Acer platanoides*) just to the south (21–24 m in height), and data were acquired between the Norway maple and the southern forest edge. Data for site 6 were taken within the small mixed-species forest in approximately the midpoint between sites 3 and 4. In 2018, data were collected on 28 May, 13 June, 2 July, and 6 July for sites 1–4 and 6, and data were collected 30 May, 31 May, 12 June, and 11 Aug. 2020 for site 5. Data were acquired between 13:00–14:00 h for all sites on clear sky or mostly sunny days only.

We also collected data under three agronomic crops: wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and canola (*Brassica napus*) in 2018 (Additional file 1: Supplemental Figure S3). Wheat data were collected within a field that was seeded on 14 May 2018 in St. Paul MN, and spectral data were collected on 2 and 6 July 2018. Twelve independent scans under wheat were collected in between rows, at least four rows in from plot edges, and were collected in random locations. Data for both barley and canola were collected under plants seeded in six rows on 4 March 2018 in a greenhouse in St. Paul MN. Six independent scans were taken between rows 3 and 4 for both canola and barley on 23 April 2018 only.

To collect data under foliar shade, a spectroradiometer was placed directly on the turfgrass/soil surface, and was leveled to only measure vertical flux. An automatic integration time was used while taking data, and data were acquired using an average of three scans in Apogee SpectroVision software.

Data analysis

For the spectral data collected, we evaluated the overall SED, and also calculated specific spectral ratios and reductions in PPF as follows: 1) R:FR ratio = 655–665 / 725–735 (9); 2) phytochrome photoequilibria [PPE; derived within SpectroVision software; (31)]; 3) B:G ratio = 420–490 / 500–570 (10); and 4) reduction in PPF relative to full sun. All SED data were normalized to 800 nm to factor out the effects of photon flux when comparing SED data. Data collected under foliar shade and agronomic crops in the field were used as a reference to evaluate the accuracy of the photoselective filters as a proof-of-concept, and we did not make any statistical comparisons between these foliar shade data. These data are presented as the mean $\pm$ the standard deviation. Data for spectral ratios and reductions in the PPF collected under photoselective filters were subjected to ANOVA using a mixed model where filter was treated as a fixed effect, replicate (date of data acquisition) was treated as a random effect, and the interaction between filter and replicate was treated as a random effect. Means were compared using Fisher's protected LSD ($P = 0.05$). All data were analyzed using JMP® version 14.0 (SAS Institute Inc., Cary, NC).

Results And Discussion

Foliar shade SEDs and spectral ratios: Significant reductions in the R:FR ratio and changes in the relative amount of blue light were observed between foliar shade sites and under the agronomic crops evaluated

relative to full sun (Fig. 4, Table 2). The range in R:FR ratios observed across all the sites we evaluated was similar with previous research examining spectral changes under various species of trees and crops (7, 16, 32–36).

Deep shaded areas, such as under the northern most row in the maple grove (site 5), and within a forest, like site 6, along with agronomic crops had a greater amount of green light (500–600 nm) relative to the other wavelengths of PAR (Fig. 4D–J, Table 2) (7, 8). While green light and its proportion to blue light are known to effect plant growth and development, to our knowledge, few published papers have presented extracted B:G ratio data from the overall SED. However, Sellaro et al. (10) showed that under dallisgrass (*Paspalum dilatatum*), the B:G ratio could be as low as 0.30.

Table 2
Average data collected under either full sun or foliar shade.

Site	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
				%
Full sun ^e	1.18 ± 0.03 ^f	0.72 ± 0.00	0.87 ± 0.01	□
Maple grove-southern row (1)	0.38 ± 0.07	0.57 ± 0.02	1.11 ± 0.06	94.0 ± 1.4
Oak grove (2)	0.46 ± 0.06	0.60 ± 0.01	1.05 ± 0.07	95.0 ± 0.8
Northern forest edge (3)	0.23 ± 0.06	0.48 ± 0.04	0.79 ± 0.05	97.8 ± 0.5
Southern forest edge (4)	0.22 ± 0.03	0.46 ± 0.03	0.82 ± 0.03	98.0 ± 0.8
Maple grove-northern row (5)	0.11 ± 0.03	0.34 ± 0.04	0.77 ± 0.03	99.0 ± 0.0
Within a forest (6)	0.14 ± 0.02	0.37 ± 0.02	0.66 ± 0.04	99.0 ± 0.0
Under a wheat canopy	0.34 ± 0.08	0.53 ± 0.06	0.76 ± 0.07	93.3 ± 0.3
Under a barley canopy	0.54 ± 0.09	0.62 ± 0.03	0.73 ± 0.03	78.7 ± 5.8
Under a canola canopy	0.20 ± 0.08	0.46 ± 0.06	0.53 ± 0.07	93.6 ± 2.5
^a R:FR = 655–665 / 725–735				
^b PPE = Phytochrome photoequilibria				
^c B:G = 420–490 / 500–570				
^d PPF reduction = Percent reduction in PPF relative to full sun				
^e Site description and site number in parentheses				

^e Mean ± standard deviation; Data are presented as the average SED from the following dates for each site: 28 May, 13 June, 2 July, and 6 July for 2018 (full sun, sites 1–4, and site 6), 30 May, 31 May, 12

June, and 11 Aug. 2020 (site 5), 2 and 6 July 2018 (wheat), and 23 April 2018 (barley and canola). Data were acquired between 13:00–14:00 h on clear sky or mostly sunny days only.

In moderately shaded sites (sites 1 and 2), there was a prominent increase in the B:G ratio compared to full sun (Fig. 4B and 4C, Table 2). McKee (37) indicated that shade underneath trees with a higher canopy is more enriched in blue PAR, akin to data collected under oak shade in site 2. Similar observations have been shown to occur higher in forest canopies (32, 38) where more light diffuses in.

Photosensitive filter SEDs and spectral ratios: For all evaluated ND filters there was a non-linear reduction in the R:FR ratio with increased filter strength. This feature was previously noted by Jackman (25) to occur when using ND filters for photography, and our data shows that strength of the filter (i.e. full, 0.15, 0.60, $\frac{1}{2}$, $\frac{1}{4}$, etc.) does not necessarily indicate the strength of the modification to spectral quality as well. LEE and Rosco e-colour + ND filters were not significantly different (except for 0.60 ND filters) for the R:FR ratio, but Rosco Cinegel ND filters led to significantly lower R:FR ratios compared to the other two brands (Table 3), more than likely due to the non-neutral PAR reductions from Cinegel ND filters (Fig. 5I, J, K, and L).

The effects of ND filters on spectral quality can be easily confused with ND black shade cloths, which are commonly used to reduce PPF for shade experiments. Compared to ND filters, which lead to neutral reductions in visible light (400–700 nm), ND black shade cloths lead to neutral reductions in all wavelengths of solar radiation, and do not alter spectral ratios like the R:FR or B:G ratios. Arthurs et al. (12) showed that black shade cloths did not alter the R:FR ratio beyond natural levels in an Apopka FL greenhouse, and Kotilainen et al. (13) showed that multiple brands of black shade cloth also did not alter the R:FR ratio beyond natural levels or lead to alterations in the overall SED compared to full sun in Raleigh NC. Altogether, ND black shade cloths never alter spectral quality similar to that of foliar shade. Colored shade cloths are also available, but these have been shown to have limited effects on spectral quality (12, 13).

While called “neutral density”, the ND filters still did not reduce all wavelengths of PAR equally. This was most apparent with LEE 0.30 ND and, in particular, 0.90 ND filters which led to a greater decrease in the PAR between 400–500 nm relative to the other filters (Fig. 5). Along the same lines of neutrality, the blue light selective nature of the LEE ND filters could be seen in the B:G ratios where all LEE ND filters led to a significant reductions in the B:G ratio compared to both Rosco filters (Table 3). On the other hand, the Rosco e-colour + ND filters were significantly less selective for blue light (Table 3).

Neutral density filters alone did not provide a full simulation of foliar shade SEDs, largely due to their overall PAR neutrality, which did not occur under foliar shade in St. Paul MN. While the simulation of foliar shade by ND filters may not be completely accurate, having a degree of neutrality may be a good option for researchers who do not have a specific SED simulation in mind and are more interested in reductions in the R:FR ratio, which ND filters can simulate well. Based on data we acquired under foliar shade, LEE Filters and/or Rosco e-colour + ND filters would be best suited for future research.

Table 3
Average data collected neutral density (ND) photosensitive filters.

Filter	Brand	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
					%
0.15 ND	LEE	0.85 A ^e	0.69 A	0.84 F	29.7 H
	e-colour+	0.84 A	0.68 B	0.86 E	36.0 G
	Cinegel	0.76 B	0.68 B	0.86 E	36.0 G
0.30 ND	LEE	0.61 C	0.64 C	0.83 G	51.7 F
	e-colour+	0.61 C	0.64 C	0.88 D	53.0 EF
	Cinegel	0.53 D	0.64 C	0.86 E	54.0 E
0.60 ND	LEE	0.36 E	0.56 D	0.78 H	76.0 D
	e-colour+	0.30 F	0.53 E	0.91 B	79.7 C
	Cinegel	0.23 G	0.53 E	0.90 BC	79.7 C
0.90 ND	LEE	0.18 GH	0.42 H	0.77 I	90.0 A
	e-colour+	0.18 GH	0.43 G	0.95 A	88.3 AB
	Cinegel	0.13 H	0.45 F	0.89 CD	88.0 B
^a R:FR = 655–665 / 725–735					
^b PPE = Phytochrome photoequilibria					
^c B:G = 420–490 / 500–570					
^d PPF reduction = Percent reduction in PPF relative to full sun					
^e Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).					

Color temperature blue filters reduced PAR between 550–700 nm, with variation in the magnitude of the reduction being related to the strength of the filter (Fig. 6). Similar to ND filters, the strength of the CTB filter did not reflect the magnitude change in the R:FR ratio or the other ratios that we calculated (Table 4). Rosco Cinegel CTB filters reduced the R:FR ratio to a greater degree compared to LEE and Rosco e-colour + filters, which was also reflected in the PPE (Table 4). All CTB filters increased the B:G ratio, similar to what was observed under moderate foliar shade (Fig. 4, Table 2), with varying effects depending on the strength of the filter (Table 4). However, only ¼ CTB filters increased the B:G ratio to a range that was comparable to what was observed under moderate foliar shade (Fig. 6A, E, I, Table 4, Table 2). Rosco

Cinegel CTB filters stood out specifically due to their ability to maintain the initial shape of the SED with increasing filter strength, leading to a more “natural” change in spectral quality, primarily due to decreasing a broader range of PAR wavelengths. While both LEE and Rosco e-colour + filters led to more synthetic changes in light quality as filter strength increased (Fig. 6). On their own, $\frac{1}{4}$ CTB filters, and to some extent $\frac{1}{2}$ CTB filters, provided a modest simulation of moderate foliar shade SEDs. The initial SED shape produced by the CTB filter, especially $\frac{1}{4}$ CTB filters, is well suited to simulate moderate foliar shade, but the R:FR ratio and the B:G ratios are not in line with what we observed under foliar shade (Fig. 6B, F, and J).

Color temperature blue filters have not been used for shade-based research, but other blue filters have been commonly used. Petrella and Watkins (20) and Studzinska et al. (24) used a blue polyethylene filter that only reduced the R:FR ratio to approximately 0.70 and did not provide an accurate simulation of moderate foliar shade due to a lack of a strong increase in the B:G ratio (Fig. 1, Table 1). Runkle and Heins (22) used a LEE Filters Peacock blue filter (Product No. 115) which reduced the R:FR in sunlight to 0.04, lower than any common type of foliar shade, and the overall SED of the Peacock blue filter in sunlight does not accurately simulate any type of foliar shade (Fig. 1, Table 1). Hurdzan and Klein (18) used a Slate blue filter (Cinemoid 61) in combination with a Medium amber filter (Cinemoid 4) to simulate deciduous shade, resulting in a R:FR ratio of 0.75, with no mention of other ratios or the overall SED. McVey and Mayer (39) were the first to report using blue-filtering materials to simulate foliar shade on an agricultural crop, Kentucky bluegrass (*Poa pratensis*), where they used blue acrylic plastic to alter spectral quality of sunlight in the field; no spectral ratios were provided, but SED data that were provided showed that their treatment did not lead to an accurate simulation, and the strength of the alteration in light quality was unrealistic. Compared to this previous research, our data show that CTB filters provide much improved accuracy in regards to simulations of moderate foliar shade compared to blue filters used in previous research.

Table 4
Average data collected under color temperature blue (CTB) photosensitive filters.

Filter	Brand	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
					%
1/8 CTB	LEE	0.91 A ^e	0.69 A	0.94 I	20.7 G
	e-colour+	0.90 A	0.68 B	0.98 H	24.7 F
	Cinegel	0.92 A	0.70 A	0.94 I	24.3 F
1/4 CTB	LEE	0.78 B	0.67 C	1.01 G	28.3 E
	e-colour+	0.76 BC	0.66 D	1.06 F	30.0 E
	Cinegel	0.71 C	0.67 C	1.05 F	35.0 D
1/2 CTB	LEE	0.57 D	0.63 E	1.21 E	44.0 C
	e-colour+	0.60 D	0.62 F	1.32 D	45.7 C
	Cinegel	0.51 E	0.63 E	1.22 E	45.7 C
Full CTB	LEE	0.41 F	0.57 G	1.66 B	56.3 B
	e-colour+	0.37 F	0.56 H	1.49 C	57.7 B
	Cinegel	0.19 G	0.51 I	1.71 A	67.7 A
^a R:FR = 655–665 / 725–735					
^b PPE = Phytochrome photoequilibria					
^c B:G = 420–490 / 500–570					
^d PPF reduction = Percent reduction in PPF relative to full sun					
^e Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).					

Plus green filters were evaluated to determine how well they simulate deep foliar shade spectral motifs. Both ¼ and ½ PG filters led to B:G ratios that were comparable to what was observed under deep foliar shade (~ 0.53–0.75), and full PG filters resulted in a too extreme reduction in the B:G ratio. Other spectral ratios, including the R:FR ratio, were not comparable to what is observed under moderate or deep foliar shade, and because of this PG filters (all strengths) would not be suitable on their own in simulations.

Green filters like PG, have been used in previous research, but do not provide accurate simulations of foliar shade on their own (Fig. 7). Hilton et al. (26) used green Cinemoid filters (Product No. 39) to

examine the effects of reductions in the PPE on the germination of *Poa trivialis*, and while the authors stated that their filter treatment reduced the PPE to 0.03, no further spectral data were provided. Skálová and Krahulec (23) used a green filter that reduced the R:FR by only 31% compared to full sun, and the SED of the green filter used did not provide an accurate simulation. Gautier et al. (15) used a LEE Filters Dark green filter (Product No. 124) that reduced the R:FR ratio to 0.04, and similar to the Peacock blue filter, the Dark green filter led to a strong alteration in light quality that was very inaccurate (Fig. 1, Table 1). Pallas, et al. (40) used green saran shade cloth of varying strength and showed that this material simulated foliar shade somewhat well at lower strengths, but at higher strengths, led to mostly neutral reductions in PAR. Overall, while PG filters provided more accurate simulations compared to other green filters previously used, green filters in general do not provide accurate simulations of deep foliar shade. These filters are less accurate than CTB filters overall, even if some spectral ratios match with data collected under foliage.

Table 5
Average data collected under plus green (PG) photoselective filters.

Filter	Brand	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
					%
1/4 PG	LEE	0.97 AB ^e	0.70 C	0.71 AB	20.0 D
	e-colour+	1.00 A	0.71 B	0.67 BC	19.0 D
	Cinegel	1.06 A	0.71 A	0.74 A	17.3 D
1/2 PG	LEE	0.86 CD	0.69 D	0.62 C	25.7 C
	e-colour+	0.96 ABC	0.70 BC	0.63 C	24.7 C
	Cinegel	0.87 BCD	0.70 C	0.62 C	27.3 C
Full	LEE	0.65 F	0.67 F	0.44 D	39.3 A
PG	e-colour+	0.78 DE	0.68 E	0.47 D	36.0 AB
	Cinegel	0.75 EF	0.69 D	0.47 D	34.7 B
^a R:FR = 655–665 / 725–735					
^b PPE = Phytochrome photoequilibria					
^c B:G = 420–490 / 500–570					
^d PPF reduction = Percent reduction in PPF relative to full sun					
^e Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P=0.05$).					

For ND, CTB, and PG filters there were differences in the overall SED and specific spectral ratios between the brands we evaluated. Jackman (25) indicated that inconsistencies can exist between brands even if filters, like ND, CTB, and PG, are considered industry standards, which could be seen when looking at the filters themselves (Fig. 2). The Rosco e-colour + line of filters is meant as an American version of LEE Filter's European filters, and even with this, the two brands are different enough to lead differences in important spectral ratios, especially with increased filter strength, without strong visual differences in the filters themselves (Fig. 2). Taken together, even if two filters look similar, the way in which they alter light quality can be very different. If a researcher wanted to use, for example, a CTB filter, it would also be important to choose a specific brand rather than choosing a generic filter.

Layering photoselective filters: Each filter had its own benefits and shortcomings when it came to more accurately simulating foliar shade; with that in mind, layering the filters to combine these benefits may further the ability to simulate foliar shade. Based on the results of the single filters, we moved forward with layering Rosco e-colour + ND, Rosco Cinegel CTB, and Rosco PG filters as well as LEE ND, CTB, and PG filters (LEE Filters data are presented in Additional file 1: Supplemental Figures S4-S7 and Additional file 2: Supplemental Tables S1-S4).

Layering CTB and ND filters improved upon the SED and spectral ratios of the single filters (Fig. 8, Table 6). The addition of a ND filter on top of a CTB filter significantly reduced the R:FR ratio compared to either of these types of filters by themselves. Increasing strength of the ND filter also led to significant increases in the B:G ratio for all CTB filters evaluated (Table 6). The spectral shape and B:G ratio of the $\frac{1}{4}$ CTB filter on its own simulated the SED of moderate foliar shade well, but the R:FR was too high; with the addition of a ND filter, the R:FR ratio was reduced to a level that accurately simulated what we reported from the field (Table 6, Table 2). Spectral changes from both $\frac{1}{4}$ and $\frac{1}{2}$ combined with 0.15–0.60 ND filters provided for more accurate simulations, while $\frac{1}{2}$ CTB and ND combinations lead to B:G ratios that may be too high to be realistic (Fig. 8).

Table 6
Average data collected under layered color temperature blue (CTB) neutral density (ND) filters.

Filter(s)	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
				%
0.15 ND ^e	0.84 B ^f	0.68 B	0.86 K	36.0 K
0.30 ND	0.61 D	0.64 E	0.88 K	54.0 H
0.60 ND	0.30 H	0.53 J	0.91 J	79.7 C
1/8 CTB	0.92 A	0.70 A	0.94 I	24.3 L
1/4 CTB	0.71 C	0.67 C	1.05 F	35.0 K
1/2 CTB	0.51 E	0.63 F	1.22 C	45.7 J
1/8 CTB				
+ 0.15 ND	0.62 D	0.65 D	0.96 HI	48.7 I
+0.30 ND	0.45 F	0.61 H	0.98 H	63.3 F
+ 0.60 ND	0.22 I	0.49 K	1.00 G	83.7 B
1/4 CTB				
+ 0.15 ND	0.49 E	0.62 G	1.08 E	57.7 G
+0.30 ND	0.35 G	0.57 I	1.09 E	69.3 E
+ 0.60 ND	0.18 J	0.45 L	1.12 D	86.7 A
1/2 CTB				
+ 0.15 ND	0.34 G	0.57 I	1.25 B	65.3 F
+ 0.30 ND	0.25 I	0.52 J	1.27 B	74.7 D
+ 0.60 ND	0.13 K	0.40 M	1.31 A	88.7 A
^a R:FR = 655–665 / 725–735				
^b PPE = Phytochrome photoequilibria				
^c B:G = 420–490 / 500–570				
^d PPF reduction = Percent reduction in PPF relative to full sun				
^e Rosco Cinegel was used for CTB and Rosco e-colour + was used for ND filters				

^f Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).

Layering ND filters on PG filters also improved upon the overall shade simulation of both filters alone (Fig. 9); however, in instances under foliar shade in the field where the B:G ratio is lower than that of full sun, the R:FR was also generally low (Table 2). Only $\frac{1}{4}$ and $\frac{1}{2}$ PG filters with 0.60 ND filters led to the more accurate simulations of deep foliar shade (Table 7). While the B:G ratios of $\frac{1}{4}$ and $\frac{1}{2}$ PG filters provided improved simulations of what occurs under deep foliar shade, the R:FR ratios under these filters were relatively too high.

Table 7
Average data collected under layered plus green (PG) and neutral density (ND) filters.

Filter(s)	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
				%
0.15 ND ^e	0.84 B ^f	0.68 B	0.86 B	36.0 J
0.30 ND	0.61 D	0.64 E	0.88 AB	53.0 H
0.60 ND	0.30 H	0.53 I	0.91 A	79.7 C
1/4 PG	1.00 A	0.71 A	0.67 DE	19.0 L
1/2 PG	0.96 A	0.70 A	0.63 EF	24.7 K
Full PG	0.78 B	0.68 B	0.47 G	36.0 J
1/4 PG				
+ 0.15 ND	0.70 C	0.67 C	0.71 CD	46.7 I
+0.30 ND	0.50 E	0.62 F	0.72 C	61.7 F
+0.60 ND	0.26 HI	0.50 J	0.74 C	83.0 B
1/2 PG				
+ 0.15 ND	0.62 D	0.65 D	0.61 F	51.0 H
+ 0.30 ND	0.44 F	0.60 G	0.61 F	66.7 E
+0.60 ND	0.22 IJ	0.48 K	0.62 F	84.3 AB
Full PG				
+ 0.15 ND	0.52 E	0.63 E	0.47 G	56.7 G
+ 0.30 ND	0.37 G	0.58 H	0.47 G	69.7 D
+ 0.60 ND	0.19 J	0.45 L	0.49 G	86.3 A
^a R:FR = 655–665 / 725–735				
^b PPE = Phytochrome photoequilibria				
^c B:G = 420–490 / 500–570				
^d PPF reduction = Percent reduction in PPF relative to full sun				
^e Rosco e-colour + filters were used for both PG and ND filters				

^f Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).

Simultaneously layering ND, CTB, and PG filters resulted in the most accurate simulations of deep foliar shade SEDs, but not for moderate foliar shade SEDs (Fig. 10). Specifically, $\frac{1}{2}$ or $\frac{1}{4}$ CTB filters combined with $\frac{1}{2}$ PG and 0.60 ND filters led to the most accurate deep foliar shade simulation due to the overall SED shape and the magnitude in the reduction of the R:FR, B:G ratios, and the % green PAR in particular (Table 8, Fig. 10P and 10Q). The combination of $\frac{1}{2}$ CTB with $\frac{1}{2}$ PG and either 0.30 or 0.60 ND filters did not simulate the reduction in the B:G ratio well, while the R:FR was in line with expectations for deep foliar shade. Similarly, the use of $\frac{1}{4}$ PG in the triple-layered combination did not lead to the more accurate simulated spectral reduction exhibited by the combination of $\frac{1}{2}$ PG and $\frac{1}{2}$ or $\frac{1}{4}$ CTB filters (Table 8). Only the combination of $\frac{1}{2}$ CTB and $\frac{1}{4}$ PG with either 0.30 or 0.60 ND filters led to a more accurate simulation of moderate foliar shade; however, this did not improve simulation of moderate foliar shade compared to layering CTB and ND filters only.

The layering scheme that we have proposed could be tailored by researchers by mixing and matching different strengths of CTB, PG, and ND gels that best simulate selected spectra. Researchers can simulate a desired foliar shade SED by first gathering spectral data in a target environment they hope to mimic, and then comparing the overall SED shape and specific ratios like the R:FR and B:G ratios to those of single-, double-, and triple-layered filters to determine which is the most accurate (Fig. 11). With this method researchers will be able to generate accurate foliar shade simulations for both field and greenhouse experiments, eliminating the need for ND black shade cloth in foliar shade-related research.

Table 8
Average data collected under layered color temperature blue (CTB), plus green (PG), and neutral density (ND) filters.

Filter(s)	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
				%
1/4 PG + ^e 1/8 CTB	0.76 A ^f	0.68 A	0.77 J	36.7 Q
+ 0.30 ND	0.38 F	0.58 F	0.78 I	69.7 K
+ 0.60 ND	0.19 JK	0.46 L	0.80 H	86.3 E
1/4 PG+ 1/4 CTB	0.58 C	0.65 C	0.85 F	46.3O
+ 0.30 ND	0.30 H	0.55 H	0.87 E	74.0 I
+ 0.60 ND	0.15 LM	0.43 N	0.89 D	88.3 C
1/4 PG+ 1/2 CTB	0.42 E	0.61 E	0.99 C	55.7M
+ 0.30 ND	0.21 J	0.50 J	1.00 B	79.0 G
+ 0.60 ND	0.11 N	0.38 P	1.03 A	90.3 B
1/2 PG+ 1/8 CTB	0.66 B	0.67 B	0.65 P	43.1P
+ 0.30 ND	0.33 G	0.57 G	0.66 O	72.3 J
+ 0.60 ND	0.17 KL	0.44 M	0.68 N	87.3 D
1/2 PG+ 1/4 CTB	0.52 D	0.63 D	0.72 M	51.7N
+ 0.30 ND	0.26 I	0.53 I	0.73 L	76.3 H

^a R:FR = 655–665 / 725–735

^b PPE = Phytochrome photoequilibria

^c B:G = 420–490 / 500–570

^d PPF reduction = Percent reduction in PPF relative to full sun

^e Rosco Cinegel was used for CTB and Rosco e-colour + was used for PG and ND filters

Filter(s)	R:FR ^a	PPE ^b	B:G ^c	PPF reduction ^d
+ 0.60 ND	0.14 M	0.41 O	0.75 K	89.0 C
1/2 PG+	0.36 F	0.59 F	0.83 G	61.1 L
1/2 CTB				
+ 0.30 ND	0.19 K	0.48 K	0.85 F	81.3 F
+ 0.60 ND	0.10 N	0.36 Q	0.87 E	91.3 A
^a R:FR = 655–665 / 725–735				
^b PPE = Phytochrome photoequilibria				
^c B:G = 420–490 / 500–570				
^d PPF reduction = Percent reduction in PPF relative to full sun				
^e Rosco Cinegel was used for CTB and Rosco e-colour + was used for PG and ND filters				

^f Data are presented as averages acquired on three different clear sky or mostly sunny days between 13:00–14:00 h: 27 May, 30 May, and 12 June 2020. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).

Photoselective filters and electric lighting

Because foliar shade simulations using filters would be advantageous in greenhouses, we next evaluated the effect of common greenhouse supplemental lighting on the spectral properties of the filters evaluated. To examine the maximum potential effect of supplemental lighting on spectral quality, we measured the SED of HPS and quartz MH lamps under photosensitive filters used in the triple-layered system at night when the lamps were the sole light source.

Table 9

The effects of high-pressure sodium (HPS) or metal halide (MH) lamps on filter spectral quality.

Filter(s)	R:FR ^a	PPE _b	B:G ^c	PPF reduction ^d	R:FR	PPE	B:G	PPF reduction
				%				%
	High-pressure sodium (HPS)				Metal halide (MH)			
Lamp only	3.45 A _e	0.87 A	0.23 C	-	1.44 A	0.80 B	0.55 E	-
0.60 ND ^f	0.73 D	0.80 C	0.20 D	79.0 D	0.40 D	0.72 D	0.63 C	77.0 D
1/2 CTB	1.25 C	0.84 B	0.40 A	53.0 E	0.57 C	0.74 C	0.82 B	44.0 E
1/2 PG	2.47 B	0.87 A	0.14 E	22.3 F	1.24 B	0.81 A	0.35 G	23.7 F
0.60 ND+ 1/2 CTB	0.28 F	0.73 E	0.29 B	90.3 B	0.18 F	0.64 E	0.93 A	87.0 B
0.60 ND+ 1/2 PG	0.54 E	0.79 D	0.11 F	83.3 C	0.32 E	0.71 D	0.40 F	82.3 C
0.60 ND+ 1/2 PG+ 1/2 CTB	0.21 F	0.70 F	0.15 E	92.3 A	0.15 F	0.63 F	0.58 D	90.0 A
^a R:FR = 655–665 / 725–735								
^b PPE = Phytochrome photoequilibria								
^c B:G = 420–490 / 500–570								
^d PPF reduction = Percent reduction in PPF relative to full sun								
^f Rosco Cinegel was used for CTB and Rosco e-colour + was used for PG and ND filters								

^e Data are presented as averages acquired on three different days: 12 June, 13 June, and 14 June 2020 at 22:00 hrs in a greenhouse. Means are only compared within column and were separated with Fisher's LSD. Means followed by a common letter are not significantly different ($P = 0.05$).

Under HPS lamps, only 0.60 ND filters led to a reduction the R:FR ratio that was below what is normally observed under natural sunlight (~ 1.10–1.20), due to the synthetic spectra of the HPS lamp itself (Table 9). The combination of 0.60 ND and ½ CTB or ½ PG led to reductions in the R:FR ratio that were

more in line with our foliar shade observations, but for all filters under HPS lamps, the PPE was at or near levels normally associated with full sun (Table 9). These differences in the R:FR ratio and the PPE may be due to the already altered spectral quality of the lamps and the small quantity of far-red light from the supplemental lamps in combination with the lower PPF output from the lamps (30). Also, supplemental lighting has been previously indicated to have differential effects on the R:FR ratio and the PPE (31, 41). The B:G ratios under all filters and all filter combinations also did not simulate foliar shade well under HPS lamps (Table 9).

Under MH lamps, spectral ratios were more similar to data we acquired under the filters in natural sunlight (Table 9). The reductions in R:FR ratio data were more extreme, in particular for the layered filters, but overall, the R:FR ratios of 0.60 ND and CTB filters provided more accurate simulations of foliar shade. The PPE under MH lamps was higher than what was observed from the field, but under the layered filters, the PPE was lower than ambient sunlight (~ 0.72). The B:G ratios of the filters under MH lamps were also improved. The CTB filter alone or in combination with ND filters did not increase the B:G ratio above 1.0 like it did under sunlight, but it was more elevated compared to HPS lamps. Similarly, the B:G ratios of the triple-layered filters were more reduced and in line with expectations with the B:G ratio under deep foliar shade (Table 9).

Overall, MH lamps maintained desired levels of specific ratios like the R:FR and B:G ratios relative to data from the field, and the ratios simulated foliar shade with improved accuracy compared to HPS lamps. These results represent the maximum potential change in spectral quality due to supplemental lighting, and more minor modifications could be expected if the lighting is on during daytime hours. The PPE was higher under the filters, even with reduced R:FR ratios, and because of this, the altered spectral quality of the filter may have less of an effect on plant growth and development, as the PPE and the relative amount of far-red absorbing phytochrome (Pfr) are better correlated to plant responses compared to the R:FR ratio (31). This effect was lessened with MH lamps, but the relatively higher PPE may lead to less dramatic shade avoidance symptoms on the plants being tested.

Conclusions

Our results showed that not all filters lead to accurate simulations of foliar shade, and that layering combinations of filters with contrasting qualities can produce an accurate simulation of different types of foliar shade, including spectral motifs of moderate and deep foliar shade. Interestingly, increasing strength of all filter types did not result in linear changes in spectral quality, and the same model filters from different brands did not lead to the same exact changes in spectral quality. In our study, Rosco filters, e-colour+ and Cinegel, provided a more accurate simulation of moderate and deep foliar shade spectra collected in St. Paul MN compared to LEE Filters, but LEE Filters may similarly be more accurate for others' collected spectra. Photosensitive filters can be used in the field or in greenhouses to provide foliar shade simulations, but in greenhouses, supplemental lighting will further alter spectral quality. However, the use of MH supplemental lighting can help to limit these effects compared to HPS lamps. Simulating spectral ratios and SEDs of foliar shade, such as deep foliar shade, are especially important

for advancing agroforestry and intercropping research, in which researchers are currently aiming to sustainably maximize yield in highly shaded environments (42, 43). This is equally as important to help researchers simulate light found within forests to further understanding of forest ecology. Additionally, simulating deep and moderate foliar shade using the layered photoselective we have described can help plant breeders improve the selection of shade adapted plants, such as turfgrasses that are more fit for foliar shade. We have shown the ability to re-create foliar shade spectral quality using layered photoselective filters, something that cannot be done using neutral density shade cloth. This approach can be used to further our understanding of plant responses to foliar shade as well as improve the breeding of plants for shaded environments.

Abbreviations

B:G, blue to green; CTB, color temperature blue; HPS, high-pressure sodium; MH, metal halide; ND, neutral density; Pfr, far-red absorbing phytochrome; PPF, photosynthetic photon flux; PAR, photosynthetically active radiation; PPE, Phytochrome photoequilibria; PG, plus green; R:FR, red to far-red

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: Data will be made available on acceptance of this manuscript at the University of Minnesota digital conservancy Data Repository of U of M (DRUM).

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: DP conceived the idea, collected data under photoselective filters, collected data under foliar shade, analyzed and interpreted data, wrote and edited the manuscript. FS collected data under agronomic crops and wrote and edited the manuscript. EW acquired funding and edited the manuscript. All authors read and approved the final manuscript

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Figures

Figure 1

Photoselective filters used in previous research do not simulate foliar shade well. A) A generalized spectral energy distribution (SED) of sun and foliar shade (left and right y-axes are scaled differently to represent differences in light intensity while maintaining visible differences in spectral quality). B) SED of LEE Filters Peacock blue filter used by Runkle and Heins (22) [figure modified from Petrella and Watkins (28)]. C) SED of LEE Filters Dark green filter used by Gautier et al. (15) [figure modified from Petrella and Watkins (28)]. D) SED of a Mitsubishi blue polyethylene filter used by Studzinska et al. (24) and Petrella and Watkins (20) [figure modified from Petrella and Watkins (20)]. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars.

Figure 2

Digital images of the photosensitive filters from LEE Filters, Rosco e-colour+, and Rosco Cinegel used in this research. Multiple strengths of each filter were evaluated including; 0.15 – 0.90 neutral density (ND), ½ - full strength color temperature blue (CTB), and ¼ - full strength plus green (PG). Model numbers of each filter are inset in the top-right corner of each filter picture.

Figure 3

Digital images of A) layered LEE Filters 1/2 color temperature blue (CTB) on the bottom, LEE Filters 1/2 plus green (PG) in the middle, and LEE Filters 0.60 neutral density (ND) filter on top. B) Layered Rosco Cinegel 1/2 CTB on the bottom, Rosco e-colour+ 1/2 PG in the middle, and Rosco e-colour+ 0.60 ND filter on top.

Figure 4

Relative spectral energy distributions (SED) acquired under different foliar shade sites in St. Paul MN during 2018 and 2020. A) full sun, B) maple grove-southern row (site 1), C) oak grove (site 2), D) northern forest edge (site 3), E) southern forest edge (site 4), F) maple grove-northern row (site 5), G) within a forest (site 6), H) under a wheat canopy, I) under a barely canopy in a greenhouse, and J) under a canola canopy in a greenhouse. Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 28 May, 13 June, 2 July, and 6 July for 2018 (A-E and G), 30 May, 31 May, 12 June, and 11 Aug. 2020 (F), 2 and 6 July 2018 (H), and 23 April 2018 (I and J). Data were acquired between 13:00-14:00 h on clear sky or mostly sunny days only. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars.

Figure 5

Relative spectral energy distributions (SED) acquired under 0.15 – 0.90 strength neutral density (ND) filters from LEE Filters (A-D), Rosco e-colour+ (E-H), and Rosco Cinegel (I-L). Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically (PAR) active radiation between the red bars.

Figure 6

Relative spectral energy distributions (SED) acquired under ☀ – full strength color temperature blue (CTB) filters from LEE Filters (A-D), Rosco e-colour+ (E-H), and Rosco Cinegel (I-L). Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars.

Figure 7

Relative spectral energy distributions (SED) acquired under ¼ – full strength plus green (PG) filters from LEE Filters (A-C), Rosco e-colour+ (D-F), and Rosco Cinegel (G-I). Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars.

Figure 8

Relative spectral energy distributions (SED) acquired under the combination of $\frac{1}{8}$ – $\frac{1}{2}$ Rosco Cinegel color temperature blue (CTB) and Rosco e-colour+ 0.15 – 0.60 neutral density (ND) filters. A-C) 0.15 ND + $\frac{1}{8}$, $\frac{1}{4}$, or $\frac{1}{2}$ CTB. D-F) 0.30 ND + $\frac{1}{8}$, $\frac{1}{4}$, or $\frac{1}{2}$ CTB. G-I) 0.60 ND + $\frac{1}{8}$, $\frac{1}{4}$, or $\frac{1}{2}$ CTB. Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars. Black lines represent the relative SED of the layered filters, and blue lines represent the SED of the CTB original filter.

Figure 9

Relative spectral energy distributions (SED) acquired under the combination of $\frac{1}{4}$, $\frac{1}{2}$, or full strength Rosco e-colour+ plus green (PG) and Rosco e-colour+ 0.15 – 0.60 neutral density (ND) filters. A-C) 0.15 ND + $\frac{1}{4}$, $\frac{1}{2}$, or full strength PG. D-F) 0.30 ND + $\frac{1}{4}$, $\frac{1}{2}$, or full strength PG. G-I) 0.60 ND + $\frac{1}{4}$, $\frac{1}{2}$, or full strength PG. Data were normalized to the photon flux at 800 nm, and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars. Black lines represent the relative SED of the layered filters, and green lines represent the SED of the original PG filter.

Figure 10

Relative spectral energy distributions (SED) acquired under the combination of 1) $\frac{1}{4}$, $\frac{1}{2}$, or $\frac{1}{2}$ Rosco Cinegel color temperature blue (CTB), 2) $\frac{1}{4}$, $\frac{1}{2}$, or full strength Rosco e-colour+ plus green (PG), and 3) Rosco e-colour+ 0.30 or 0.60 neutral density (ND) filters. A-F) Combinations of CTB filters only. G-L) 0.30 ND filter layered on CTB + PG filters. M-R) 0.60 ND filter layered on CTB + PG filters. Data were normalized to the photon flux at 800 nm and are presented as the average of relative SEDs acquired on 27 May, 30 May, and 12 June 2020 on clear sky or mostly sunny days between 13:00-14:00 h. Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars. Black lines represent the relative SED of the layered filters, blue lines represent the SED of the original CTB filter (A-F), green lines represent the SED of the original PG filter (A-F), and teal lines represent the SED of layered CTB and PG filters (G-R).

Figure 11

Two general models for simulating different types of foliar shade. In all panels, black lines in SEDs represent either moderate or deep foliar shade, and colored lines represent the SED from the designated filter(s). Red bars indicate 400 and 700 nm respectively, designating photosynthetically active radiation (PAR) between the red bars. A) An area of moderate foliar shade with more diffuse light has an SED with a (1) relatively high B:G ratio and a reduced R:FR ratio. A single Rosco Cinegel $\frac{1}{4}$ CTB filter (2) simulates the B:G ratio of the SED from the moderate foliar shade site, but does not simulate other parameters well. A single Rosco e-colour+ 0.30 ND filter (3) similarly does not accurately simulate the moderate foliar shade SED. The combination of the $\frac{1}{4}$ CTB and the 0.30 ND filters (4) accurately simulates the entire moderate foliar shade SED. B) An area of deep foliar shade with a (1) relatively low B:G ratio and a much lower R:FR ratio. A single Rosco e-colour+ $\frac{1}{2}$ PG filter (2) does not simulate the deep shade foliar shade SED. The combination of Rosco e-colour+ $\frac{1}{2}$ PG and a Rosco Cinegel $\frac{1}{4}$ CTB filters (3) still does not

provide an accurate deep foliar shade simulate. The combination of the PG, CTB, and a Rosco e-colour+ 0.60 ND filter (4) accurately simulates the entire moderate deep shade SED.

Supplementary Files

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- [Petrellaetal.2021AdditionalFile1.docx](#)
- [Petrellaetal.2021AdditionalFile2.docx](#)