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EXPERIMENTAL MEASUREMENTS OF LIGHT EMISSIONS FROM ONTARIO GREENHOUSES USING SUPPLEMENTAL LIGHTING AT NIGHT

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ABSTRACT Ontario greenhouse growers are moving towards year-round production supported by increasing use of supplemental lighting. Some municipalities have started to implement by-laws to limit light emissions, including the Kingsville and Leamington areas of Ontario Canada. Current literature contains little information on the magnitude of light pollution produced by greenhouses and effective light pollution abatement methods. Further, there is little quantitative information on the intensity and spectrum of nighttime light emissions from commercial greenhouses. This study sought to begin addressing this shortcoming by developing and trialing a method to measure upward nocturnal light emissions from greenhouse roofs using UAV overflights. The UAV carried a visible spectrum camera and a sky quality meter (SQM), which were used to collect simultaneous independent light intensity measurements. Tests were conducted at eight greenhouses that had either light abatement or energy curtains installed and employed LED and/or high pressure sodium (HPS) supplemental lighting. The effect of available light abatement and energy curtains at different opening states were compared to base cases with lights operating and curtains fully open. The camera and SQM-based measurements generally gave well-correlated results. In most cases fully closed light abatement curtains (manufacturers report 99 % reduction of light emissions) were found to emit less than 1 % of the light emitted with curtains fully open. The study results suggest that the UAV-based measurement method is practical and light abatement curtains are effective at reducing the light emitted by greenhouses.

Keywords: Greenhouse, supplemental lighting, blackout, light abatement, LED, high pressure sodium light, light pollution, light emissions, drone, sky glow.

INTRODUCTION Commercial greenhouse growers are increasingly using supplemental lighting to increase yield and facilitate production of high-light crops during the lower-light seasons. Electricity use in Ontario greenhouse operations is forecast to rise almost

200% from 2019 levels by 2024 (Greenhouse Canada, 2019), prompting the IESO to plan for additional transmission lines to bring electricity to areas experiencing significant greenhouse growth and development. Much of this demand growth is to support increasing use of supplemental lighting, which is critical for proposed year-round production in Ontario.

One of the emerging issues for Ontario’s expanding greenhouse industry is how to balance new and upcoming requirements for minimizing nocturnal light pollution (CBC, 2019) while maintaining or increasing overall production. Physically blocking the light is the most common away to prevent reflected supplemental lighting from leaving the greenhouse. Light abatement curtains can be retrofit into existing greenhouses or designed into new ones. Light abatement curtains or blackout curtains have different properties than conventional shade or energy curtains, particularly in the degree to which blackout curtains prevent air exchange between the regions above and below the gutter. Depending on the conditions, light abatement or blackout curtains may be an energy benefit, by reducing heating requirements on cold nights, or they may have a negative impact on production, by trapping excess heat produced by supplemental lights, interfering with humidity management, and hindering proper air circulation and ventilation of excess humidity (Greenhouse Canada, 2019).

Nocturnal Greenhouse light emissions are becoming an important issue, highlighted by recent actions of municipal governments in areas with significant greenhouse production. Pelham, Ontario has imposed moratoriums on greenhouse construction and expansion while the municipality works to balance increasing resident concerns over stray light and odour (esp. cannabis greenhouses) with the crop production requirements of greenhouse operators (Ligaya, 2019). As of November 2020, the municipality of Kingsville (Ontario, Canada) has implemented a municipal bylaw requiring both vertical and horizontal light abatement curtains to be installed in newer greenhouses that use supplemental lighting (CBC, 2019). The Municipality of Leamington now requires blackout curtains to be closed in any greenhouse if supplemental lighting is used at night (Leamington, 2021). While information from other intensive greenhouse production regions is sparse, it is noted that the Netherlands have regulations in place that require the blockage of 95 % to 98 % of all light coming out of greenhouses using blackout or light abatement curtains (Runkle, 2019).

It should be noted that blackout curtains are used to block incoming light for plants that need a reduced photoperiod, while light abatement curtains block outgoing light to reduce light pollution. Importantly, light abatement curtains are usually slightly porous to allow for some moisture and air exchange, while blackout curtains generally are not porous. Story (2014) examined the light blocking potential of blackout curtains intended to block incoming solar radiation in buildings using two- and three-layer curtain systems. The three-layered curtain system was able to block 99.98 % of solar radiation and the two layered curtains were able to block 99.93 % of solar radiation (Story, 2014). After testing material samples of blackout curtains Szkudlarek et al. (2017) found light blocking capabilities of 99.88%, 99.90%, and 98.72% for three different types of blackout fabrics. Conversely, most light abatement curtains are intended to block 99% of exiting light, and this is typically what manufacturer's specifications state as the expected performance. This study will focus on light abatement curtains.

Many greenhouses have energy curtains installed in order to reduce heat losses, shade crops, and diffuse light. A wide range of energy curtains are available. They can be made from many materials, and are designed to balance heat retention with needs for ventilation and moisture management. Most energy curtains are much more porous and transparent than light abatement or black curtains, typically allowing a significant fraction of ambient light to pass. Light abatement curtains can also act as energy curtains, to reduce heat loss during the winter (Runkle, 2019). In most installations, curtains can be precisely retracted to allow controlled openings to help regulate humidity and temperature inside the greenhouse. However, fully closed light abatement curtains can significantly impact heat and moisture exchange, and in certain conditions it can be difficult to maintain environmental conditions within optimum levels for the crops when the light abatement curtains are fully closed. Without alternative ways to quickly modulate temperature and humidity there is a high probability of negative impacts on the crop productivity including increasing the prevalence of foliar and fruit diseases, and reduction in optimum growth cycles.

Measuring Light Emissions A range of methods are available for measuring light intensity in the context of light pollution studies, including spectroradiometers, cameras and specialized light intensity meters (Hänel et al., 2018). Since the focus of this study was measuring upward light emissions from greenhouses, it was necessary to position light meters directly above a greenhouse. Unmanned aerial vehicles (UAVs), or drones, have previously been used for similar studies. For example, a UAV was utilized by Sielachowska et al. (2018) to assess light pollution by measuring the distribution of luminous flux emitted by sports facilities. Fiorentin et al. (2019) developed an extremely compact autonomous sensor system designed for monitoring light pollution using off-the-shelf components including conventional camera. The system can efficiently measure the luminous intensity and the spectral power density of on-ground pollution emissions that can be easily installed on drones or balloons. While no prior study was found using UAVs to quantify greenhouse light emissions, it seemed probable that a UAV would be a feasible instrument platform for this study.

The choice of light sensing methods for this study was constrained by the need to be able to carry sensing equipment on a UAV. Additionally, the methods needed to be relatively accessible, practical and low cost. The two available sensing methods that met these criteria were to (1) use the visible light camera integrated with the UAV, and (2) the sky quality meter (SQM), a lightweight light intensity meter which was originally developed for dark sky studies. Photos taken by UAVs have been used to analyze light pollution in a variety of studies (Bouroussis and Frangiskos, 2020; Li et al., 2020). The protocol for using cameras to measure light intensity is discussed further in the Methods section.

Sky Quality Meter The sky quality meter (SQM) is a light intensity meter (Unihedron; Grimsby, Ontario, Canada) intended primarily for measuring night sky brightness. SQMs have been used extensively in dark sky research (Hänel et al., 2017; Birriel et al, 2014).

The SQM sensor is a crystalline silicon photodiode (TSL237; Texas Advanced Optoelectronic Solutions) which responds to light in the visible spectrum. The photodiode is covered by a color-compensating filter HOYA CM-500 with spectral transmittance between 350 nm and 750 nm. Onboard circuitry converts the current produced by the photodiode to an output frequency proportional to incident light intensity (Pravettoni et al., 2016). An entire SQM system including sensor, datalogger and batteries is compact and light-weight enough to be carried on a small UAV.

METHODS Tests were conducted at eight different greenhouses facilities. All experiments were conducted at night (8pm – 11pm) or early morning (3:00 – 6:00) to prevent natural sunlight interfering with the measurements. The first facility measured (Greenhouse H) was the Bovey research greenhouse on the University of Guelph main campus (43.527 °N, -80.229 °E). All other greenhouses were large commercial facilities in southern Ontario. The greenhouses had a range of glazing, curtain types, lighting types, and crops (Table 1).

Table 1. Characteristics of test greenhouses (LA: Light Abatement).

Greenhouse	Roof Glazing	Curtain Type	Lighting	Crop
A	Triple Poly	LA	HPS	Propagation (empty)
B	Clear Glass	LA	HPS	Cucumbers
C	Clear Glass	Energy	HPS	Tomatoes
D	Clear Glass	Energy	LED (49% red, 38% green, 10% blue)	Peppers
E	Clear Glass	LA	LED (full spectrum)	Tomatoes
F	Clear Glass	LA	½ HPS ½ LED	Tomatoes
G	Triple Poly	LA	LED intercrop (95% red 5% blue)	Cucumbers
H (Bovey)	Clear Glass	Energy	HPS	Mostly Empty

Before the UAV flights, the weather conditions were recorded. Temperature data was obtained from the SQM sensor and averaged using time stamps corresponding to the flight time of the UAV. Data on the moon cycle was taken from the NASA Skycal website (https://eclipse.gsfc.nasa.gov/SKYCAL/SKYCAL.html). The conditions for each flight are presented in Table 2.

Upward light intensity from the roof of greenhouses was measured using a commercial UAV. All measurements were conducted using a DJI Matrice 210 UAV. The UAV carried a X4S Zenmuse visible light camera with a 84° field of view (FOV) visible light camera. The camera was oriented vertically downward and set to ISO 1600 with an aperture of f2.8 mm and manual (sunlight) white balance for all tests. All images were saved in the DNG native raw format of the camera. The UAV was flown at an altitude of 25 m above the ground for all the greenhouses except Greenhouse D, where an altitude of 50 meters was required to maintain line-of-site visibility of the UAV from the operator location.

For greenhouses A-G (Table 1) a downward-looking SQM was included on the UAV and recorded observed intensity during camera operation. Details of greenhouse interiors (e.g. lighting configurations, crops) were reported by greenhouse owners. While some of this information could be verified from outside the greenhouse, the investigators did not confirm reported interior information by entering the greenhouses due to public

Table 2. Flight conditions for greenhouse experiments.

Greenhouse	Temperature Mean °C	Temperature Range °C	Weather	Moon Phase
A	6.2	9.3 to 4.5	Clear	4 days before new moon
B	-1.1	0.9 to -2.3	Foggy	1 day before first quarter
C	6.9	8.3 to 6.1	Clear	1 day after first quarter
D	8.9	9.3 to 8.3	Slight fog	1 day after first quarter
E	10.7	11.2 to 9.9	Cloudy	1 day after first quarter
F	10.5	10.9 to 10.3	Cloudy	1 day after first quarter
G	8.1	9.9 to 7.4	Cloudy w/ slight fog	2 days after first quarter
H (Bovey)	-4.0	-3.2 to -4.2	Clear	1 day before full moon

health requirements at the time of the experiments to maintain physical distancing to minimize potential spread of Covid-19.

At all greenhouses, the UAV was flown after the sun was fully set or before sky-brightening began at sunrise. Time on-site was typically less than two hours. The UAV was flown above a fixed representative point above the greenhouse to photographically record light emissions for a particular light configuration, with a range of curtain settings from fully open to fully closed. Light emissions with lights on and all curtains open were measured first. A series of photographs were taken with 1600 ISO, f2.8 mm aperture (Jechow et al., 2018) and varying shutter speed from highest available (1/8000 s) to long shutter speeds (Fig. 1).

The set of images were checked immediately to ensure several of the photos were not over-exposed. Once this was complete, the operator was requested to close curtains to several partial open settings (usually 50%, 20%, 10%, 5%) as well as fully closed, while a similar series of images at a range of shutter speeds were collected for each curtain setting. The UAV position above each greenhouse was selected to be a representative view of several bays (with the exception of Greenhouse H, which was a single-span structure) and centered on a recognizable reference point to allow consistent positioning of the UAV to ensure a consistent view across all respective image sets. This was important because typical time on station, which included multiple movements of curtains, typically exceeded the life of a single battery, and the UAV usually had to return to the ground for a replacement battery during testing.

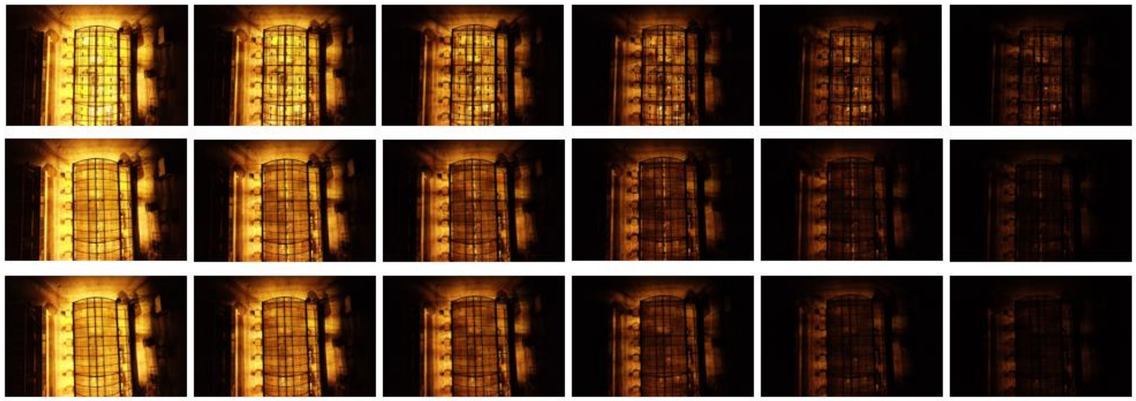

Figure 1. Set of images of Greenhouse H with a range of exposure levels (left to right) and energy curtain positions (top to bottom). Shutter opening time *t* decreases to right. Energy curtains are fully open (100 %), 5% open and 0% open (closed) in the top, middle, and bottom rows, respectively. Note Greenhouse H is a small facility with energy curtains, not light abatement curtains. All other greenhouses were large/commercial, and the roof area filled the images. The commercial greenhouse images are not shown in this report for privacy reasons.

SQM measurements The downward-looking SQM on the UAV recorded a continuous time-stamped log of intensity readings throughout the experiment using a 30 second averaging period. Note that at Greenhouse A an averaging period of 60 seconds was used, while the SQM was not flown at Greenhouse H. Time stamps from the photographs were used in post-processing to identify SQM data corresponding to each curtain setting. The average of the SQM readings for each opening case was taken as the SQM-measured intensity for each curtain setting. The number of readings in each average was typically two to four and was dependent on the amount of time needed to collect the corresponding set of photographs.

The SQM measures radiance in magnitudes/arcsecond^2 but is readily converted to cd/m^2, amore common light intensity measurement by using the formula seen in Eq. 1. These values are to be compared with the values obtained by the photo analysis to determine correlation between the SQM results and photo analysis process.

$$[cd/m2] = 10.8 \times 10^4 \times 10^{(-0.4 \times [mag/arcsec\hat{}2\ ])} \quad (1)$$

The research team recognizes the limitations of using SQMs as a light sensor. SQMs are one dimensional instruments that do not capture spectral variations. The sensitivity range of an SQM does overlap with the photopic region but the sensor has a greater sensitivity to higher energy (blue and green) wavelengths (Sánchez de Miguel et al., 2017). However, in this study the SQM-measured intensity data for different greenhouses will not be compared, instead the SQM data will be compared to the corresponding image analysis data only for the same greenhouse. This decreases spectral sensitivity importance since the same lighting and curtain conditions are present for the experiment in both data sets. The fraction of light transmitted to the SQM sensor (F_{SQM}) for each curtain position was determined using:

$$F_{SQM} = R_p / R_o \quad (2)$$

where R_p is the radiance (cd/m^2) for the curtain closed or partially open (5%, 10%, 20%, 50%) and R_o is the radiance (cd/m^2) with the curtains fully opened.

Photographic measurements The DNG format image files were converted to a lossless TIFF format with no correction or balancing. MATLAB/Octave (https://www.gnu.org/software/octave; equivalent to MathWorks MATLAB) was used to extract pixel values. The image sets at increasing shutter speeds were filtered for over-exposed pixels to reduce issues with nonlinearity of the mean pixel values and the shutter speeds. Since removing too many images from each set skewed the results, only images with less than 1 % saturated pixels were used for the analysis. Each of the images were reduced to a circular 20° field of view (FOV) to match the FOV of the SQM that was used in tandem with the camera. A representation of this area can be seen in Figure 2. This reduction was conducted using a binary mask (image size-based matrix of zeros with a defined area of ones which are indexed to corresponding image pixels) to extract the center portion of image. The central area in the circular image was analyzed to calculate the mean pixel intensity value.

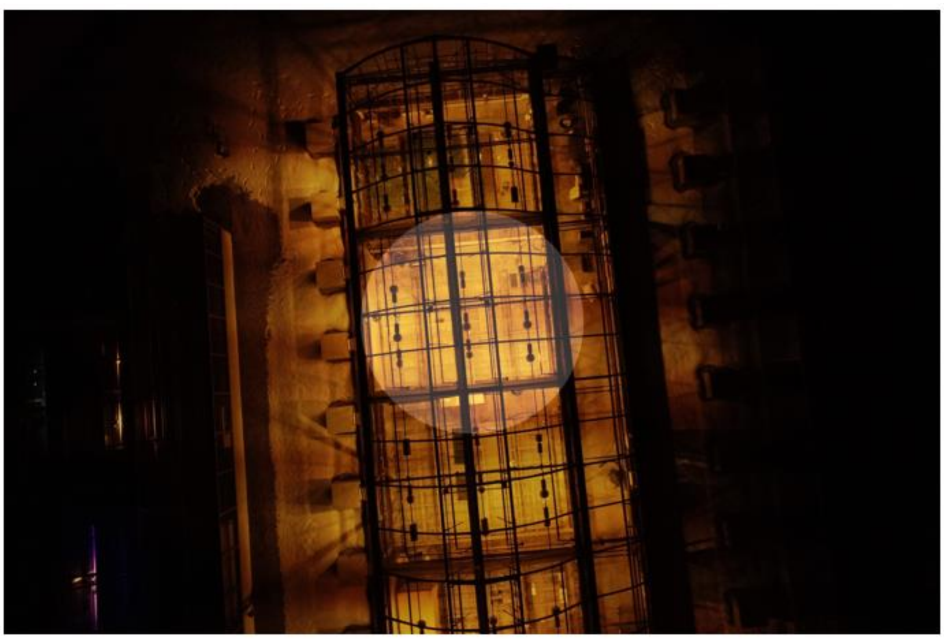

Figure 2. Representation of the analyzed area of the camera images which match the FOV (field of view) of the SQM. The lighter shaded circle in the center is the portion of the camera image that was analyzed for intensity values.

The amount of exposure to a pixel is proportional to the product of illuminance and exposure time (Hiscocks, 2011). Using this correlation, the pixel value (from Octave image analysis) is directly proportional to the luminance. Therefore, if luminance is constant while exposure time (or ISO) is doubled, the pixel value should also double. This means that the mean pixel values of an unaltered image are proportional to the luminance, or light intensity, as long as no pixels are saturated (i.e., overexposed to light) which is evident when individual pixel values reach the maximum possible pixel value. This linear relationship between the luminance level and the pixel values was verified for the UAV camera prior to these experiments.

Hiscocks (2011) presents a model relating the camera settings of exposure time (t), ISO setting (S) and aperture number (f) also known as the “f stop number”, the luminance of the scene (typical units of candela/m^2) (L) and a camera calibration constant (K) to the pixel value (digital number) of the image (p):

$$p = K\,L\,S\,t\,/\,f^2 \quad (3)$$

In these experiments, f and S were held constant. Given that K is a constant for the UAV camera. Then the pixel value p is proportional to the product of L and t. In a given set of images of the same test case where only t is varied.

Eq. 3 suggests it is theoretically possible to use a single image of each curtain position to determine relative intensities between curtain positions, provided that the images are well exposed but without significant pixel saturation in the image. A series of photos were taken at different exposure times by the investigators. The linear relationship between t and p was determined (and then confirmed), after which the ratio of the slopes of the fit line were used to determine the ratio of light intensity between two cases (such as cases of fully open vs., partially closed, curtains). Fig. 3 shows a typical example (from Greenhouse G data) of the linear relationship between t (shutter speed) and p (mean pixel value). The slope of this linear fit for an image set for a particular opening condition is divided by the slope of the linear fit for the image set for the case of fully open curtains which describes the relative magnitude of the light blocking effects of the given curtain condition. Mathematically, the fractional light emission (F_{Camera}) for each curtain condition is equal to the slope for when the curtains were partially open (S_p) (e.g. closed, 5%, 10%, 20% or 50%) divided by the slope for when the curtains were fully open (S_o):

$$F_{Camera} = S_p\,/\,S_o \quad (4)$$

The values for F_{Camera} are directly comparable to the corresponding value of F_{SQM}: both values quantify the fraction of light emission for the particular opening case relative to having curtains fully open: only the measurement method is different.

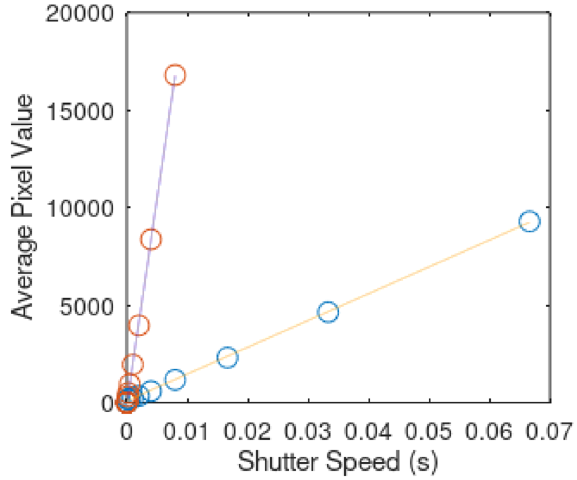

Figure 3. Example of the linear relationships between shutter speed and average pixel value for Greenhouse G with curtains 100% open (left trace) and curtains 5% open (right trace).

RESULTS The data for all the image sets from Greenhouses A to H were analyzed using custom-written GNU Octave code (https://www.gnu.org/software/octave; equivalent to MathWorks MATLAB) by analyzing mean pixel intensity in the 20°C FOV for all the image sets. Mean pixel values were correlated then to shutter speed using Eq. 3. The slope values from these correlations were used to generate comparisons of the different curtain settings (using Eq. 4) for each of the greenhouses. The SQM data was analyzed using Eqs. 1 and 2. SQM data was not collected at Greenhouse H. Table 3 shows results of these analyses for greenhouses with light abatement curtains, while Table 4 shows results for greenhouses with energy curtains. The values shown are the light emissions expressed as fractions of the light emission that occurred with the curtains 100% open.

Table 3. Relative light intensity as a fraction of 100% (open) case for greenhouses with light abatement curtains, for both measurement methods.

Curtain Open Setting	A Image	A SQM	B Image	B SQM	E Image	E SQM	F Image	F SQM	G Image	G SQM
100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50%	0.60	0.63	0.47	0.63	0.47	0.63	0.52	0.51	0.53	0.52
20%	0.24	0.26	0.15	0.19	0.19	0.24	0.16	0.21	0.24	0.22
10%	0.12	0.14	0.03	0.05	0.09	0.10	0.07	0.10	0.11	0.14
5%	0.14	0.12	0.02	0.03	0.05	0.04	0.02	0.04	0.07	0.08
0%	0.045	0.045	0.005	0.004	0.003	0.003	0.002	0.007	0.022	0.036

Table 4. Relative light intensity as a fraction of 100% (open) case for greenhouses with energy curtains, for both measurement methods.

Curtain Open Setting	C Image	C SQM	D Image	D SQM	H Image
100%	1.00	1.00	1.00	1.00	1.00
50%	0.77	0.88	0.79	0.79	--
20%	0.64	0.78	0.68	0.69	--
10%	0.65	0.75	0.67	0.72	--
5%	0.66	0.73	0.65	0.70	0.40
0%	0.64	0.69	0.64	0.69	0.36

DISCUSSION The digital image analysis showed similar results to the independent SQM sensor data that was attached to the UAV. The average percent difference between the SQM- and the digital image data was 17.8%; however, this value does not accurately represent the differences between the SQM and image analysis data. This value is skewed by large percent difference values between the two datasets for closed and nearly closed curtains (5%). Small differences in magnitude of some small curtain opening measurements lead to large percent differences between the two datasets. These discrepancies may reflect the precision of curtain opening levels, material types, age of infrastructure, and any number of other factors that can vary from one greenhouse to another.

The variability between SQM- and image-derived data was not consistent across all greenhouses or curtain condition cases. For example, there are large differences between the two measurements in Greenhouses B and E at the 50% setting, but the data are similar at the lower opening settings. In most cases the SQM-measured light fractions were greater than the corresponding image-based fractions.

The correlation between the SQM and image analysis datasets for the greenhouses with energy curtains has less similarity than the light abatement curtains. The minimum and maximum difference between the SQM fractions and the image analysis fractions was 0.05 and 0.07 respectively. There are some factors that could have caused these discrepancies. Fog was present during some of the energy curtain flights, which may have impacted either the sensor or the camera. Overall, the greenhouses with energy curtains showed less agreement between the SQM- and the image-based data than the greenhouses with light abatement curtains (Tables 3 and 4). Additional investigation should be conducted to determine if this is a general trend or if the differences are coincidental.

The combined results of the image and the SQM analyses show that the reductions in light transmission was significant, especially with light abatement curtains. Overall, the data in Table 3 show that light reduction is approximately proportional to the proportion of light abatement curtain coverage. The light emission fraction with light abatement curtains fully closed (0 % open) was less than 1 % (0.01) for three of the greenhouses (B, E, F). Two greenhouses had higher light emission fractions: the light emission fraction from Greenhouse A was 4.5 %, and from Greenhouse G was 2.2 % to 3.6 %.

The data in Table 4 shows that energy curtains in the three measured greenhouses blocked some light emissions when closed, with a light emission fraction of approximately 2/3 for Greenhouses C and D, and 1/3 for Greenhouse H. It is notable that reducing opening settings from 20 % to 0 % resulted in only minimal or no further reduction in light emissions. Since energy curtains vary significantly in composition and degree of light transmission, these results serve as typical examples, but should not be extrapolated to specific greenhouse energy-curtain scenarios.

The use of intercrop lighting (Greenhouse G) did not appear to significantly impact the ability for the light abatement curtains to reduce light transmittance. However, it should be noted that this greenhouse had a triple-layer polyethylene roof. SQM intensity data and visual inspection of the images suggests there appears to be substantial light blocking potential for this roofing material, which is much more diffusive than clear glass.

Although there are some notable variations, the general correlation of the SQM data and the image analysis data provides support for the overall reliability of the image analysis methods that were used in this trial. It should be noted that the results presented herein are preliminary and should not be taken as definitive. There are multiple potential sources of uncertainty in these measurements, including the effect of glare or indirect lighting, and the selection of the measurement area (e.g., weighting more or less of the unshaded regions in a given image area). Reported curtain opening percentages were not measured value, rather they came from the growers' settings of their environmental control systems. Therefore, the uncertainty of a given opening state could be substantial (e.g., a nominal 5 % open setting could easily actually correspond to 4 % or 6 % in practice). This could have substantial effects on the relationship between closure percentage and measured, especially at higher screen closure levels. This study has also not examined spectral effects of different light sources. Given the substantial phototropic effects of spectrum on the human perception of intensity, especially at scotopic levels (Falchi, 2011), further investigation of spectral effects of HPS vs. LED supplemental lighting technologies is warranted. Additional investigations should be conducted to determine the effect of different types of curtains and how different types of supplemental lighting affect the amount of light emitted from the greenhouse.

CONCLUSION Nocturnal light emissions from greenhouses using supplemental lighting are increasingly of interest and in some cases contention. This study used a UAV carrying a visible-light camera and a SQM light sensor to measure the impact of different greenhouse curtain types and opening positions on the amount of light emitted vertically from eight different greenhouses. The results from the SQM and the image analysis were generally comparable which enhances the reliability of the results. Most curtains in this study provide the expected rates of light abatement with regards to their type and degree of opening. Greenhouses with light abatement curtains could reduce light emissions significantly. When curtains were fully closed, three of the five greenhouses emitted less than 1 % of the amount of light emitted when curtains were fully open, while the remaining two greenhouses emitted less than 5 %. The percentage of light emitted by the greenhouses with curtains fractionally open was generally proportional to the degree of curtain opening, although some notable deviations were observed in specific cases. Since these deviations have not yet been fully explained, follow-up studies and additional data analyses are planned to reduce experimental uncertainty and enhance understanding of the factors impacting greenhouse light emissions. Readers are strongly cautioned not to generalize the preliminary results presented to other scenarios.

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