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UAV-based hyperspectral imaging for river algae pigment estimation and development of a low-cost multispectral imager

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ABSTRACT

Harmful and nuisance algal blooms are becoming a greater concern to public health, riparian ecosystems, and recreational uses of inland waterways. Algal bloom proliferation has increased in the Upper Clark Fork River in western Montana, USA, due to a combination of warming water temperatures, naturally high phosphorus levels, and an influx of contaminants through anthropogenic nitrogen enrichment along its banks. To improve understanding of bloom dynamics, such as algal biomass, a UAV-based hyperspectral imaging system was deployed to monitor several locations along the Upper Clark Fork River. Image data were collected across the spectral range of 400 - 1000 nm with 2.1 nm spectral resolution during two field sampling campaigns in 2021. Included are methods to estimate chlorophyll *a* standing crops using regression analysis of salient wavelength bands, before and after separating the pigments according to growth form. Estimates of total chlorophyll *a* standing crops generated through a brute-force analysis are compared to in-situ data, resulting in a maximum r-squared of 0.62 for estimating filamentous plus epiphytic chlorophyll *a*. Estimates of total and epilithic pigment standing crops are also included. The salient wavelengths bands used to estimate these pigments were then used as the basis for creating a low-cost imaging system for identifying algal blooms.

Keywords: River Remote Sensing, Hyperspectral Imaging, Ecology, Algal Blooms, Unoccupied Aerial Vehicles

1. INTRODUCTION

In the early 1970s, the Upper Clark Fork River (UCFR) in western Montana began experiencing its first recorded blooms of the the nuisance algae, *Cladophora glomerata*.[1] The UCFR has a long history of contamination through the influx of mining waste and anthropogenic nitrogen enrichment, which, combined with naturally high phosphorus levels and warming water temperatures, has led to algal bloom proliferation.[2,3] The presence of large nuisance blooms of *Cladophora* has been associated with decreased benthic biodiversity,[4] disrupted pH and dissolved oxygen levels,[5,6] interrupted recreational opportunities,[5,7,8] and a general decrease in water quality.[5,7–9] The severity and extent of an algal bloom is often measured in terms of its pigment concentration and spatial coverage in the water body.

Like many green plants, *Cladophora* relies on the pigment, chlorophyll *a* (chl *a*), for photosynthesis, the concentration of which is commonly used to assess bloom severity for several different algal types.[10,11] The concentration of chl *a* is commonly used to indicate the trophic state of a water body due to its direct relationship with algal production and nutrient cycling, making it an effective proxy for water quality. Conventional

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methods for measuring chl *a* concentrations require gathering algal samples *in situ*, then processing them in the laboratory. Though *in situ* sampling is an effective means of gathering information on an algal bloom, such spot sampling introduces several shortcomings. As each sample contained within a plot must be cleaned, rinsed, and separated, analyzing a single plot can be a lengthy process. These samples are gathered from a small number of plots distributed in a limited area, leading to poor spatial resolution. Finally, samples must be collected in the field then processed in the laboratory, causing long delays between sample collection and results. Spaceborne and airborne remote sensing systems have emerged as a common means of overcoming the shortcomings of *in situ* sampling.[12]

Satellite-based remote sensing systems have been employed to measure freshwater algal bloom activity through estimates of chl *a* concentration in lakes[13,14] and reservoirs;[15] however, the coarse spatial resolution of most satellites limits their application to large water bodies. Airborne systems are capable of solving this problem by capturing high-spatial-resolution imagery[16] and have been used to assess bloom characteristics in lakes[17,18] and, in limited cases, large rivers.[19,20] Airplane-based remote sensing systems solve the problem of poor spatial resolution, but introduce problems associated with fly-over paths and high costs.[21] Unoccupied aerial vehicles (UAV) have been introduced as a solution to the poor spatial resolution of satellite-based systems, while also being a low-cost alternative to airplane-based systems.

UAV-based remote sensing systems have become a popular method for estimating pigment concentration in lakes[22–24] and large rivers.[25,26] in addition to pigment concentration estimation, UAV-based systems have been used to assess the spatial coverage of algal blooms in smaller rivers.[27] Estimation of pigment concentration and assessment of spatial coverage of a bloom relies on the analysis of spectral content of imagery, regardless of the platform from which the imagery is obtained. Due to this, hyperspectral imagers are commonly employed to take advantage of their high-spectral-resolution and imaging ability. Analysis of spectral data commonly involves the use of band ratios, or the manipulation of the spectral bands captured by the imager;[16,28,29] however, most methods for monitoring algal bloom activity are developed to measure pigment concentration (density per volume) instead of standing crops (density per area).

In this paper, a method for estimating both the spatial extent of nuisance blooms of *Cladophora* and algal standing crops of the pigment chl *a* using a UAV-based hyperspectral imaging system are outlined. In addition, these proposed methods are used to inform the design of a low-cost multispectral imager capable of identifying blooms of *Cladophora*. This works is based off of the manuscript *UAV-Based Hyperspectral Imaging for River Algae Pigment Estimation*.[30]

2. METHODS

2.1 Study Sites

Algal monitoring was performed at field sites along the UCFR in western Montana (Figure 1). The UCFR forms at the confluence of Warm Springs Creek and Silver Bow Creek, creating a clear and shallow cobble-bed river with a history of eutrophication and large nuisance algal blooms.[1–3] Two primary field sites were chosen along the main stem of the UCFR for data collection: Gold Creek (*46.59°N, 112.93°W*) and Bear Gulch (*46.70°N, 113.43°W*). The selected field sites had similar width (30 and 28 m) and depth (35 cm) during data collection, have little shading from the surrounding canopy, and have historically contained elevated nutrient levels likely due to anthropogenic activity,[31] combining to create conditions conducive to algal bloom growth.

2.2 UAV-Based Imaging System

2.2.1 Imager

Hyperspectral image data were collected using a Pika L airborne hyperspectral imaging system (Resonon Inc., Bozeman, MT, USA) fitted with a 17-mm objective lens, with a 17.6° full-angle field of view. The Pika L is a pushbroom-style imager that collects spectral data from 387 - 1023 nm with a nominal spectral resolution of 2.1 nm, leading to 300 spectral channels. The Pika L interfaced with an airborne system that included a flight computer with onboard storage, GPS, IMU, and downwelling irradiance sensor, creating the payload for the UAV.

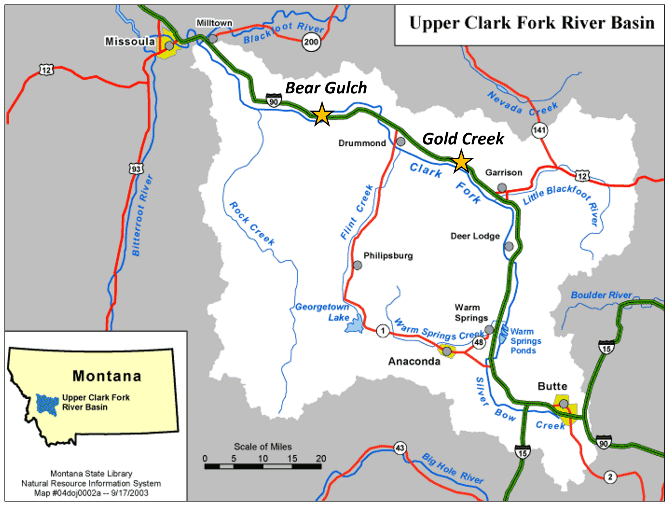


Figure 1. The Upper Clark Fork River forms at the confluence of Warm Springs Creek and Silver Bow Creek in western Montana. The Bear Gulch and Gold Creek field sites are marked with gold stars.[32]

2.2.2 UAV

The Pika L imaging system was mounted to a DJI Matrice 600 Pro hexacopter (DJI, Shenzhen, China) using a DJI Ronin-MIX gimbal system. When in a flight-ready state, with frame arms, propellers and GPS antennae unfolded, the Matrice 600 Pro measures 16.7 x 15.2 x 72.7 cm and weighs approximately 9.5 kg. The UAV is capable of maintaining flight with a total of 15 kg, yielding a maximum payload of 5.5 kg.

The UAV was controlled via a remote controller using a 2.4 GHz radio link with a maximum transmission distance of approximately 5 km. Flight plans were generated using DJI Ground Station Pro software and linked to the remote controller via a tablet. In addition to the airborne imaging system GPS, location information was gathered by three additional GPS antennae aboard the UAV.

2.2.3 Flight Overview

UAV flights were performed by, or under the supervision of, a pilot certified through the Federal Aviation Administration (FAA) Part 107 licensure process during each data collection campaign. The airspace above each field site was verified using the FAA-certified AirMap software (AirMap, Santa Monica, CA, USA). Flights were planned and conducted at 120 m above ground level using DJI Ground Station Pro software on clear days with calm wind within two hours of solar noon (between approximately 11:00 - 15:00 MDT) to minimize changes in solar lighting conditions. Prior to flights, the imaging system and UAV were calibrated and inspected according to manufacturer recommendations[33,34] and imager settings were held constant throughout each flight.

3. RESULTS AND DISCUSSION

Estimation of pigment abundance began by analyzing total chl *a* standing crops (i.e., sum of filamentous, epiphytic, and epilithic growth forms) from all field sites and dates, with one outlying point removed from the 17 August Gold Creek data set (n = 33). This analysis generated three products: a correlation map, showing the R^2 values for every band ratio (Figure 3a); a histogram showing the frequency distribution of R^2 values generated by all possible band ratios (Figure 3b); and a linear regression between the best-performing band ratio and the targeted pigment standing crops (Figure 3c).

Analysis of total chl *a* standing crops from all field sites showed promising results, with the linear regression between standing crops and the optimal band ratio generating an R^2 = 0.57 with a root-mean square error (RMSE) = 66.29 mg/m^2. The brute-force method selected an optimal band ratio of 684/674 nm for estimating chl *a* standing crops, a spectral region which contains a known chl *a* absorption line near 670 nm.[35,36] The optimal band ratio had fairly unique performance, being one of eight which produced an R^2 above 0.4, of the 45,796 possible band ratios.

Although the brute-force algorithm produced favorable results for predicting total chl *a* standing crops, the ground truth data collection method provided a means of estimating standing crops from all growth forms present, as each was measured separately. Estimation of separate algal growth forms may be particularly useful when large filamentous blooms are present. Under these conditions, the filaments may obscure an aerial imaging system's view of epilithic growth on the surface of stones. Due to the nature of epiphytic algae, growing on the surface of the larger filamentous algae, these two forms cannot be separated. Therefore, growth forms were separated into two categories: filamentous plus epiphytic and epilithic.

After separating by growth form, the brute-force analysis was applied to each newly modified data set, excluding the outlying data point from 17 August at Gold Creek. The performance of standing crops estimations increased after separating into filamentous plus epiphytic growth forms, with the linear regression between chl *a* standing crops and the optimal band ratio of 684/674 nm generating an R^2 = 0.62. This band ratio was one of six which generated an R^2 above 0.50. Of particular note is the convergence on the band ratio of 684/674 for estimating both total and filamentous plus epiphytic standing crops, which may be indicative of a strong relationship with the known chl *a* absorption line, as well as supporting the claim that the aerial imaging system primarily detected filamentous growth.

Performance decreased after separating by, and estimating, epilithic algal growth. The brute-force method selected an optimal band ratio of 729/809 nm and generated an R^2 = 0.44 after linear regression. This optimal band ratio, which utilized longer wavelengths than those selected for estimating total and filamentous plus epiphytic standing crops, was less salient, being one of 47 which generated an R^2 above 0.40. Though analyzing epilithic growth forms separately led to decreased performance and a change in optimal band ratio, estimation performance for all growth forms showed promising results for a variety of chl *a* standing crop levels (Table 1).

Table 1. Average standing crops of chl *a* for each growth form (data are averaged across all field sites and dates, with n=6 at Gold Creek on 17 August, n=7 at Bear Gulch on 17 August, and n=20 at Gold Creek on 9 September), optimal band ratio, and R^2 after linear regression.

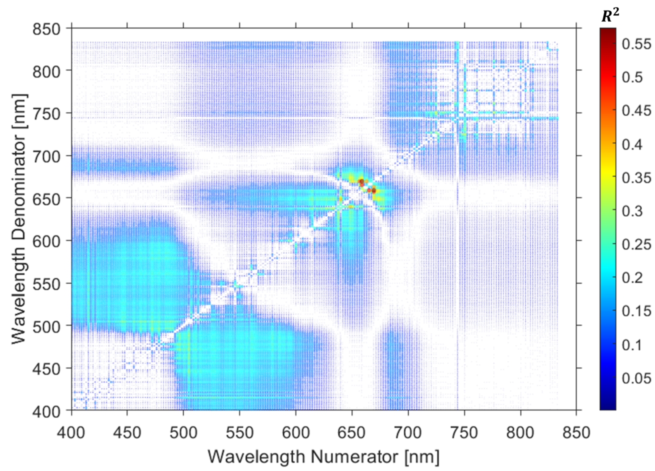
Growth Form	**Average Chl *a* Standing Crops (mg/m^2)**	**Optimal Band Ratio**	R^2
Total	187.0	674/684	0.57
Filamentous plus epiphytic	159.1	674/684	0.62
Epilithic	27.9	709/824	0.44

4. CONCLUSION

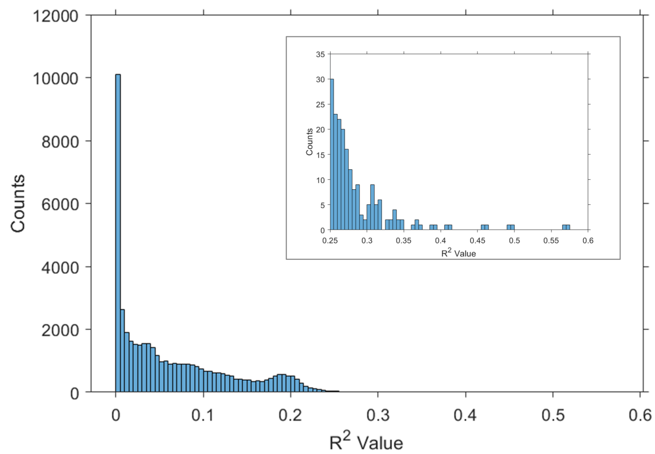
The optimal band ratios identified by the brute-force method presented here suggest that spectral analysis is a promising tool for estimating standing crops of chl *a* in nuisance blooms of *Cladophora* contained in clear and shallow rivers. Band ratios were capable of estimating standing crops for several growth forms of chl *a*, including filamentous plus epiphytic, epilithic, and their sum. The regions most sensitive to pigment abundance were often near chl *a* absorption lines, likely driving the selection of the optimal band ratios.

The optimal band ratios selected by the brute-force method informed the design of an early prototype multispectral imager. The imager relies on two spectral channels near the optimal band ratio for estimating total and filamentous plus epiphytic chl *a* standing crops of 674/684 nm, as well as green and near-infrared channels to aid in bloom identification. The multispectral imaging system will address some of the disadvantages of UAV-based hyperspectral imaging, such as high cost and the need for flight operators, by establishing a semi-permanent network of algae sensors capable of routine monitoring. A full description of the design and testing of this multispectral imager is presented elsewhere.[37]

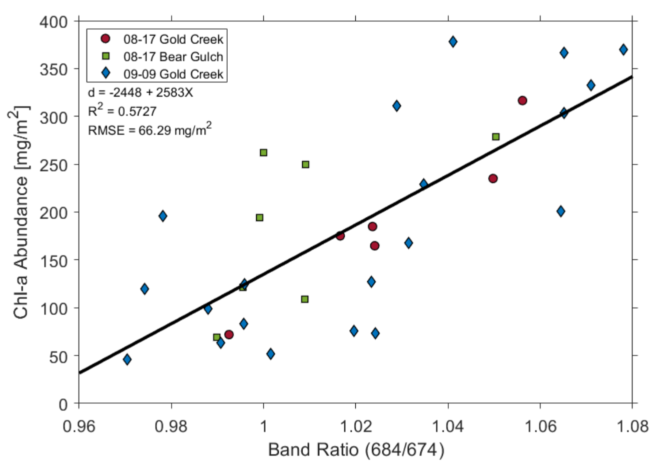
Though promising, more data must be collected to verify the performance of the optimal band ratios when estimating pigment standing crops throughout the summer growth season. The methodology and design of a multispectral imager represents early framework in developing a network of sensors capable of identifying and monitoring stretches of rivers that suffer from frequent algal bloom proliferation. In future work, more data will be collected to further refine and verify the performance of the work presented here, along with classification methods for mapping percent cover along river corridors.



(a) Correlation map of R^2 values calculated from each spectral band ratio using the brute-force analysis.



(b) Frequency distribution of R^2 values shown in the correlation map. The insert shows counts beyond an R^2 = 0.25, showing that the number of band ratios that generate an R^2 in this region decreases significantly.



(c) Linear regression between chl *a* standing crops (y-axis) and best-performing band ratio (x-axis).

Figure 2. Results from the regression analysis of total chl *a* standing crops (sum of filamentous, epipythic, and epilithic sources).

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