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Smartphone Calibration for Crowd-Sourced Determination of the Presence of Cyanobacteria in Water Samples

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Abstract

Current techniques for identifying the presence of cyanobacteria in a given water sample are cumbersome. This project is an attempt to simplify the process by using image capture with smartphones. Experiments were designed to ascertain if it is possible to detect cyanobacteria present in a water sample based on measurements of color and transmission spectra. Four types of organisms were used in the experiment. A colonial and a filamentous variant of cyanobacteria and of green algae were measured and compared. In these tests, the results from the four smartphones followed the same trends. All four smartphones displayed a linearity in the relationship between the C values measured by the spectrophotometer vs. the C* values captured by the smartphone cameras for both types of cyanobacteria and for the colonial green algae. The behavior of the filamentous green algae differed from the behavior of the other organisms and presented an S-shaped curve when comparing the C* values from the spectrophotometer and camera. Each smartphone was able to capture this strange behavior, lending hope that it may be possible to successfully use smartphone cameras for the purpose of detection with further work. Only four smartphones were tested, so more would need to be tested to make greater generalizations about the use of this technique.*

Introduction

The rise of smartphones has brought with it numerous possibilities for improving scientific practice. The current method for cyanobacteria identification used by the government consists of collecting a water sample from various lakes and ponds around the state, shipping them to the state capital for analysis, and testing them over the span of a week. The idea of this research is to determine if it is possible to streamline this process to simply using a smartphone to take a picture of a water sample and determine from the image the presence, or lack thereof, of the cyanobacteria.

Two strains of cyanobacteria, one colonial and one filamentous, were acquired and grown in the lab for continued testing. Similarly, two strains of green algae of similar cellular structure to the cyanobacteria were also grown simultaneously. The algae were used to determine if the smartphone cameras can distinguish between the analogous in appearance, though mostly benign, green algae from the harmful cyanobacteria.

Measurements of the transmission spectra and L*a*b* coordinates of the cyanobacteria and green algae in fresh water were made at concentrations between 5% and 100% using a spectrophotometer. Images were taken of each sample using four mobile phone cameras of varying quality. The color information of each sample was then extracted from the images to determine how the colors captured matched the colors measured by the spectrophotometer. These data were also used to create a preliminary customized color checker for matching in the field to better help workers judge if the sample is cyanobacteria or green algae.

Background

Cyanobacteria was historically known as blue-green algae because of its similarities to green algae. Algae and cyanobacteria are both photoautotrophs, they both use water as an electron donor, and they both contain the photopigments chlorophyll a and β-carotene that are key to photosynthesis [1]. Photoautotrophs create energy using light and carbon dioxide [2]. Despite the behavioral resemblance to algae, cyanobacteria more closely resemble bacteria in terms of cellular structure and in the organisms themselves [1]. Where most forms of green algae are harmless, cyanobacteria can range from bothersome, giving water an undesirable smell and taste, to being toxic. The toxins produced affect a wide array of the human body's function; they include hepatotoxins, neurotoxins, microcystin, and elements inducing allergic reactions [3]. Additional treatment is required for drinking water in which elevated levels of cyanobacteria are detected before it can be safely consumed [4].

While cyanobacteria are naturally occurring in small amounts in lakes and streams, they are the most common harmful algal blooms (HABs) in New York's freshwater [5].

The current protocol for detection of HABs by the New York State Department of Environmental Conservation is a combination of methods. Visual surveillance is combined with lab testing to measure the concentrations of chlorophyll and microcystin [6]. A "Suspicious Bloom" is designated when what visually appears to be a bloom of cyanobacteria is found. [7] The visual surveillance images and water samples are transported to the DEC headquarters in Albany for testing [6]. A "Confirmed Bloom" is declared when the level of blue green chlorophyll is measured in the lab to be ≥25 □g/L and with confirmation under a microscope that the majority of the sample is cyanobacteria. A "Confirmed with High Toxins Bloom" is designated when the samples from a Confirmed Bloom also are found to contain ≥20 □g/L of microcystin for shoreline samples or ≥10 □g/L of microcystin for open water samples [7]. Transport and testing of the samples uses valuable resources that, should a handier way of determining the presence of cyanobacteria become available, could be better spent elsewhere. If a DEC worker could take out a mobile smartphone and simply take an image of a water sample while on site then the process of detection could be vastly expedited.

Color Information

The color of the cyanobacteria was characterized in terms of the transmission spectrum and $L^*a^*b^*$ coordinates measured for each strain measured at concentrations of 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%, where the sample was mixed with water. These concentrations are much greater than the levels at which blooms become dangerous.

Transmittance is defined as "the ratio of the transmitted light to the incident light under specified geometric conditions" [8]. Transmittance is related to reflectance. Reflectance is defined as "the process by which radiant energy is returned from a material or object" [8]. Reflectance is typically what non-color scientists understand color to be. A reflectance spectrum shows the degree to which an object reflects light at each wavelength. For example, if a reflectance spectrum is measured for an object that appears red, an observer would expect the spectrum to have a peak in the long wavelengths; dips in the spectrum indicate wavelengths where the light is being absorbed more strongly by the object. Similarly, transmittance spectra indicate how much light is transmitted through the target being measured at each wavelength. Peaks in the spectra indicate wavelengths where more of the light is allowed to pass through the target, while dips indicate wavelengths where light is absorbed and does not pass through the target in such large amounts.

The color system used to characterize the measured colors of the cyanobacteria and algae was the CIELAB color space and color coordinates, developed by the Commission International d'Eclairage (CIE) in 1976 [9]. The CIELAB color space is designated by three color coordinates: L^*, a neutral lightness-coordinate with no hue between 0 and 100, with 0 being black and 100 being the relative white; a^*, a redness-greenness approximation, where the more negative the a^* value is the greener the color is and the more positive the a^* value the redder the color is; and b^*, a yellowness-blueness approximation, with $-b^*$ being bluer and $+b^*$ being yellower [8]. Together, the three coordinates allow for objective scientific description of color. Additionally, there are two further equations that supplement the $L^*a^*b^*$ values: C_{ab}^* and h_{ab} [9]. L^*, C_{ab}^*, and h_{ab} can be used as an alternate, cylindrical representation of the same CIELAB color space. C_{ab}^* represents chroma and h_{ab} represents hue. Chroma is an indication of how far a particular color is from a gray with the same lightness coordinate [8]. Hue is an indication of how similar a color is to one of the unique hues: red, yellow, green, blue, or a combination of two hues [8]. The hues are represented on a circle, with 360 degrees of variability. 0° is reddish, 90° is yellowish, 180° is greenish, 270° is blueish, with 360° back around to reddish.

Differences between colors can also be calculated. One such calculation is ΔC_{ab}^*, the difference in chroma between two colors [8]. This calculation is performed using a^* and b^* values:

$$\Delta C_{ab}^* = C_{ab,meas}^* - C_{ab,match}^* = (a_{meas}^{*2} + a_{match}^{*2})^{1/2} - (b_{meas}^{*2} + b_{match}^{*2})^{1/2} \quad (1)$$

This calculation of the change in chroma can also be characterized as differences along hue-angle lines. Since this is a measure of color change, and because a^* and b^* can be negative, ΔC_{ab}^* can also be negative. With the $C_{ab,meas}^*$ value first in the equation, a positive ΔC_{ab}^* means the measured value is more chromatic than the match and a negative ΔC_{ab}^* means the measured value is less chromatic than the match [10].

The Munsell Book of Colors is, just as the name suggests, a collection of colors varying in hue and chroma for which standard measurements have been made [8]. Its inclusion in the study was for the purpose of creating a customized Color Checker to match cyanobacteria color samples. A standard color-rendition chart, or color checker, exists for general use in photography and other such applications. The colors on this chart were chosen to represent colors that are frequently the target of images, such as different skin tones, foliage, and blue sky [11]. Creating a customized variation on this idea for a more specific purpose was previously exemplified for farmers' use in cultivating rice crops. The University of California Cooperative Extension created a "meaningful range of green plastic chips ranging from yellowish green to dark green" in such a way to match the color of rice leaves over a range of nitrogen levels within the plant [12]. One of the goals of this study was to determine a similar "meaningful range" of colors of cyanobacteria and green algae. Ideally, the colors measured for the cyanobacteria and algae would match colors from the Munsell Book of Colors so the customized color checker could be made from samples for which the color information is already known and visual Munsell papers are available.

The CIE also defined standard illuminants for use in laboratory settings. A standard illuminant is a mathematical representation of a light source with a specific relative spectral power distribution that exists physically [8]. Illuminant A is defined as a representation of typical tungsten incandescent lighting. Illuminant D65 is defined as a representation of average daylight [13]. Since the most likely application of this project is outside, in the field near ponds or lakes, D65 will be the most relevant.

Methods

A colonial strain of cyanobacteria, gloeocapsa, and a filamentous strain of cyanobacteria, anabaena, were grown at the Rochester Institute of Technology's Munsell Color Science Laboratory. A colonial green alga, scenedesmus, and a filamentous green alga, spirogyra, were also grown contemporaneously. Each genus was sub-cultured into three 500 mL Erlenmeyer flasks. A lighting construct was placed above the flasks to suspend 40 Watt, cool white fluorescent bulbs above the flasks in which the bacteria and algae were growing. The lights were set on a timer with a circadian rhythm of 16 hours on to 8 hours off. The desk on which the flasks were placed was covered in white paper in order to reflect light back up into the samples. The samples were occasionally aerated using an aquarium pump and a tube from the aerator into the flask.

The samples were extracted from the flasks using pipettes and injected into 10 mL cuvettes for measurement and image capture. A sample was created for concentrations ranging 5-100% cyanobacteria, with the concentration starting at 100% and decreasing by increments of 5%. The cuvettes were then placed in the lab's Gretag Macbeth ColorEye 7000A spectrophotometer, where measurements of the transmission spectrum and the $L^*a^*b^*$ coordinates under illuminants A and D65 were measured. The measurements of each sample were made three times and averaged together.

After the spectrophotometric measurements, the cuvettes were placed in a sample holder on an optics bench. The phones were mounted on a tripod 20 cm from the sample. A gray board was placed 24 cm behind the sample as a neutral background. The phones were chosen in order to cover a range of camera quality. Images were then taken with each phone of the sample with HDR off and HDR on, in front of the gray background and the black wall behind the sample when the gray board was removed. The illuminance of the light was monitored using a luxmeter in order to keep the lightness and the interaction of the light with the glass cuvette as consistent as possible.

The images were next imported into MATLAB, where the color coordinates were averaged row by row. This was done using images cropped so only a rectangle cut out of the cuvette containing the sample was visible. These results were then

compared to the results measured by the spectrophotometer. This comparison was then used to determine the approximate threshold at which it could be reliably determined that cyanobacteria or algae was present in the water sample.

The $L^*a^*b^*$ values for each cyanobacteria and algae were then compared to data for the Munsell Book of Colors. The Munsell data are available for free online from the Munsell Color Science Laboratory [14]. Some of the most closely matching colors were then chosen, creating a preliminary cyanobacteria color checker. This color checker, while not necessarily meaningful directly in imaging, can provide a sanity check for field workers collecting samples.

The $L^*a^*b^*$ values were then converted to $L^*C_{ab}^*h_{ab}$ values. The values were used as another determination of whether cyanobacteria can be distinguished from green algae. C_{ab}^* values, being the most consistent between concentrations, could be used to determine a transformation of the $L^*C_{ab}^*h_{ab}$ values from the image captures in order to make them better align with the values found in the spectrophotometer measurements. h_{ab} values can also be used to judge the relative difference of the colors of the cyanobacteria and green algae. If h_{ab} values are visibly different between genus, fewer images are necessary to identify the presence of or to distinguish between cyanobacteria and green algae. The range of h values would also be expected to have a range within an individual genus with images taken at different concentrations. More image captures would be required for distinction if the ranges of h values overlap slightly between genus. If the ranges of values significantly overlap then h values are not useful in determining which organism is present.

Results

The images taken using the four smartphones for each organism at 100% concentration in front of the black background are shown in Figures 1-4. The transmittance curves of the four organisms are presented in Figures 5-8. Plots were then generated to relate the color coordinates measured by the spectrophotometer and the phones. A plot of the transmittance of each organism at 20% concentration is given in Figure 9. To interpret the data, the C_{ab}^* values measured by the spectrophotometer were plotted on the x-axes and the C_{ab}^* values taken from the images were plotted on the y-axes. The data are displayed in Figures 10-13. An example of the C^* values for all organisms on one phone camera is shown in Figure 15.

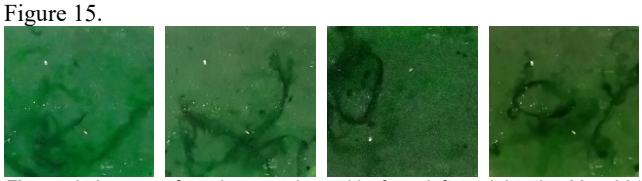

Figure 1. *Images of anabaena taken with, from left to right, the May 2015 smartphone, the April 2015 smartphone, the 2010 smartphone, and the Jan. 2015 smartphone.*

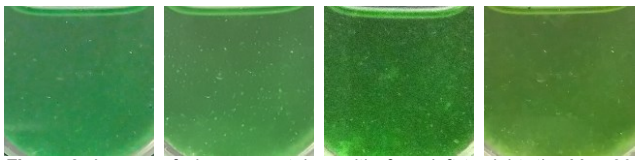

Figure 2*. Images of gloeocapsa taken with, from left to right, the May 2015 smartphone, the April 2015 smartphone, the 2010 smartphone, and the Jan. 2015 smartphone.*

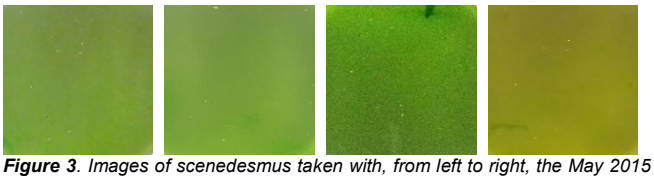

Figure 3*. Images of scenedesmus taken with, from left to right, the May 2015 smartphone, the April 2015 smartphone, the 2010 smartphone, and the Jan. 2015 smartphone.*

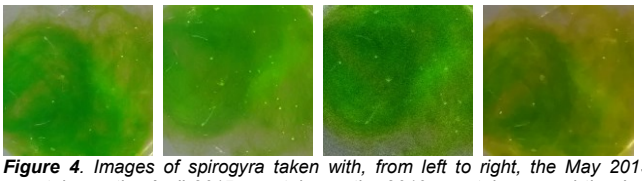

Figure 4*. Images of spirogyra taken with, from left to right, the May 2015 smartphone, the April 2015 smartphone, the 2010 smartphone, and the Jan. 2015 smartphone.*

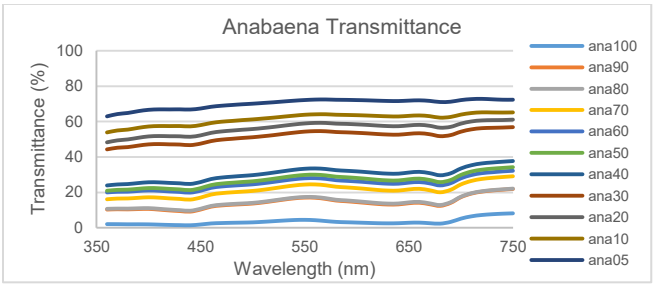

Figure 5. *The transmittance of light through samples of anabaena at different concentrations across the visible range of light.*

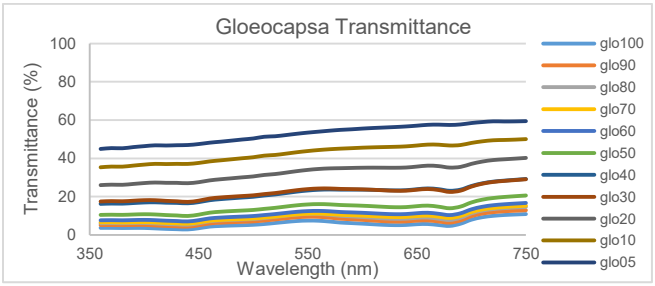

Figure 6. *The transmittance of light through samples of gloeocapsa at different concentrations across the visible range of light.*

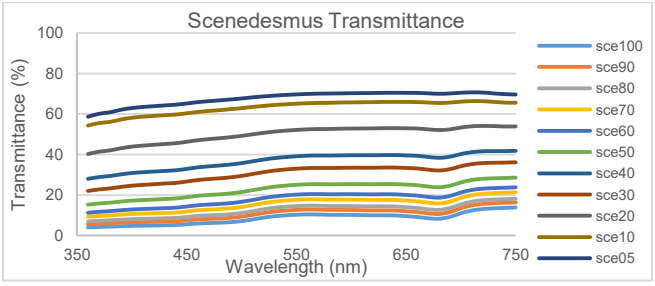

Figure 7. *The transmittance of light through samples of scenedesmus at different concentrations across the visible range of light.*

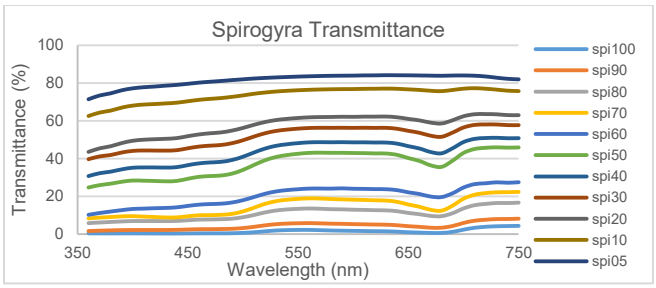

Figure 8. *The transmittance of light through samples of spirogyra at different concentrations across the visible range of light.*

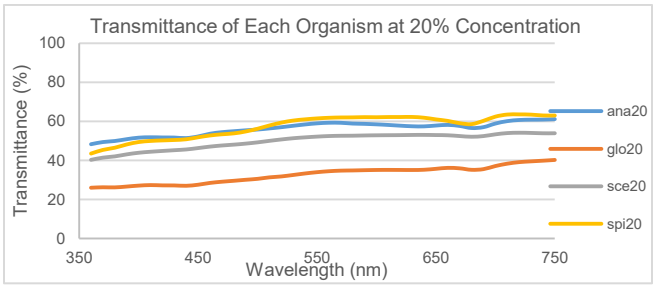

Figure 9. *An example of the behavior of each organism at one concentration.*

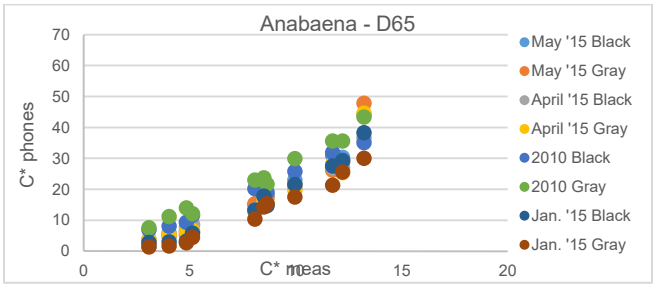

Figure 10a. *The relationship of C* measured by the spectrophotometer vs. C* taken from the phones for anabaena, the filamentous cyanobacteria.*

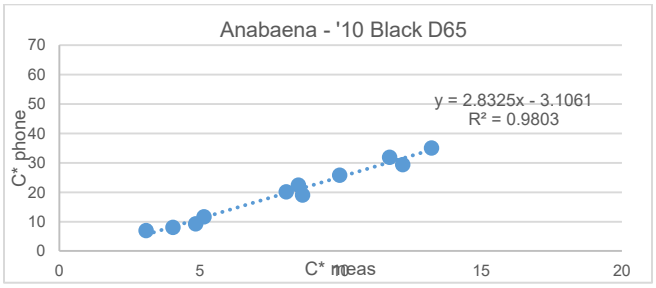

Figure 10b*. An individual example of the plot of C^*_{meas} vs. C^*_{phone} for the anabaena.*

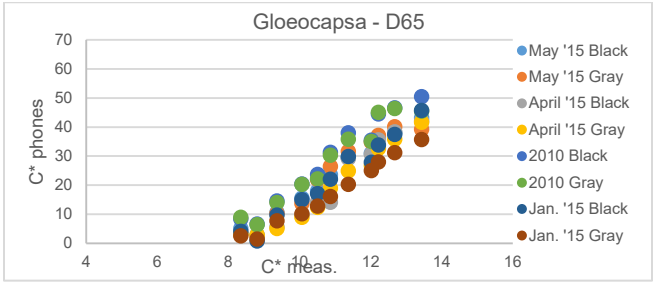

Figure 11a*. The relationship of C* measured by the spectrophotometer vs. C* taken from the phones for gloeocapsa, the colonial cyanobacteria.*

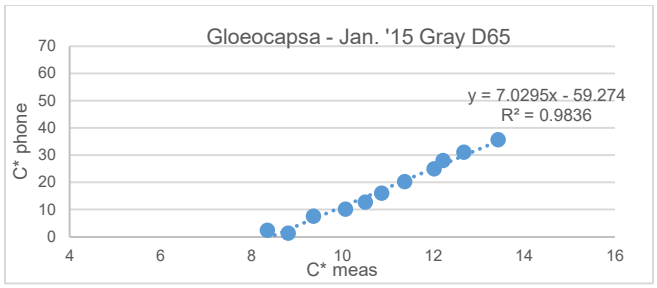

Figure 11b*. An individual example of the plot of C^*_{meas} vs. C^*_{phone} for the gloeocapsa.*

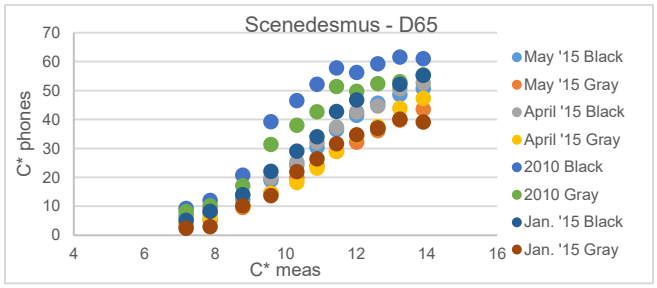

Figure 12a. *The relationship of C* measured by the spectrophotometer vs. C* taken from the phones for scenedesmus, the colonial green algae.*

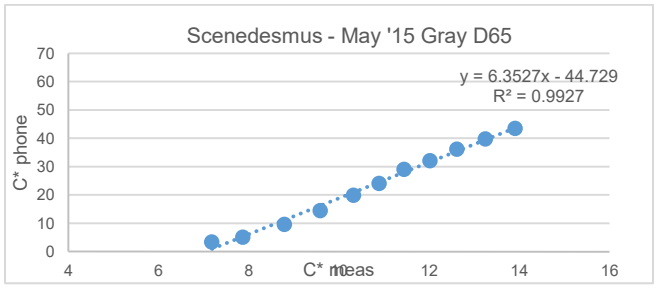

Figure 12b*. An individual example of the plot of C^*_{meas} vs. C^*_{phone} for the scenedesmus.*

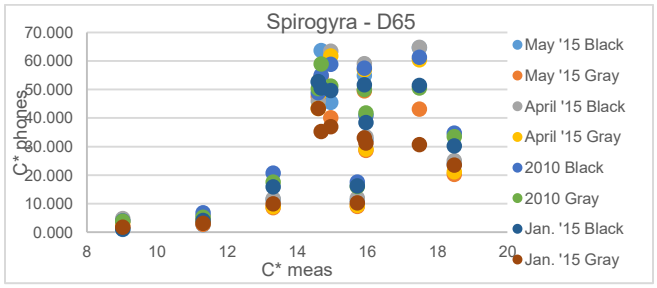

Figure 13*. The relationship of C* measured by the spectrophotometer vs. C* taken from the phones for spirogyra, the filamentous green algae.*

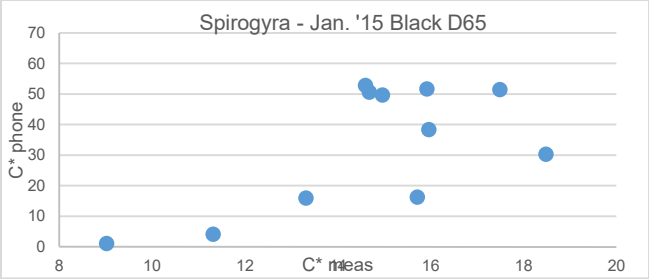

***Figure 13b**. An individual example of the plot of C^*_{meas} vs. C^*_{phone} for the spirogyra.*

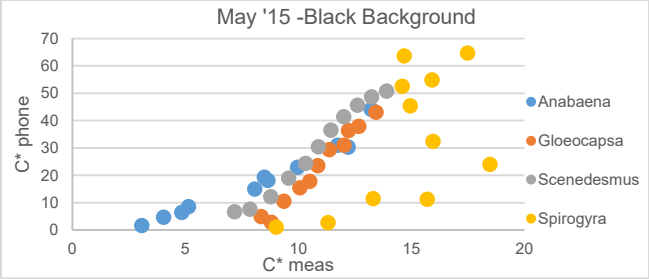

***Figure 14**. A plot of C_{meas}* vs. C_{phone}* for each organism on one phone.*

The images taken of each organism with each smartphone, shown in Figures 1-4, demonstrate how each camera behaves. The cyanobacteria appear green to blue-green, while the green algae appear green to green-yellow. This is to be expected, given the nature of the organisms, and is encouraging for the idea that the cameras are capturing the colors somewhat accurately. The May 2015 smartphone appears to capture images that appear more blue-green for the cyanobacteria and greener for the green algae. On the other hand, the Jan. 2015 smartphone tended to capture yellower images. This demonstrates that the cameras between smartphones are inconsistent. This inconsistency demonstrates the necessity for further work using a wider variety of smartphones.

According to Figure 9, the organisms tend to transmit similarly; their transmittance curves all follow roughly the same pattern, though the gloeocapsa has a significantly lower transmittance than the other three organisms. Overall, the results over the four smartphones follow the same general trends, as shown in Figures 10-13, despite the images appearing to be different colors. The x-axes of the graphs are not the same between figures, though they all cover a range of 12 C_{ab}^* units. The plots for each range of concentrations of three of the organisms all followed the same generally linear pattern. The two cyanobacteria, anabaena and gloeocapsa, and the colonial green algae, scenedesmus, behaved linearly and consistently between the phones. The filamentous green algae, spirogyra, presented a stranger pattern. The trend was still consistent between each phone, but instead of behaving linearly, the relationship was S-shaped. This is due to the filamentous nature of the spirogyra, visible in Figure 13. At low concentrations, the spirogyra behaved linearly, though as the concentration increases, spatial relationships of the sample become more of a factor in the color of the images. The colonial genus were dispersed uniformly throughout the samples. The filamentous algae, however, began gravitating together and forming clumps. Where the other organisms functioned on a monotonic relationship, the spirogyra is a non-monotonic relationship. As the clumps form, the C_{ab}^* from the smartphone continues to increase but the C_{ab}^* from the spectrophotometer decreases. A possible explanation for this is the difference in area being measured by the cameras and the spectrophotometer. The cameras average together large numbers of smaller digital measurements, while the spectrophotometer takes only the measurement through a small hole.

The anabaena, the filamentous cyanobacteria, behaves very linearly overall, shown in Figure 10b. This is in contrast with the filamentous green algae; the points of the graph of the anabaena tend to separate out into three groups in the same way that the points of spirogyra, shown in Figure 13b, separated out into three groups. However, the three groups of the spirogyra changed direction; there was first a positive linear relationship, then a negative linear relationship, back to a positive linear relationship. The anabaena's three groups continue in the same positive linear relationship. This makes sense, because the organism starts with little clumps spread out across the water in the sample. As the concentration increases, the clumps begin to aggregate more, making larger clumps and allowing more of the light through in the space around them. This behavior lasts until the concentration gets so high that the large clumps spread all the way through the sample. Then, as the clumps begin to take up the majority of the sample, the C_{ab}^* measured by the spectrophotometer increases again.

In Figure 14, the colonial gloeocapsa and scenedesmus are shown to have similar slopes to their linear behavior. This seems like a positive sign for the use of smartphone cameras to accurately model the behavior of similar organisms. The fact that the grouping of the filaments is consistent between the cyanobacteria and green algae but the overall behavior is different is interesting and perhaps should be looked into further.

The ranges of hue data for each phone are accrued in Table 1. The data show how the images skew in hue for each organism and for images taken with a black and a gray background.

Table 1. Range of hue values for each organism

		May-15		Apr-15		2010		Jan-15	
		h Black	h Gray	h Black	h Gray	h Black	h Gray	h Black	h Gray
Filamentous	Anabaena	144.4-157.5	135.2-149.7	138.9-146.0	129.2-142.8	141.4-158.7	139.2-148.6	129.3-173.3	104.9-147.5
	Spirogyra	112.8-139.4	107.8-125.4	116.1-149.6	110.6-122.9	121.1-174.7	117.8-169.7	98.2-113.1	92.7-103.7
Colonial	Gloeocapsa	147.3-185.3	142.3-157.1	135.5-148.2	121.9-137.4	139.1-162.7	137.5-165.0	105.9-136.8	94.2-132.1
	Scenedesmus	120.6-129.6	113.5-124.6	121.5-132.8	113.2-117.4	121.5-141.6	119.2-145.1	96.5-105.8	88.3-98.4

Looking at how the range of h values compare can determine if the phones can be used to distinguish between similar cyanobacteria and green algae genus. The gray background makes the images appear more yellow than the images in front of the black background, which register as closer to yellow-green. The green algae also are more yellow than their cyanobacteria counterparts, as expected. The idea of this method was to determine how many images are necessary to correctly identify the organism. Fewer images will be required when there is no overlap. Slight overlap indicates that many images will be necessary to correctly categorize the organism. When there is significant overlap then this method of comparison will not be meaningful.

The May 2015 phone works well for distinguishing the cyanobacteria from the green algae. There is a gap between the ranges of h values of both the filamentous and colonial cyanobacteria and green algae, especially the colonial ones. The April 2015 phone had a suitable gap between h values for the colonial organisms for both backgrounds and the filamentous organisms for the gray background. However, there was significant overlap in the filamentous organisms in front of a black background. There was overlap of h ranges for all categories of

comparison for the 2010 phone, suggesting that older phones might not have the color capabilities necessary for this application. The only category of overlap for the January 2015 was the colonial organisms with a gray background. The other ranges are extremely close to overlapping, though. This suggests that a camera on par with the January 2015 phone will work for these purposes, but many images will be required to ensure identification. Further work is required to determine exactly how many images will be necessary. The 2015 phones all tended to perform comparably, even though the phones were chosen to have a range of megapixels in their rear cameras. Newer phones were not tested in this project, though it may be that newer phones will work as well or better than the 2015 phones. However, newer smartphones also tend to have more white balance processing. The white balance occurs automatically and could change colors in an image to better relate to a given white point.

A table containing the measured $L^*a^*b^*$ values and the matched $L^*a^*b^*$ values for each organism at each concentration is presented in Table 2. The color checker generated to match the measured colors is displayed in Figure 15 [15].

Table 2. Color coordinates of the spectrophotometer measurements for each organism and the Munsell matches

		100%	80%	50%	20%
Anabaena	Meas L*	42.43	50.23	54.04	60.33
	Match L*	41.22	51.58	51.58	61.70
	Meas a*	-26.73	-23.06	-15.00	-6.98
	Match a*	-28.89	-18.83	20.39	-11.34
	Meas b*	21.27	18.18	11.50	4.08
	Match b*	23.42	15.25	10.49	10.49
	Color Designation	10GY 4 6	10GY 5 4	2.5G 5 4	5G 6 2
	delta C*	-3.03	5.13	-4.03	-4.00
Gloeocapsa	Meas L*	55.48	59.73	62.46	70.58
	Match L*	51.58	61.70	61.70	71.60
	Meas a*	-34.37	-26.73	-17.98	-8.66
	Match a*	-37.57	-28.67	-21.49	-11.53
	Meas b*	31.88	24.56	16.73	7.58
	Match b*	31.76	24.39	11.42	6.37
	Color Designation	10GY 5 8	10GY 6 6	2.5G 6 4	2.5G 7 2
	delta C*	-2.32	-1.34	0.22	-1.66
Scenedesmus	Meas L*	58.64	60.87	64.13	68.55
	Match L*	61.70	61.70	61.70	71.60
	Meas a*	-19.28	-15.90	-11.45	-6.52
	Match a*	-25.43	-15.50	-13.80	-6.18
	Meas b*	50.20	41.37	29.53	14.87
	Match b*	51.41	41.56	25.20	14.63
	Color Designation	5GY 6 8	10GY 6 6	2.5GY 6 4	2.5GY 7 2
	delta C*	-3.58	-0.03	2.94	0.36
Spirogyra	Meas L*	49.93	59.94	63.39	68.55
	Match L*	51.58	61.70	61.70	71.60
	Meas a*	-26.92	-20.11	-13.90	-4.36
	Match a*	-24.93	-19.81	-15.50	-9.54
	Meas b*	43.78	43.17	37.15	10.35
	Match b*	50.52	37.75	41.56	11.19
	Color Designation	5GY 5 8	5GY 6 6	2.5GY 6 6	7.5GY 7 2
	delta C*	-4.94	4.99	-4.69	-3.45

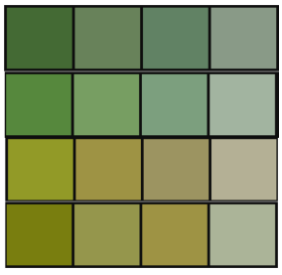

Figure 15*. Color checker for use in the field for quick comparisons. Anabaena is in the top row, followed by gloeocapsa in the second row, scenedesmus in the third row, and spirogyra in the second row. 100% concentration is shown in the leftmost column, followed by 80%, 50%, and 20% in the fourth column.*

The matches were found using the colors found for each concentration using the four smartphones. For the three linearly behaving organisms, the formulae for the trendlines, where the measured chroma values were input as X-values, were used to find "corrected" chroma values for the transmission measurements. The values from each plot were then averaged to find an adjusted C^* value. The same concept was used for adjusted L^* values, though only the values found from images in front of a black background were used in this case. This adjustment process was more difficult for the nonlinear spirogyra. For the spirogyra, three trendlines were fit to the plot as a piecewise function. The same process was then followed, where the C_{ab}^* values were input into the piecewise function based on the range of each piece of the function. However, the lightness range for the spirogyra was close enough to linear that the linear fit was also used in this case. The $L^*C_{ab}^*h_{ab}$ values were then transformed back to $L^*a^*b^*$ format in order to match the Munsell colors, which were given in $L^*a^*b^*$ format [14].

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The cyanobacteria matches are demonstrably more blue-green than the green-yellow of the green algae. This should be useful to laypeople who are not familiar with the differences between cyanobacteria and green algae but who want to participate in the crowdsourcing of water quality data or want to know if the water on their property is safe to use. However, these are still ballpark colors, because as can be seen in Table 2, the differences in chroma between the measurements and the Munsell matches are still sometimes fairly large. These ΔC_{ab}^* values are noticeably smaller for the colonial organisms, the gloeocapsa and scenedesmus, than for the filamentous organisms, the anabaena and the spirogyra. This implies that the idea of a color checker may be best implemented with the colonial organisms. This makes logical sense, because the colors of the colonial organisms are more consistent and uniform throughout the samples than throughout the filamentous samples. This is not to say that the method used here does not work for filamentous organisms, just that it is less precise for the filamentous organisms than for the colonial organisms.

Results

On the whole, the linear results are exciting. The linear relationship indicates that modeling of the behavior should be possible. Further work will be needed to characterize the relationship entirely but this study has given hope that it should be possible to do so.

The widest range of h values almost always comes from the spirogyra images, indicating even more that, while this technique is feasible for colonial organisms and some more globular filamentous organisms, it is not as successful for filamentous organisms with long, branching tendrils.

Additionally, further measurements and fine tuning would be required to make a perfectly tailored color checker for one organism. Even more work would be required to create a color checker that adequately represented multiple types of cyanobacteria. It is also almost certain that a sample from the field would contain other substances than just purely water and cyanobacteria. Possible contamination and combination of different kinds of organisms should also be taken into consideration in future work. Nevertheless, this color checker should be handy for a quick check.

References

[1] R. Y. Stanier, R. Kunisawa, M. Mandel, G. Cohen-Bazire, "Purification and Properties of Unicellular Blue-Green Algae (Order Chroococcales)," Bacteriological Reviews, 35, pp. 171-205, 1971.

[2] R. Amils, Encyclopedia of Astrobiology, Springer Berlin Heidelberg, p. 1230, 2011.

[3] M. Drikas, C. W. Chow, J. House, M. D. Burch, "Toxic cyanobacteria," American Water Works Association Journal, 93, pp. 100-11, 2001.

[4] S. Orr, "Blue-green algae toxin in drinking water worries upstate New York," Democrat and Chronicle, http://www.usatoday.com/story/news/nation-now/2016/09/29/blue-green-algae-toxin-drinking-water-worries-upstate-new-york/91294324/, 9/29/16.

[5] New York State Department of Environmental Conservation, Harmful Algal Blooms (HABs), http://www.dec.ny.gov/chemical/77118.html, 2017.

[6] Division of Water, New York State Department of Environmental Conservation, DEC Harmful Algal Bloom Program Guide Version 1, http://www.dec.ny.gov/docs/water_pdf/habsprogramguide.pdf, 2017

[7] United States Environmental Protection Agency, "Guidelines and Recommendations," https://www.epa.gov/nutrient-policy-data/guidelines-and-recommendations, 2017.

[8] R. S. Berns, Billmeyer and Saltzmann's Principles of Color Technology, 3rd ed. Wiley-Interscience, New York, 2000.

[9] M. D. Fairchild, Color Appearance Models, 3rd ed. John Wiley & Sons, Ltd., West Sussex, UK, 2013, p. 80.

[10] x-rite, Pantone, "A Guide to Understanding Color," https://www.xrite.com/-/media/xrite/files/whitepaper_pdfs/l10-001_a_guide_to_understanding_color_communication/l10-001_understand_color_en.pdf, 2016.

[11] C. S. McCamy, H. Marcus, and J. G. Davidson, "A Color-Rendition Chart," Journal of Applied Photographic Engineering, 2, pp. 95-99, 1976.

[12] C. Witt, J. M. C. A. Pasuquin, R. Mutters, and R. J. Buresh, "New leaf color chart for effective nitrogen management in rice," Better Crops, 89, pp. 36-39, 2005.

[13] CIE Standard Illuminants for Colorimetry, Joint ISO/CIE Standard, ISO 10526:1999/CIE S005/E-1998.

[14] Munsell Color Science Laboratory, "Munsell Renotation," https://www.rit.edu/cos/colorscience/rc_munsell_renotation.php

[15] ColorMunki, "Munsell | PATNONE™ Goe coated," www.colormunki.com/munsell, 2017.

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