Environmental Public Health Surveillance of Freshwater Harmful Algal Blooms in Washington State Using Drone Technology

Joey Teresi, MS Student
April 29, 2024
WSEHA AEC

UNIVERSITY *of* WASHINGTON

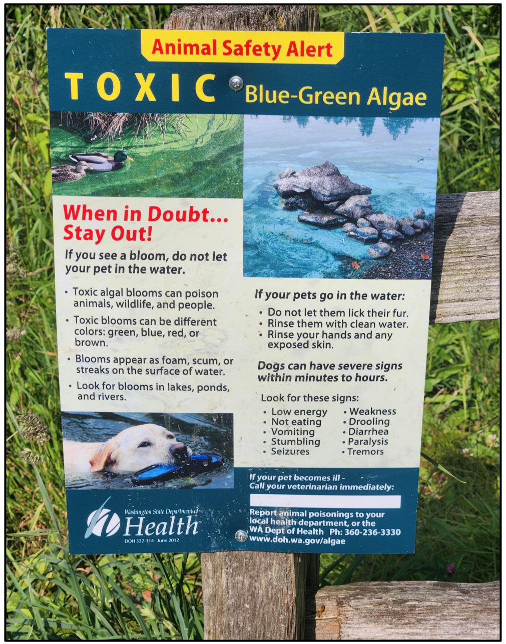
Outline

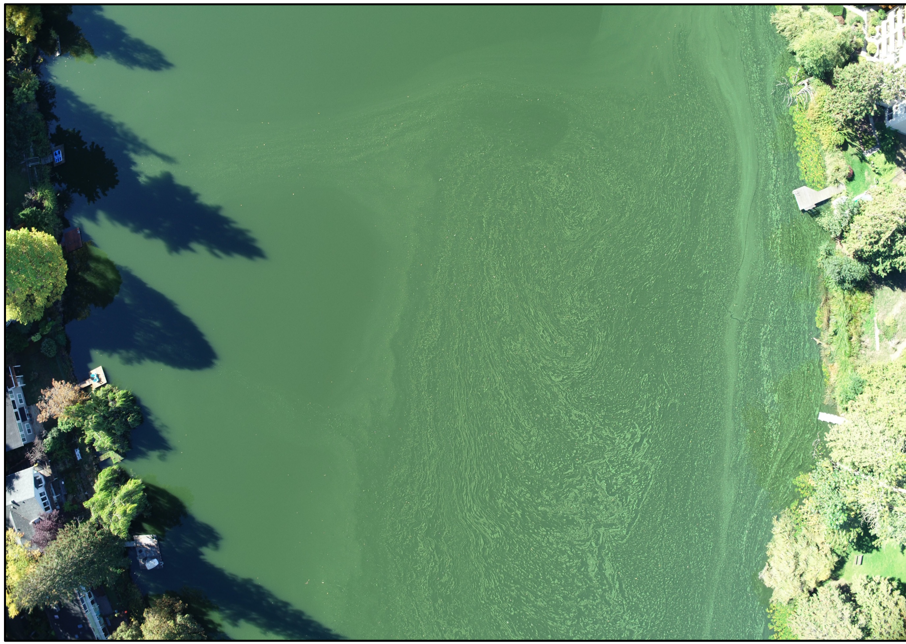
- Background
- Study Aims
- Methods
- Results
- Discussion
- Limitations
- Concluding Remarks
- Acknowledgments

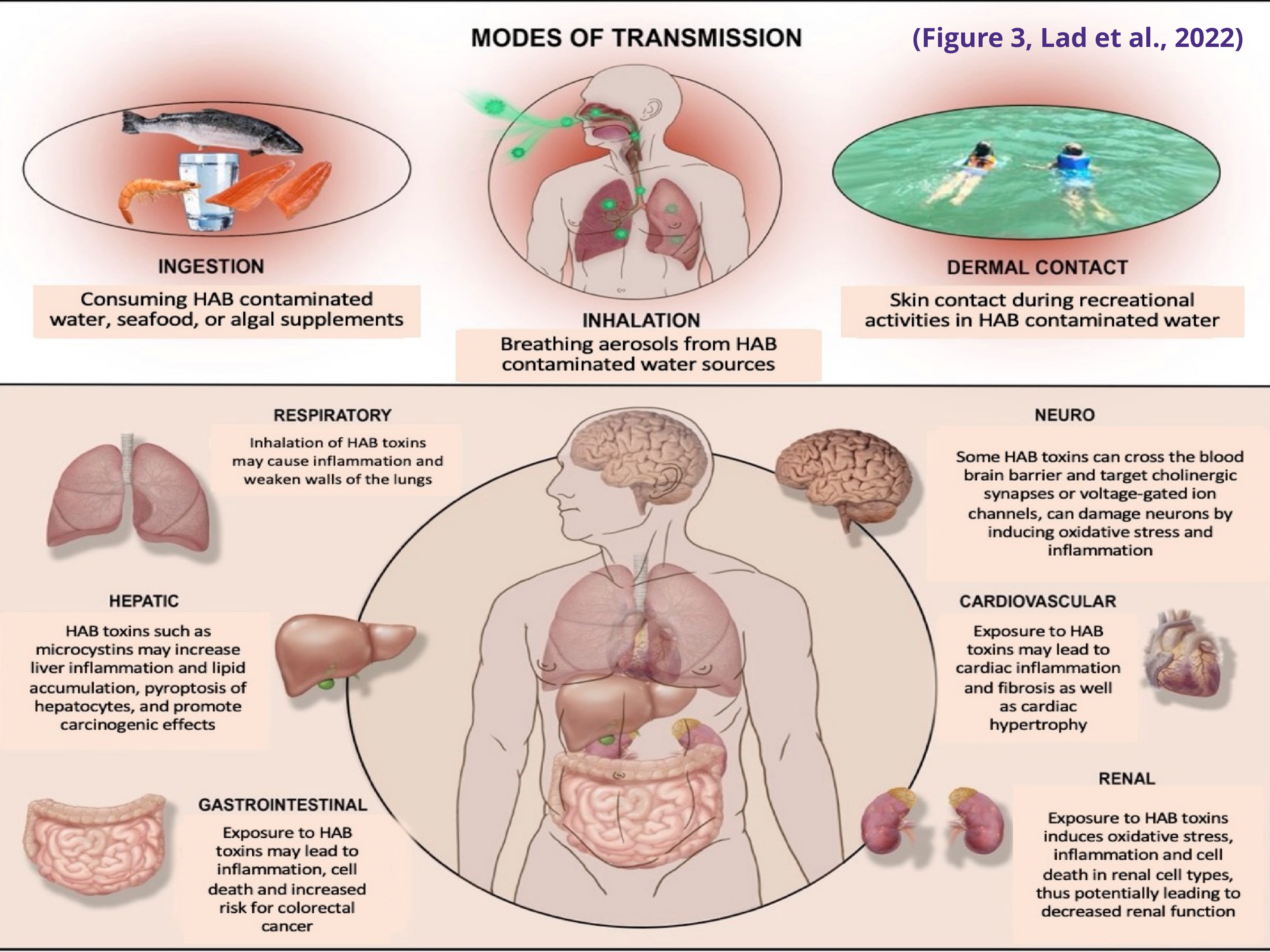
Background

Harmful Cyanobacterial Blooms (HCBs)

- Freshwater cyanobacteria (“blue-green algae”)
- Produce taste-and-odor compounds and potent toxins
- Threaten recreational and drinking water sources
- Frequency, duration, magnitude to increase with climate change



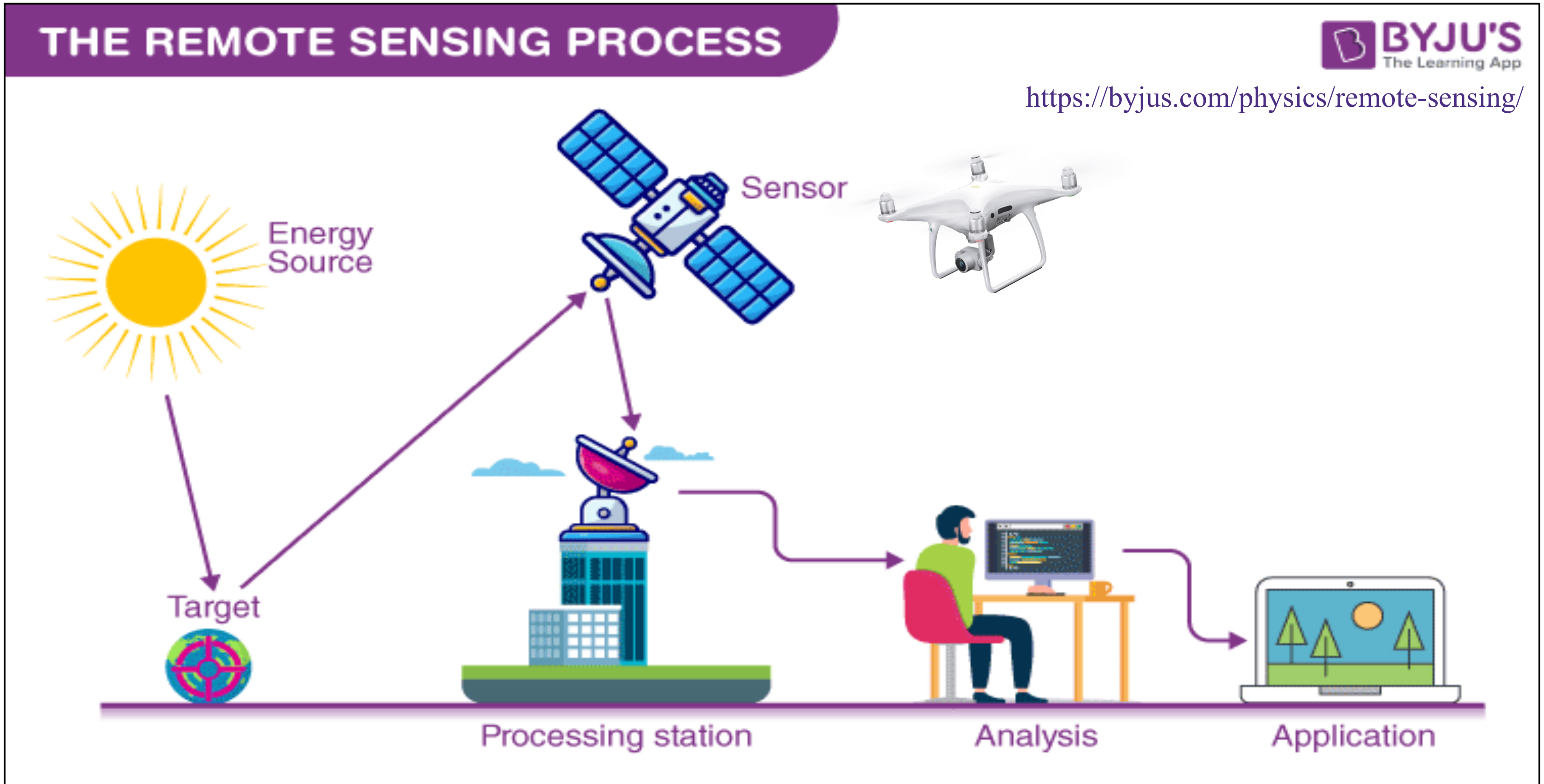




MODES OF TRANSMISSION
(Figure 3, Lad et al., 2022)
INGESTION
Consuming HAB contaminated water, seafood, or algal supplements
INHALATION
Breathing aerosols from HAB contaminated water sources
DERMAL CONTACT
Skin contact during recreational activities in HAB contaminated water
RESPIRATORY
Inhalation of HAB toxins may cause inflammation and weaken walls of the lungs
NEURO
Some HAB toxins can cross the blood brain barrier and target cholinergic synapses or voltage-gated ion channels, can damage neurons by inducing oxidative stress and inflammation
HEPATIC
HAB toxins such as microcystins may increase liver inflammation and lipid accumulation, pyroptosis of hepatocytes, and promote carcinogenic effects
CARDIOVASCULAR
Exposure to HAB toxins may lead to cardiac inflammation and fibrosis as well as cardiac hypertrophy
GASTROINTESTINAL
Exposure to HAB toxins may lead to inflammation, cell death and increased risk for colorectal cancer
RENAL
Exposure to HAB toxins induces oxidative stress, inflammation and cell death in renal cell types, thus potentially leading to decreased renal function

Remote Sensing Applications

> **Detection Tools**: **Tier I** (biological / bloom activity?) > **Tier II** (cyanobacteria?) > **Tier III** (cyanotoxins?)
  – Almuhtaram et al. (2021)



LIMNOLOGY AND OCEANOGRAPHY
Methods
ASLO
Association for the Sciences of Limnology and Oceanography

Comparative and Intercalibration Studies | Open Access

Commercially available unoccupied aerial systems for monitoring harmful algal blooms: A comparative study

Edna G. Fernandez-Figueroa, Alan E. Wilson, Stephanie R. Rogers

First published: 30 December 2021 | https://doi.org/10.1002/lom3.10477 | Citations: 7

Associate editor: Ivona Cetinic

Journal of Contemporary Water Research & Education

Case Study Article | Free Access

Monitoring Algal Blooms in Small Lakes Using Drones: A Case Study in Southern Illinois

Di Wu, Ruopu Li, Jia Liu, Nafeesa Khan

First published: 26 April 2023 | https://doi.org/10.1111/j.1936-704X.2022.3383.x

Open Access Article

Using Imagery Collected by an Unmanned Aerial System to Monitor Cyanobacteria in New Hampshire, USA, Lakes

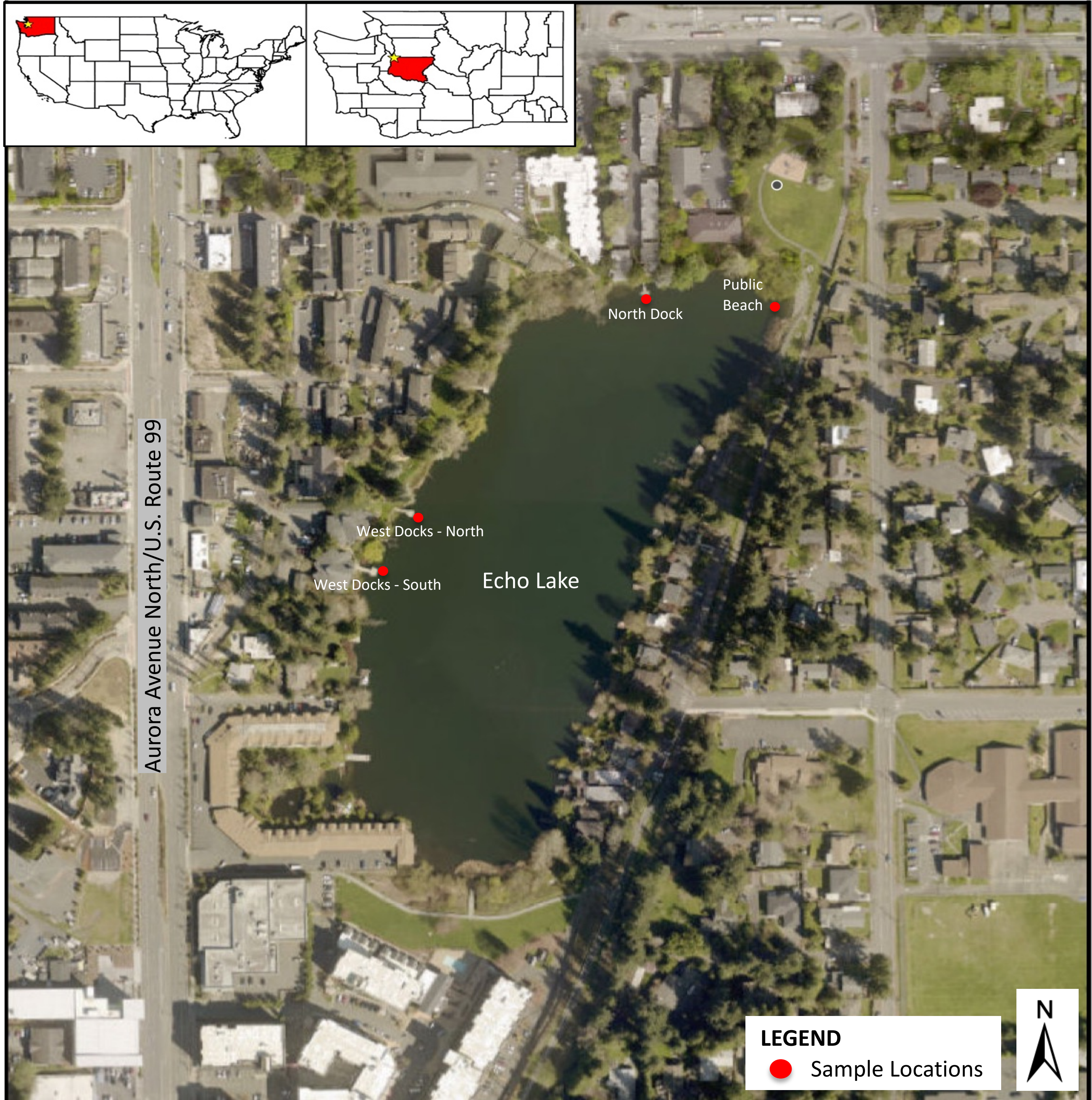
by Christine L. Bunyon [1,*], Benjamin T. Fraser [1], Amanda McQuaid [2] and Russell G. Congalton [1]

[1] Department of Natural Resources and the Environment, University of New Hampshire, 56 College Road, Durham, NH 03824, USA
[2] University of New Hampshire Cooperative Extension, 59 College Road, Durham, NH 03824, USA
[*] Author to whom correspondence should be addressed.

Remote Sens. **2023**, *15*(11), 2839; https://doi.org/10.3390/rs15112839

Submission received: 17 May 2023 / Revised: 22 May 2023 / Accepted: 24 May 2023 / Published: 30 May 2023

Study Setting



Study Aims

Study Aims

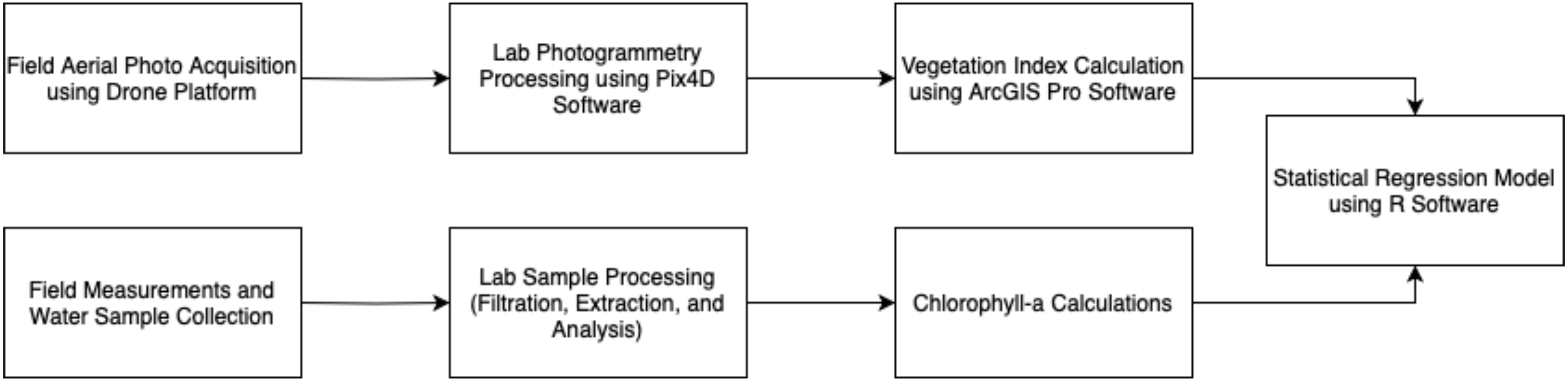
> **Aim 1**: Understand the human health risks of HCBs and the local context for their monitoring, surveillance, and risk notification.
  – Complete a narrative literature review
  – Meet with local, county, and state professionals working with HCBs

> **Aim 2**: Assess the use of remotely piloted drones as a supplemental HCB monitoring tool in a smaller-scale freshwater lake.
  – Perform drone-based aerial photo collection and water sample collection
  – Analyze data using simple linear regression models

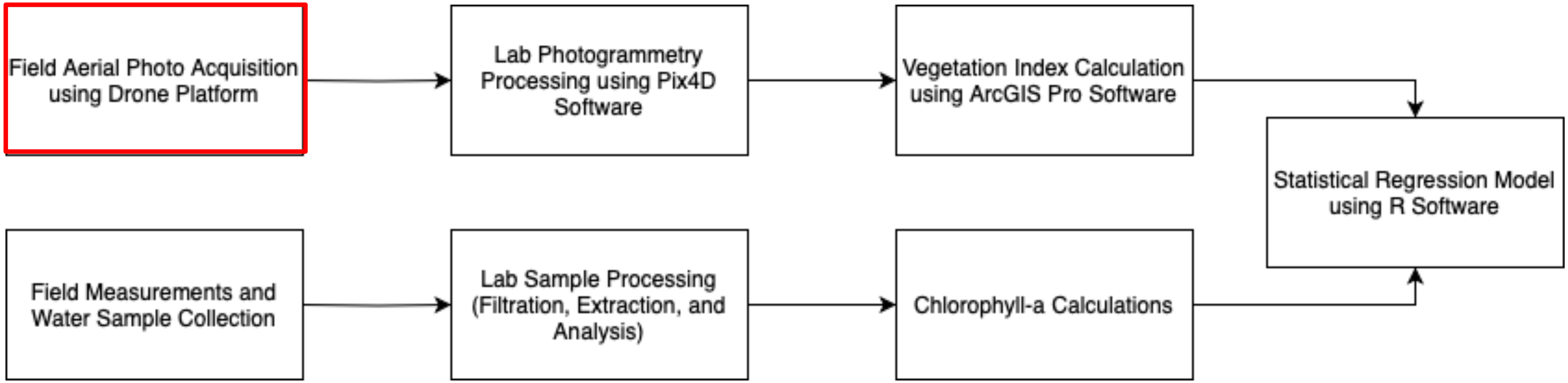
> **Aim 3**: Communicate challenges and facilitators with a drone-based data collection guidance document.
  – Provide deliverable to pertinent local agencies summarizing findings

Methods

Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

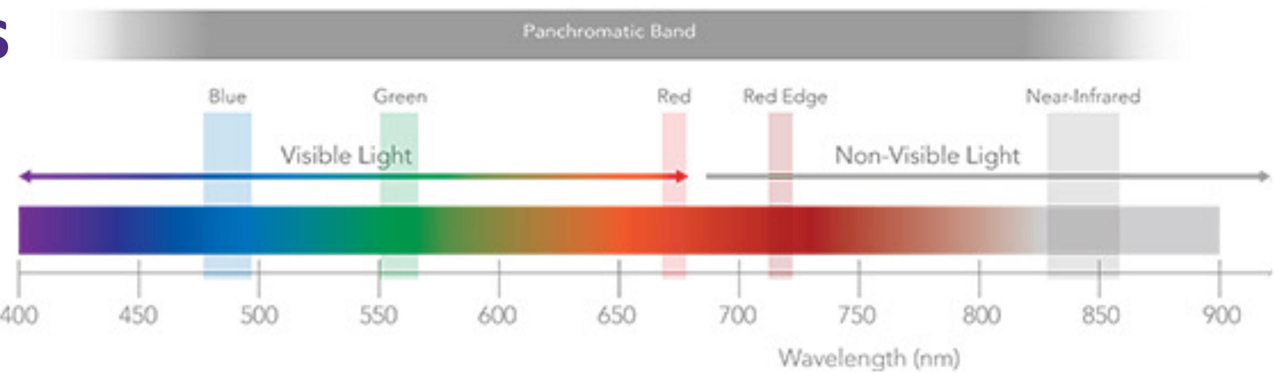
Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

Drone Platforms

Parameter	DJI Phantom 4 Pro+ RTK	DJI Matrice 210
Approximate Weight with Batteries	1.391 kg	4.8 kg
Diagonal Length	350 mm	643 mm
Vertical Position Accuracy	±0.1 m	±0.5 m
Horizontal Position Accuracy	±0.1 m	±1.5 m
Max Payload Capacity	0.5 kg	1.34 kg
Max Flight Time	30 min.	34 min.
Retail Value	$6,600 USD	$12,000 USD

Drone Sensors



RAPID NHERI
Natural Hazards Reconnaissance

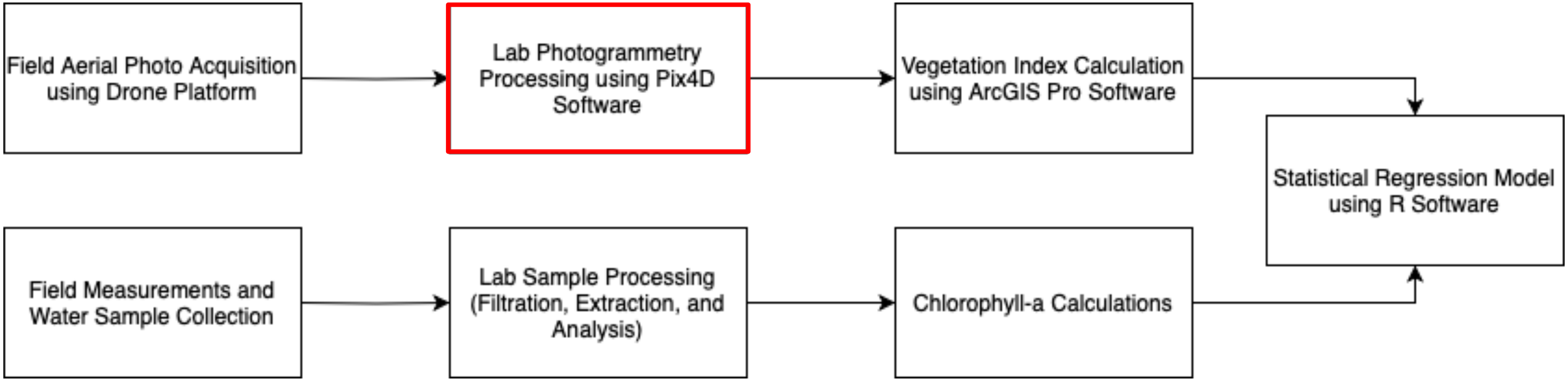
60m

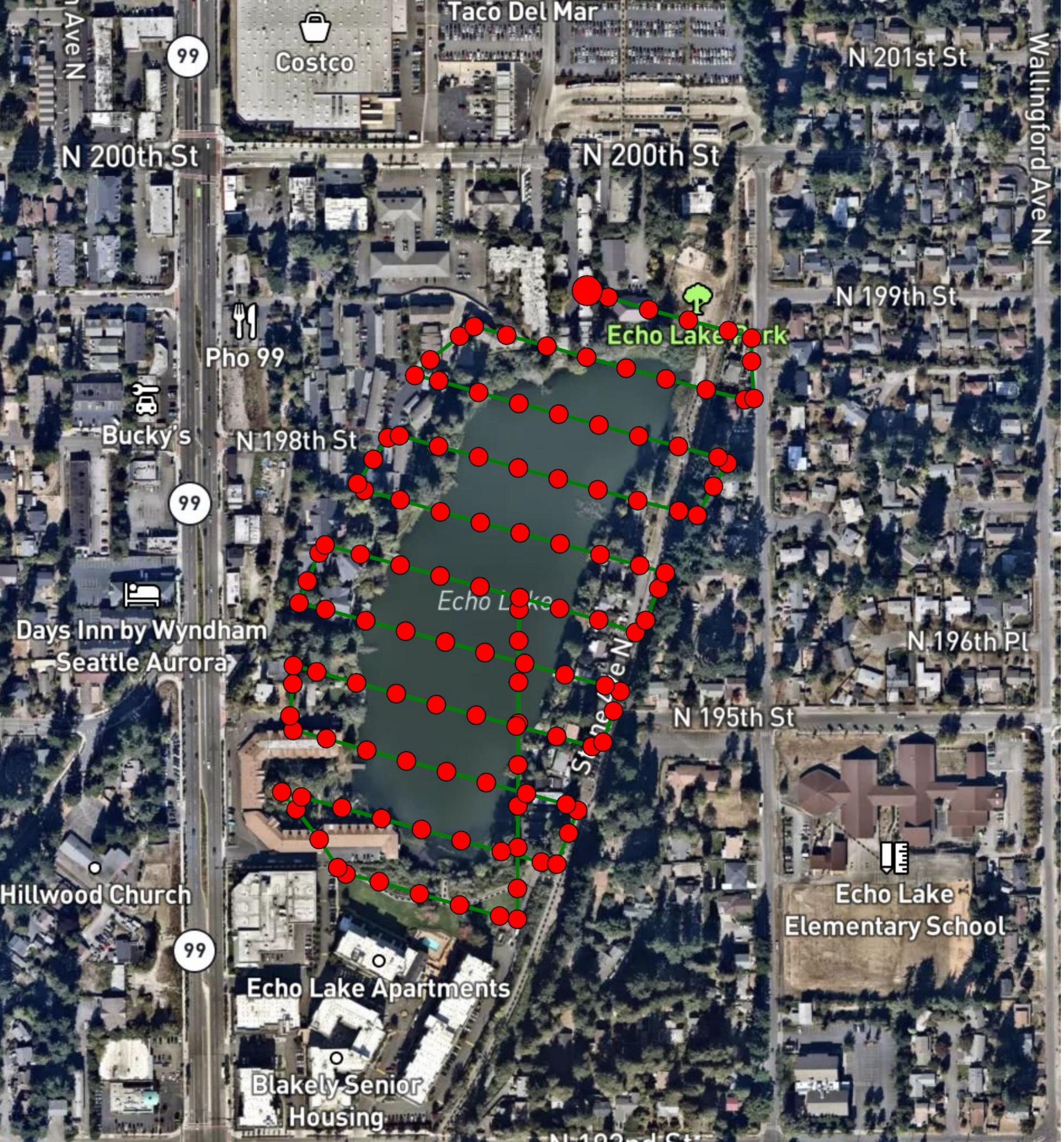
90m

120m

Parameter	DJI Phantom 4 Pro+ RTK	DJI Matrice 210
Sensor Type	1" CMOS RGB Camera	Micasense Altum Multispectral Sensor
Spatial Resolution	20 MP	2064 x 1544 pixels (3.2 MP x 5 imagers)
Focal Length	24 mm	8 mm
Field of View	84° 8.8 mm/24 mm	48° x 36.8°
Retail Value	(included with platform)	$16,000 USD

Methods

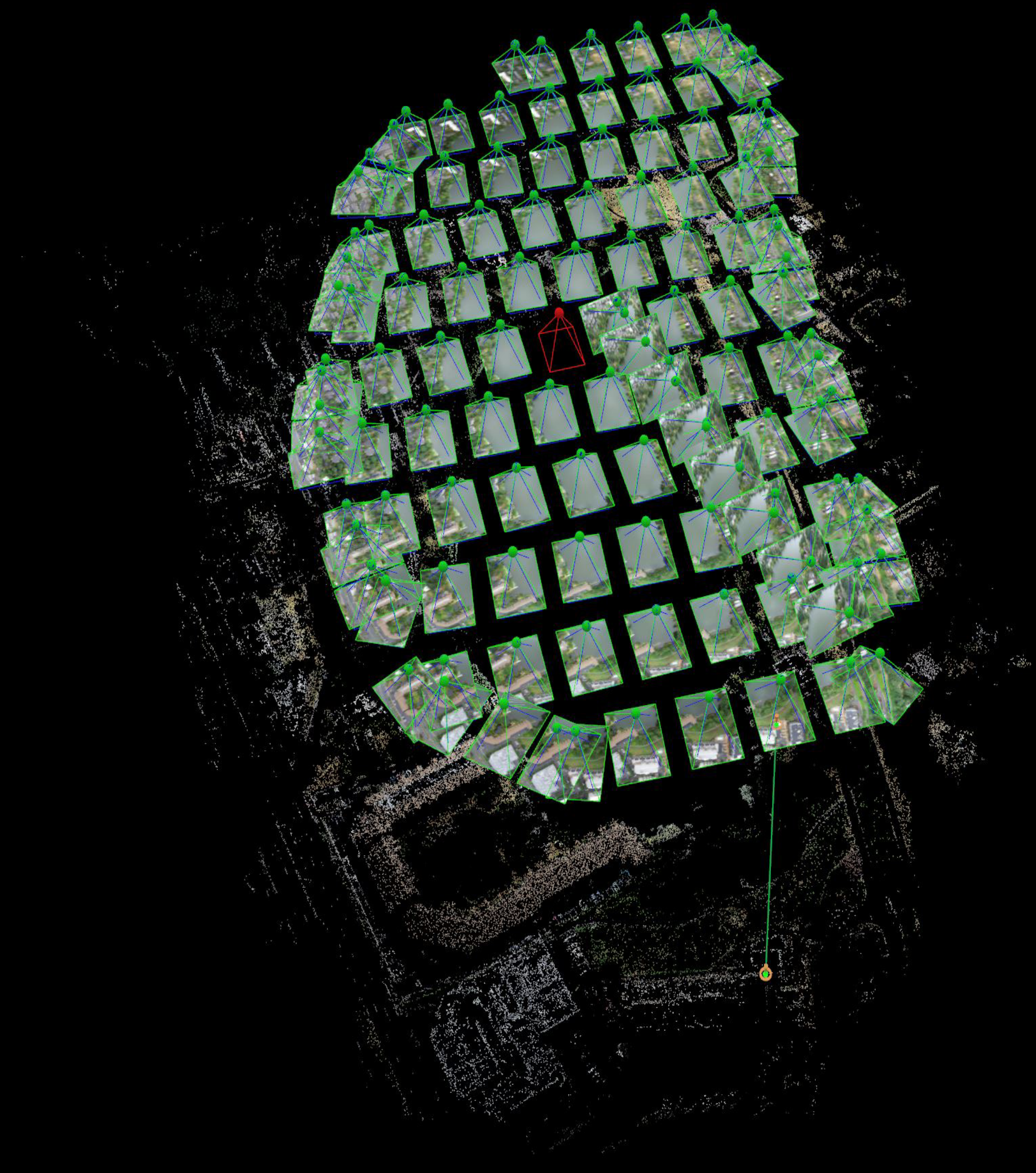

Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations



Processing Area

PIX4Dmapper

Raycloud

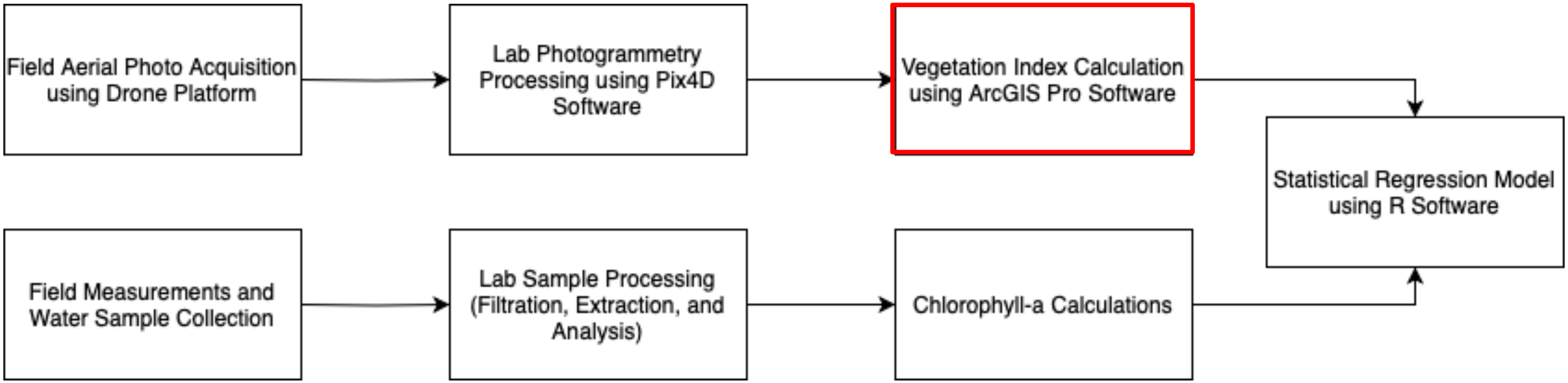


PIX4Dmapper

Orthomosaic

PIX4Dmapper

Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

Methods

> **Vegetation Index (VI):** image transformation in which the individual spectral bands (R/G/B, NIR) of an original image are manipulated to highlight vegetation properties in the new image.

Vegetation Index	Equation	Application
Color Index of Vegetation Extraction (CIVE)	(0.441 * R) - (0.881 * G) + (0.385 * B) + 18.787	Agricultural crop health
Excess Green Index (EXG)	(2 * G) - R - B	Green algae biomass
KIVU	(B - R) / G	Lake phytoplankton chlorophyll concentration
Normalized Green-Red Difference Index (NGRDI)	(G - R) / (G + R)	Green algae biomass
Visible Band Difference VI (VDVI)	(2 * G - R - B) / (2 * G + R + B)	Green algae biomass
Normalized Difference Vegetation Index (NDVI)	(NIR - R) / (NIR + R)	Terrestrial vegetation chlorophyll
Band Ratio (B/G)	B / G	Ocean color changes of chlorophyll
Ratio Vegetation Index (RVI)	NIR / R	Drinking water reservoir chlorophyll concentration
Green Normalized Difference Vegetation Index (GNDVI)	(NIR - G) / (NIR + G)	Terrestrial vegetation chlorophyll
2-Band Enhanced Vegetation Index (EVI2)	2.5*[(NIR - R) / (NIR + 2.4 * R + 1)]	Terrestrial vegetation chlorophyll

Fernandez-Figueroa et al. (2022); Kataoka et al. (2003); Sunoj et al. (2021); Xue & Su (2017); Bunyon et al. (2023); Wu et al. (2023); Zeng et al. (2016)

Methods

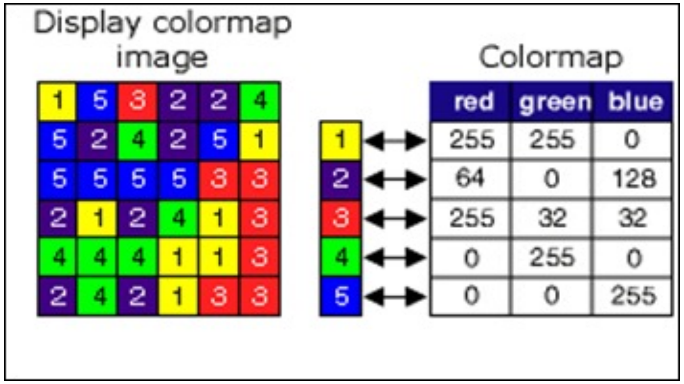
> **Vegetation Index (VI):** image transformation in which the individual spectral bands (R/G/B, NIR) of an original image are manipulated to highlight vegetation properties in the new image.

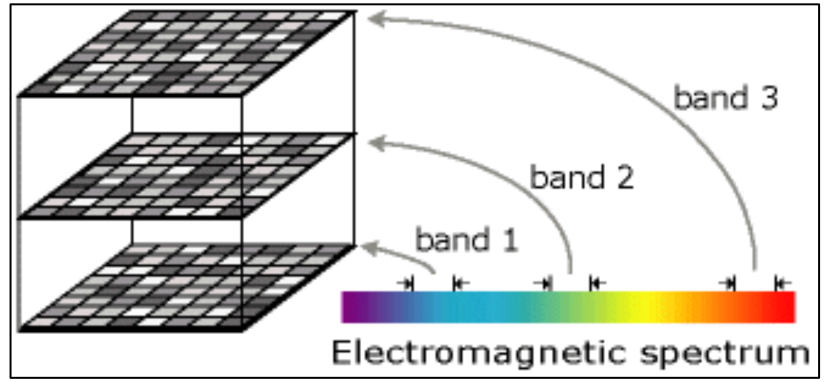
Vegetation Index	Equation	Application
Color Index of Vegetation Extraction (CIVE)	(0.441 * R) - (0.881 * G) + (0.385 * B) + 18.787	Agricultural crop health
Excess Green Index (EXG)	(2 * G) - R - B	Green algae biomass
KIVU	(B - R) / G	Lake phytoplankton chlorophyll concentration
Normalized Green-Red Difference Index (NGRDI)	(G - R) / (G + R)	Green algae biomass
Visible Band Difference VI (VDVI)	(2 * G - R - B) / (2 * G + R + B)	Green algae biomass
Normalized Difference Vegetation Index (NDVI)	(NIR - R) / (NIR + R)	Terrestrial vegetation chlorophyll
Band Ratio (B/G)	B / G	Ocean color changes of chlorophyll
Ratio Vegetation Index (RVI)	NIR / R	Drinking water reservoir chlorophyll concentration
Green Normalized Difference Vegetation Index (GNDVI)	(NIR - G) / (NIR + G)	Terrestrial vegetation chlorophyll
2-Band Enhanced Vegetation Index (EVI2)	2.5*[(NIR - R) / (NIR + 2.4 * R + 1)]	Terrestrial vegetation chlorophyll

Fernandez-Figueroa et al. (2022); Kataoka et al. (2003); Sunoj et al. (2021); Xue & Su (2017); Bunyon et al. (2023); Wu et al. (2023); Zeng et al. (2016)

Methods

https://pro.arcgis.com/en/pro-app/latest/help/data/imagery/raster-bands-pro-.htm

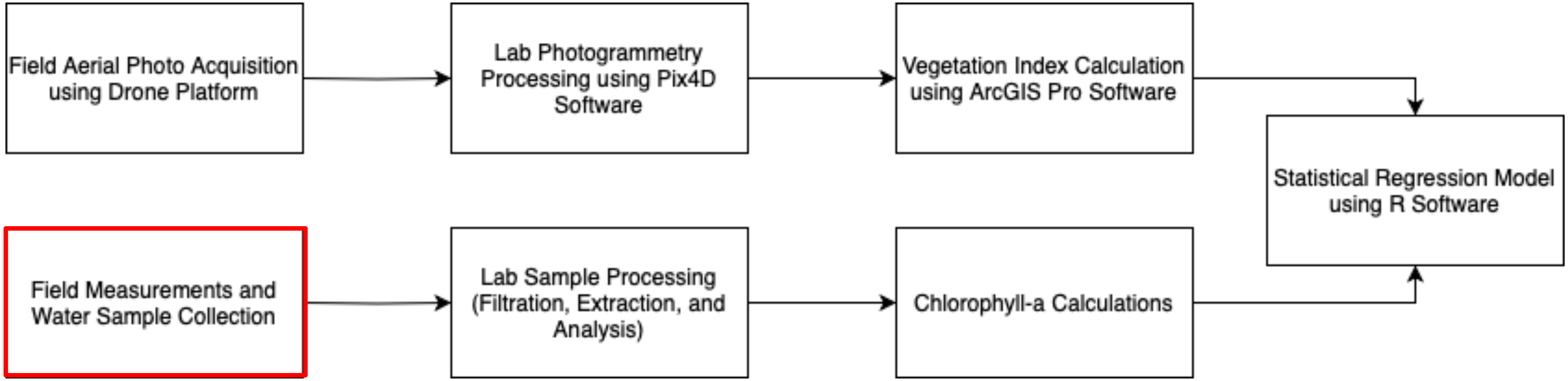




Vegetation Index	Equation	Application
Color Index of Vegetation Extraction (CIVE)	(0.441 * R) - (0.881 * G) + (0.385 * B) + 18.787	Agricultural crop health
Excess Green Index (EXG)	(2 * G) - R - B	Green algae biomass
KIVU	(B - R) / G	Lake phytoplankton chlorophyll concentration
Normalized Green-Red Difference Index (NGRDI)	(G - R) / (G + R)	Green algae biomass
Visible Band Difference VI (VDVI)	(2 * G - R - B) / (2 * G + R + B)	Green algae biomass
Normalized Difference Vegetation Index (NDVI)	(NIR - R) / (NIR + R)	Terrestrial vegetation chlorophyll
Band Ratio (B/G)	B / G	Ocean color changes of chlorophyll
Ratio Vegetation Index (RVI)	NIR / R	Drinking water reservoir chlorophyll concentration
Green Normalized Difference Vegetation Index (GNDVI)	(NIR - G) / (NIR + G)	Terrestrial vegetation chlorophyll
2-Band Enhanced Vegetation Index (EVI2)	2.5*[(NIR - R) / (NIR + 2.4 * R + 1)]	Terrestrial vegetation chlorophyll

Fernandez-Figueroa et al. (2022); Kataoka et al. (2003); Sunoj et al. (2021); Xue & Su (2017); Bunyon et al. (2023); Wu et al. (2023); Zeng et al. (2016)

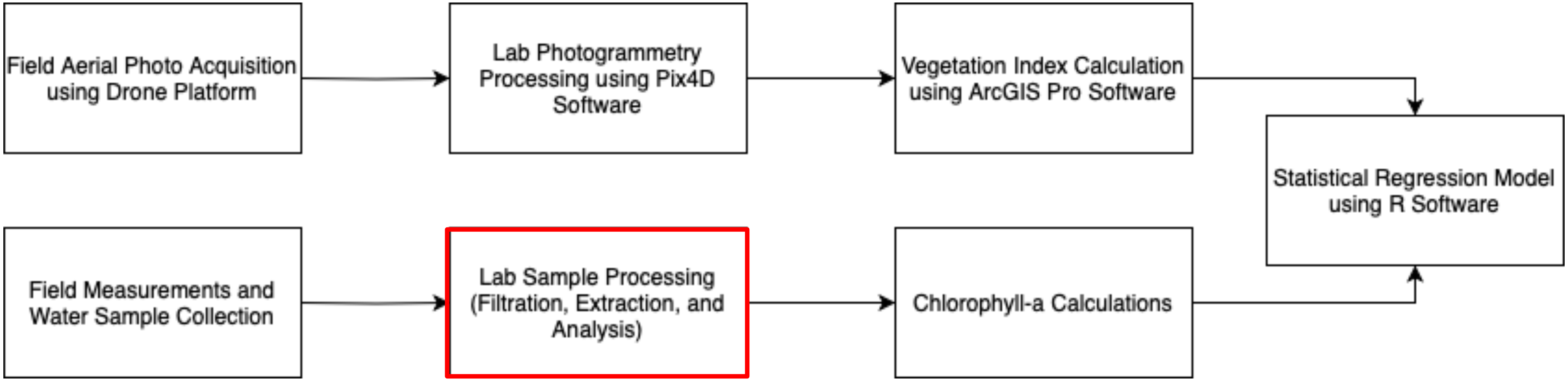
Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

Field Methods

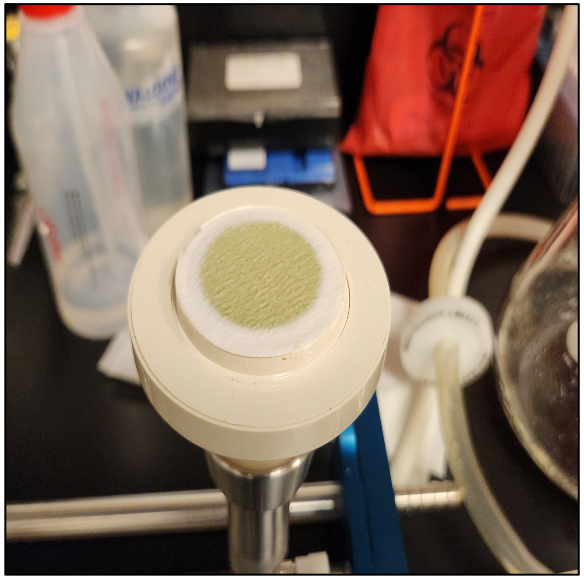
- USEPA *Standard Operating Procedure for Chlorophyll a Sampling Method Field Procedure* (2013) and state SOPs
- All water samples were analyzed in duplicate
- Meteorological and environmental conditions recorded

Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

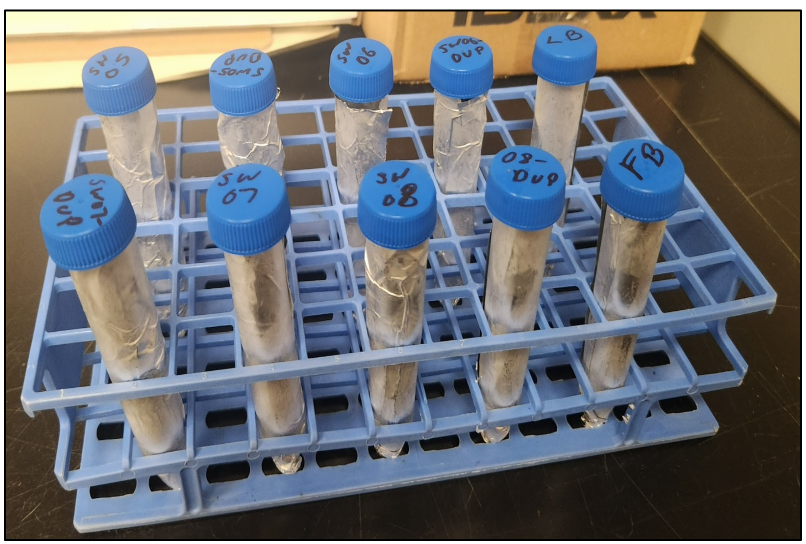
Lab Methods

- **USEPA Method 446.0**: In Vitro Determination of Chlorophylls a, b, $c_1 + c_2$ and Pheopigments in Marine And Freshwater Algae by Visible Spectrophotometry
- **APHA Method 10200H:** Spectrophotometric Determination of Chlorophyll

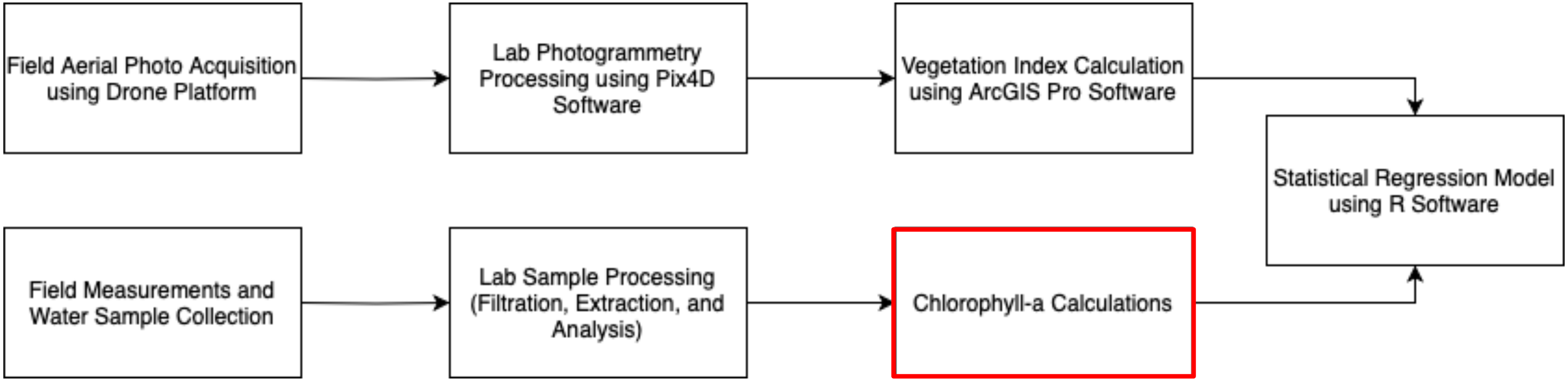


Lab Methods

- **USEPA Method 446.0**: In Vitro Determination of Chlorophylls a, b, $c_1 + c_2$ and Pheopigments in Marine And Freshwater Algae by Visible Spectrophotometry
- **APHA Method 10200H:** Spectrophotometric Determination of Chlorophyll

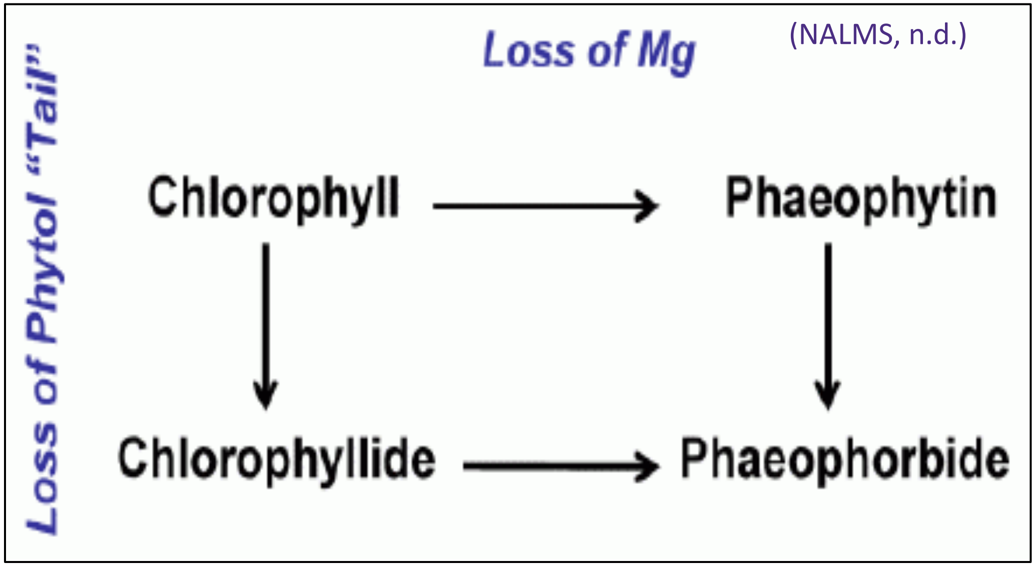


Methods


Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

Chlorophyll a Calculations

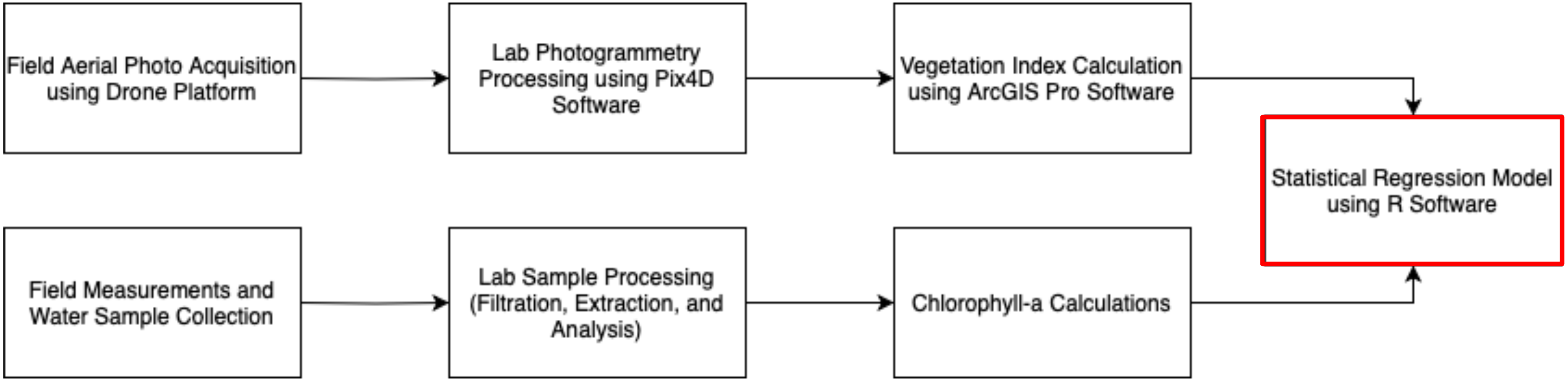
- **USEPA Method 446.0**
- Uncorrected/Unacidified Chlorophyll a
  - Jeffrey and Humphrey's Trichromatic Equations
- Corrected/Acidified Chlorophyll a
  - Lorenzen's Modified Monochromatic Equations



Quality Assurance and Quality Control

- Sample Preservation
  - Temperature, acidity, sunlight exposure, time
- Decontamination Procedures
- Negative Controls
  - Field Blank, Laboratory Blank
- Positive Controls
  - Stock Standard Solution of known chlorophyll a concentration

Methods



Field Aerial Photo Acquisition using Drone Platform
Lab Photogrammetry Processing using Pix4D Software
Vegetation Index Calculation using ArcGIS Pro Software
Statistical Regression Model using R Software
Field Measurements and Water Sample Collection
Lab Sample Processing (Filtration, Extraction, and Analysis)
Chlorophyll-a Calculations

Results

Results - Aims 1 and 3

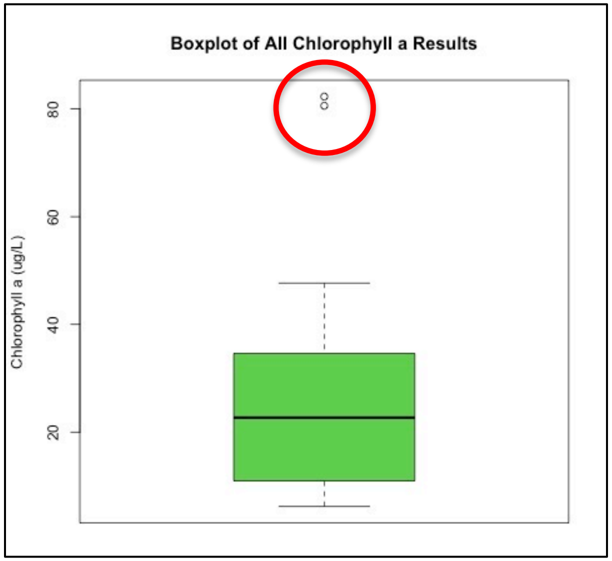
- Aim 1 – Literature Review and Local Agency Meetings
  - Synthesized 15 review articles and 5 experimental studies published across 14 academic journals
  - Local agency needs and challenges identified

- Aim 3 – Data Collection Guidance Document
  - Deliverable highlights cost and logistics encountered as well as considerations of environmental factors and flight settings needed for optimal performance

Results - Aim 2

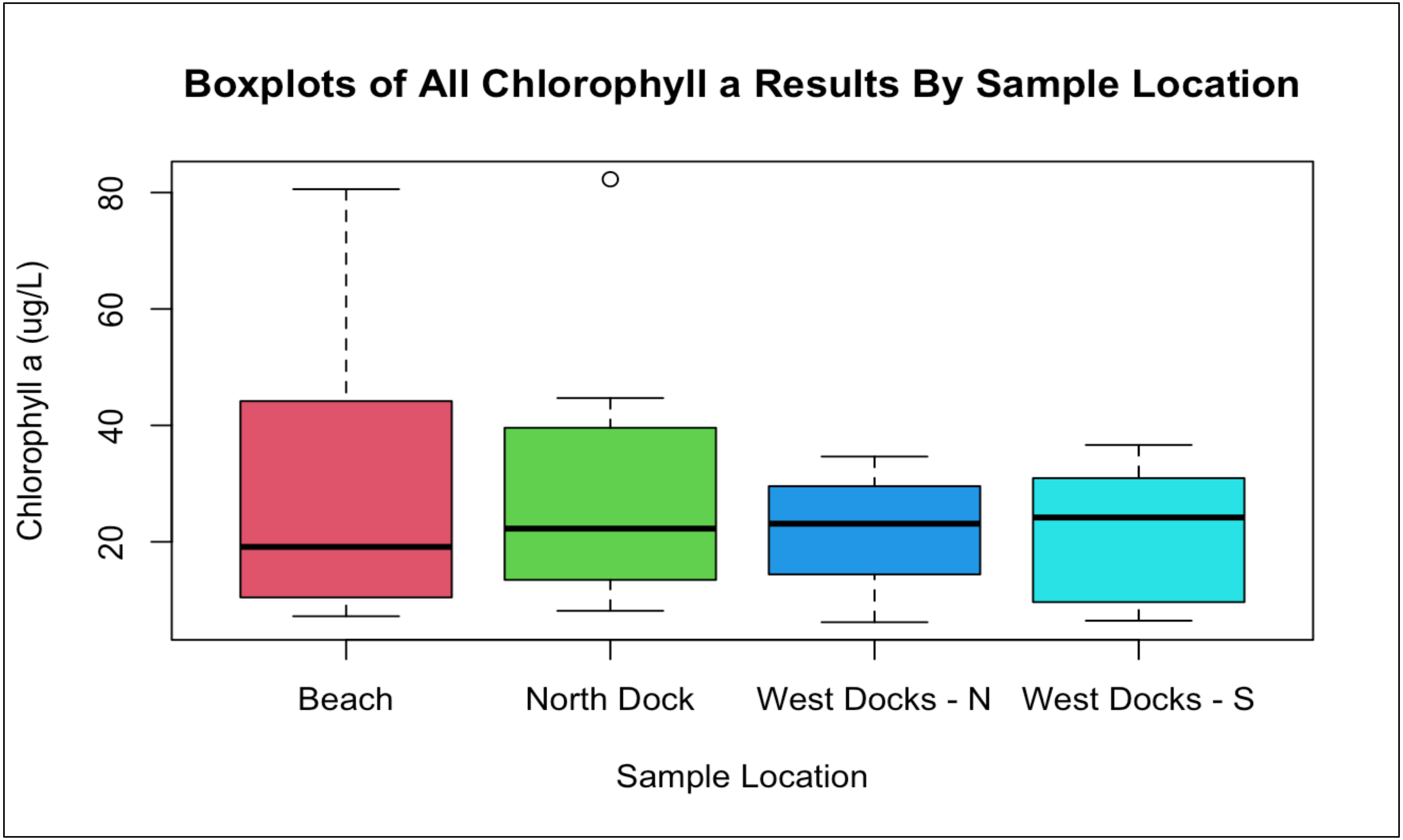
Trophic State Indices

	TP (µg/L)	Chl (µg/L)	Secchi (m)
Oligotrophic	<8	<2	>8
Mesotrophic	8-20	2-7	8-3
Eutrophic	20-100	7-40	1-3
Hypereutrophic	>100	>40	<1

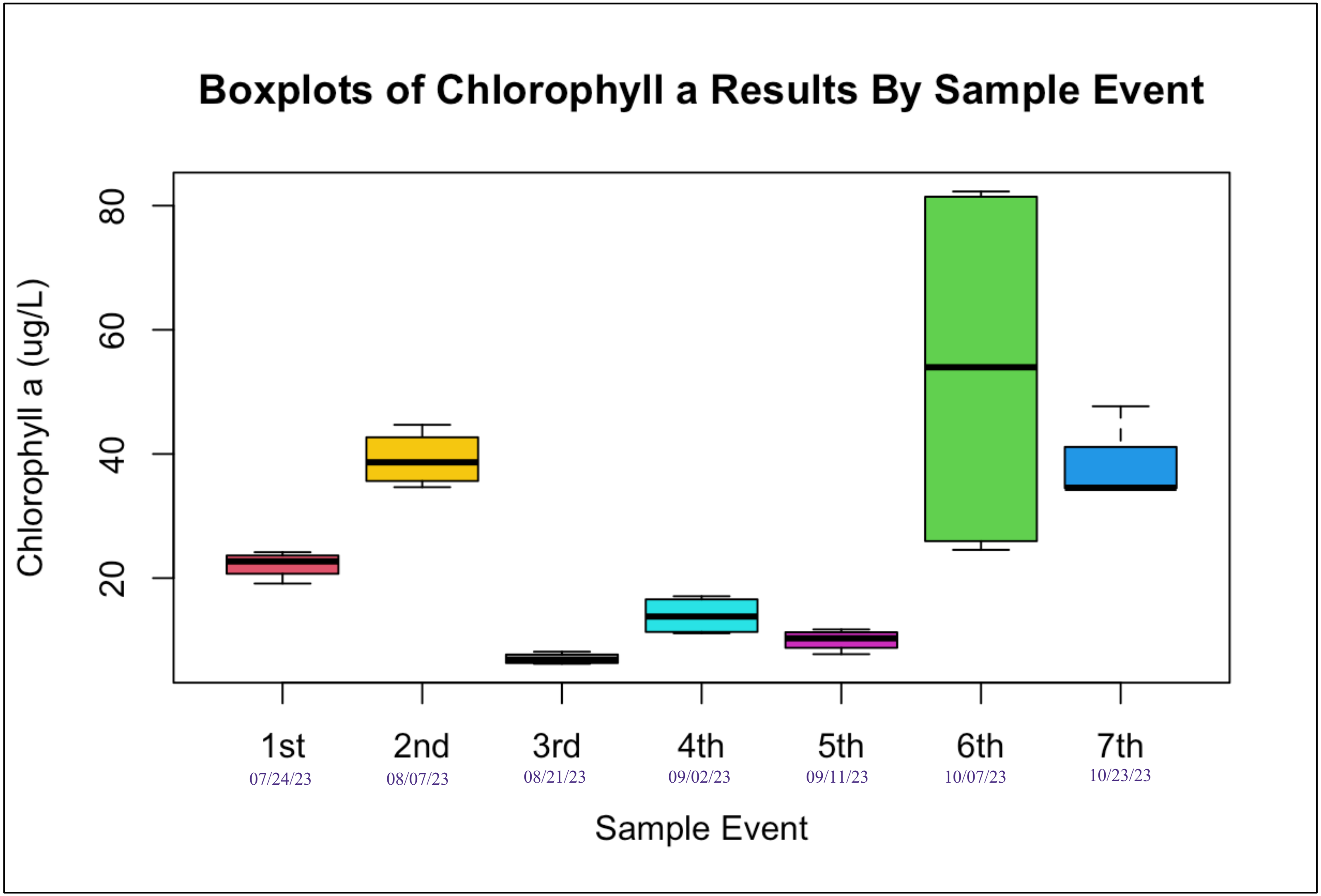


Category	Mean	SD	Median	Min	Max
All Samples (n=28)	26.26	19.95	22.70	6.19	82.28
Beach (n=7)	30.88	27.02	19.13	7.22	80.58
North Dock (n=7)	31.26	26.00	22.27	8.15	82.28
West Docks - North (n=7)	21.70	10.84	23.12	6.19	34.65
West Docks - South (n=7)	21.21	12.61	24.18	6.45	36.64
First Event (n=4)	22.18	2.18	22.70	19.13	24.18
Second Event (n=4)	39.16	4.46	38.66	34.65	44.70
Third Event (n=4)	7.00	0.88	6.84	6.19	8.15
Fourth Event (n=4)	13.96	3.07	13.81	11.12	17.08
Fifth Event (n=4)	10.03	1.71	10.31	7.75	11.73
Sixth Event (n=4)	53.70	32.05	53.97	24.56	82.28
Seventh Event (n=4)	37.82	6.58	34.55	34.49	47.68

Results - Aim 2



Results - Aim 2



Dated 06/23/2023

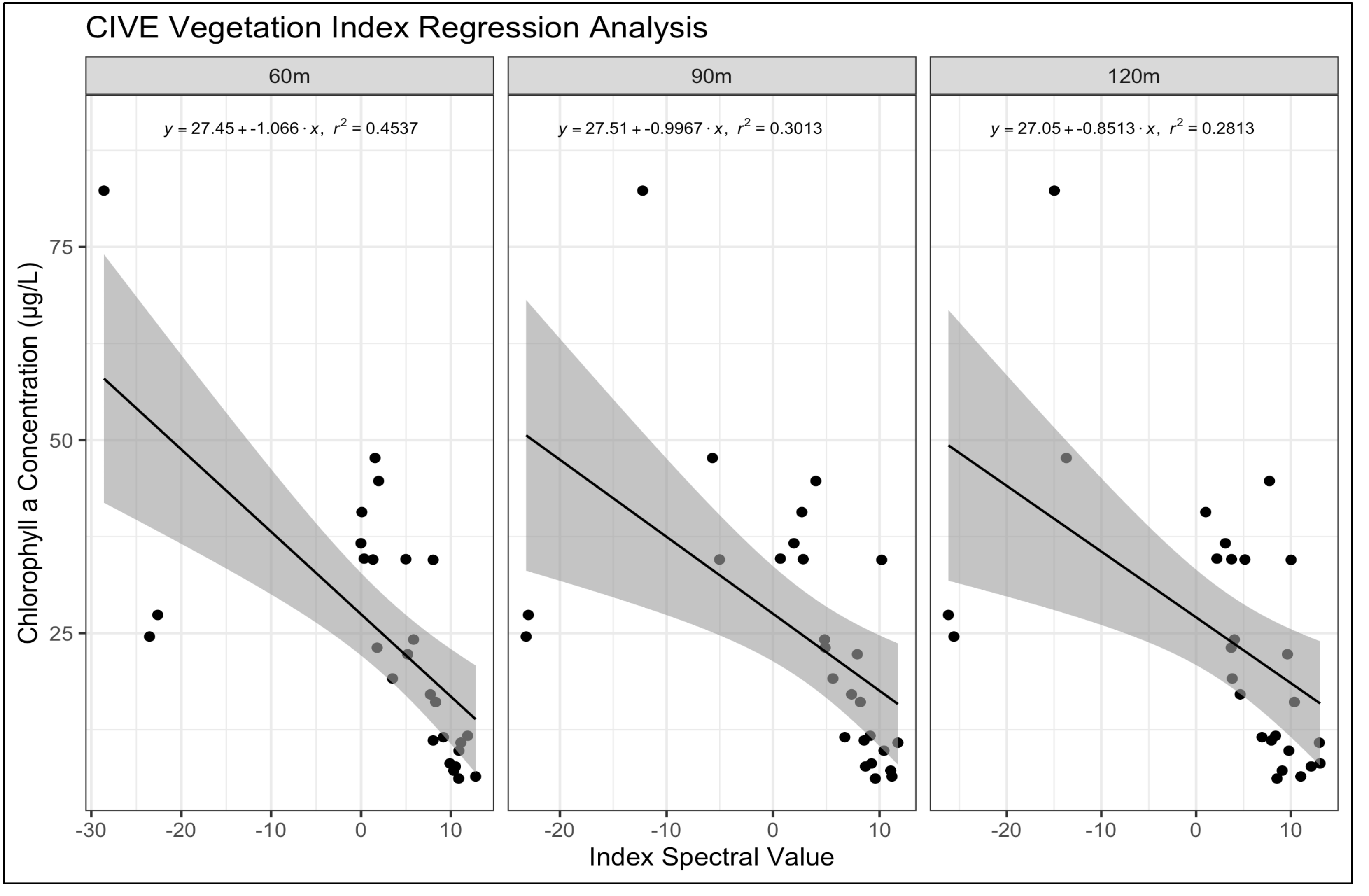
Dated 10/07/2023

Linear Regression Models - RGB VIs

N = 27 (all flight altitudes)

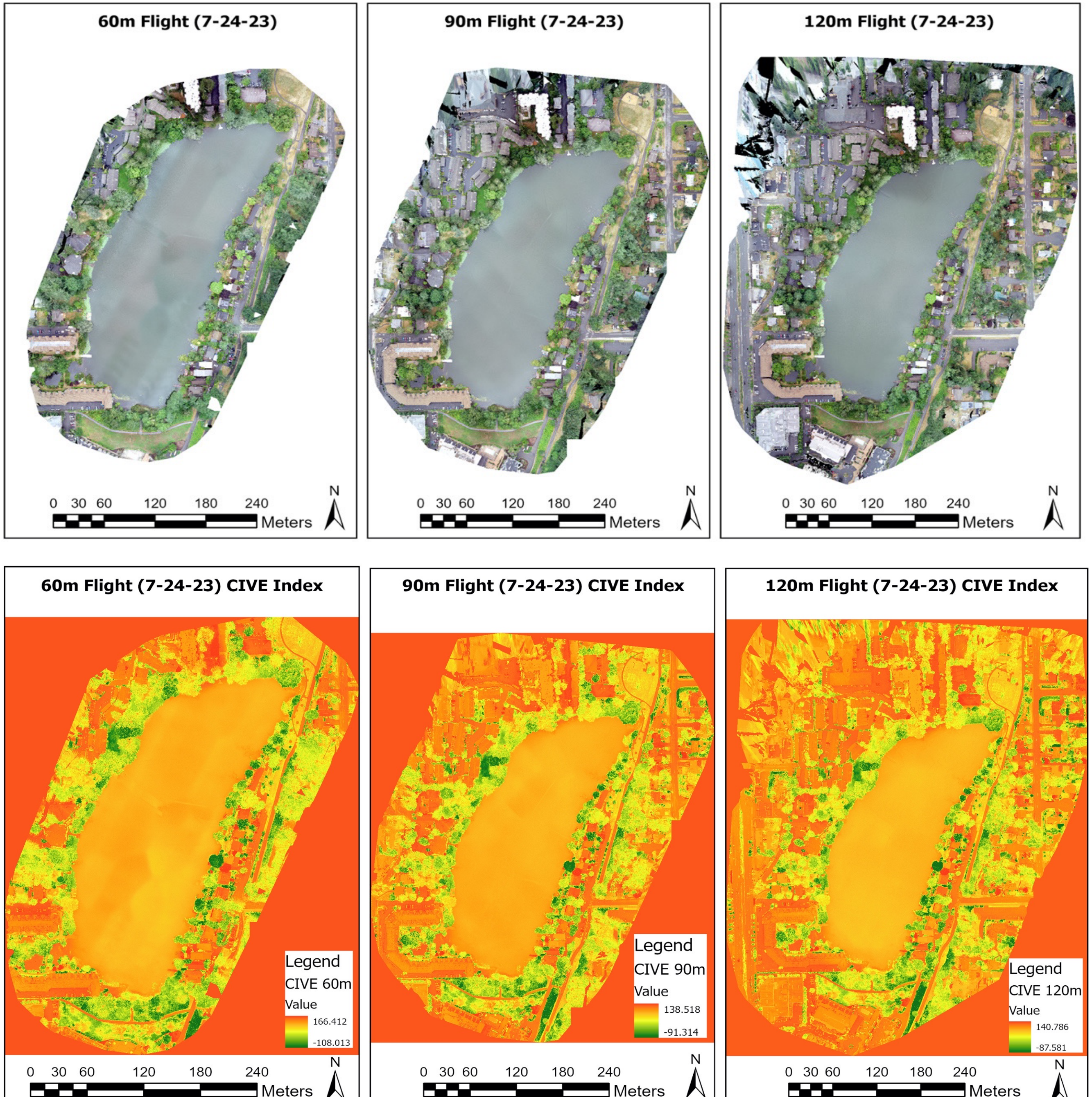
Vegetation Index	Intercept Estimate	Slope Estimate	95% CI	R^2 value (p value)
Flight Altitude		**60m**		
CIVE	27.45	-1.066	[-1.549, -0.5844]	**0.4537 (0.0001*)**
EXG	16.07	0.4192	[0.2029, 0.6356]	**0.3892 (0.0005*)**
KIVU	29.38	-40.25	[-88.02, 7.511]	0.1075 (0.095)
NGRDI	17.78	87.59	[-41.95, 217.1]	0.0720 (0.176)
VDVI	17.38	178.7	[63.32, 294.2]	**0.2892 (0.004*)**
Flight Altitude		**90m**		
CIVE	27.51	-0.9967	[-1.622, -0.3715]	**0.3013 (0.003*)**
EXG	17.11	0.3882	[0.1192, 0.6572]	**0.2611 (0.006*)**
KIVU	27.52	-25.00	[-82.65, 32.64]	0.0309 (0.380)
NGRDI	15.89	113.2	[-8.086, 234.4]	0.1288 (0.066)
VDVI	17.64	178.0	[54.18, 301.9]	**0.2596 (0.007*)**
Flight Altitude		**120m**		
CIVE	27.05	-0.8513	[-1.412, -0.2908]	**0.2813 (0.004*)**
EXG	17.89	0.3431	[0.09489, 0.5913]	**0.2448 (0.009*)**
KIVU	28.62	-33.28	[-76.22, 9.663]	0.0925 (0.123)
NGRDI	20.74	48.22	[-68.32, 164.8]	0.0282 (0.402)
VDVI	17.83	181.4	[53.10, 309.6]	**0.2533 (0.007*)**

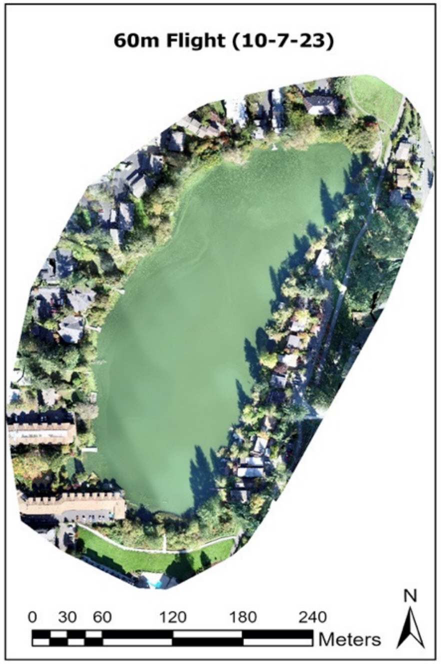
Results

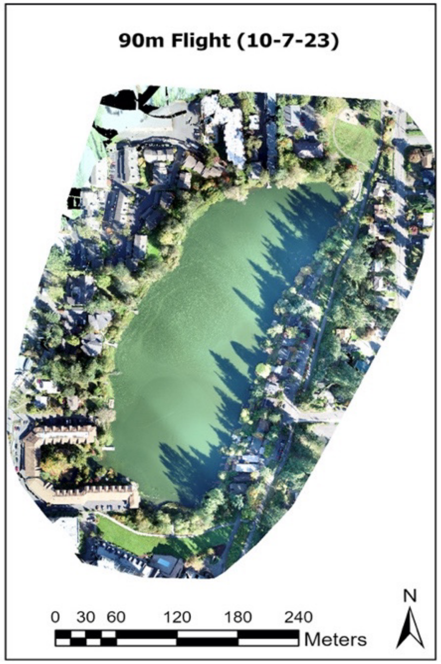


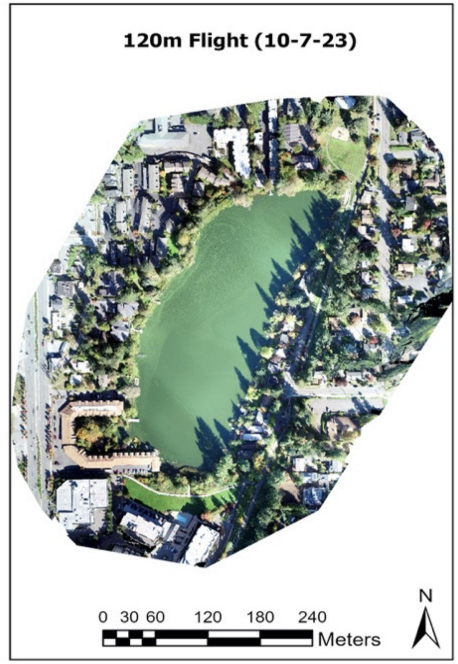
CIVE Vegetation Index Regression Analysis
60m
90m
120m
y = 27.45 + -1.066 · x, r2 = 0.4537
y = 27.51 + -0.9967 · x, r2 = 0.3013
y = 27.05 + -0.8513 · x, r2 = 0.2813
Chlorophyll a Concentration (µg/L)
75
50
25
-30
-20
-10
0
10
Index Spectral Value

07/24/2023


60m Flight (7-24-23)
90m Flight (7-24-23)
120m Flight (7-24-23)
60m Flight (7-24-23) CIVE Index
90m Flight (7-24-23) CIVE Index
120m Flight (7-24-23) CIVE Index
Legend
CIVE 60m
Value
166.412
-108.013
Legend
CIVE 90m
Value
138.518
-91.314
Legend
CIVE 120m
Value
140.786
-87.581
0 30 60 120 180 240
Meters
N

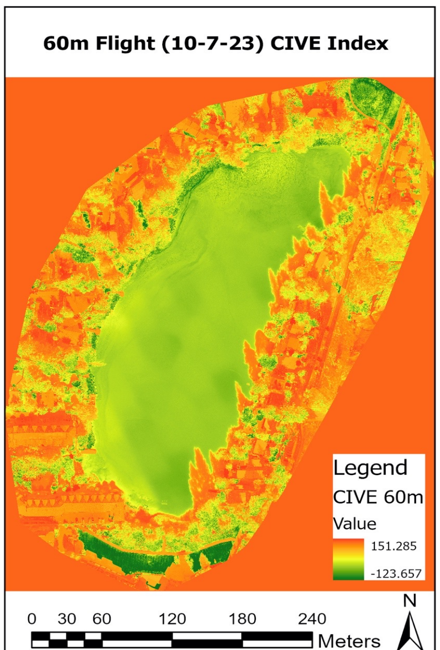


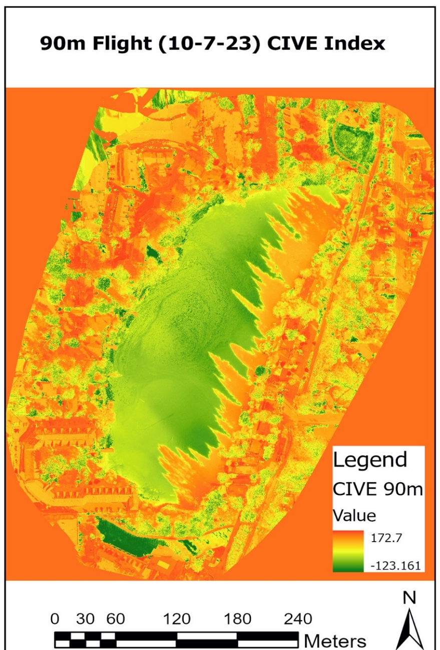


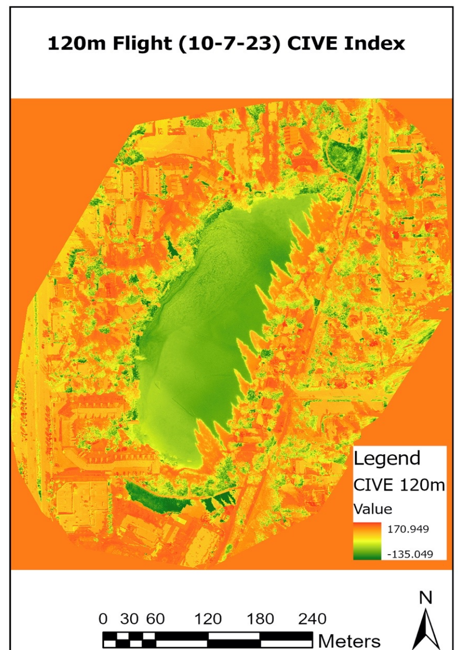


10/07/2023

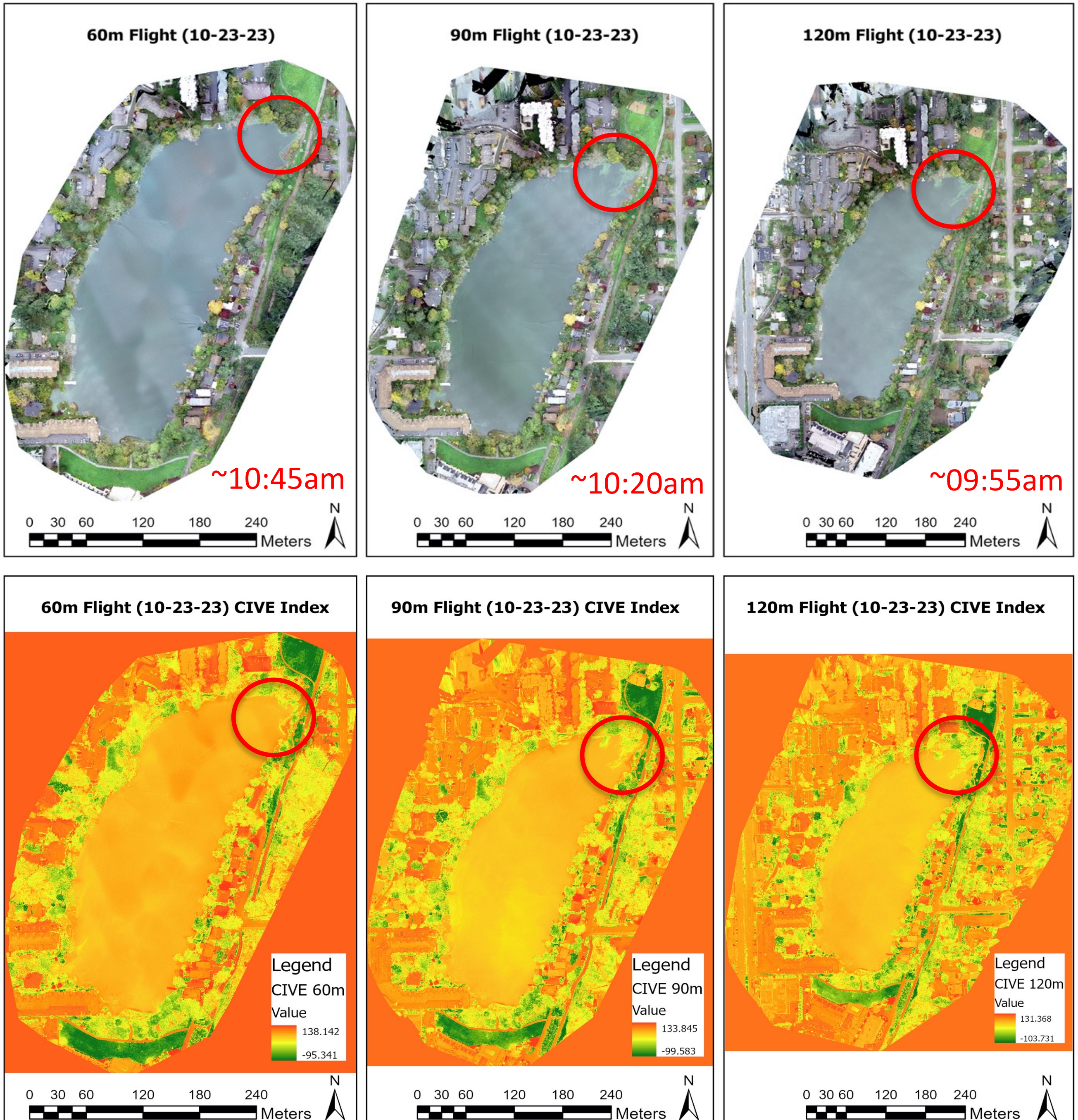
10-07-23 - 6th Sampling Event	
Sample	**Chlorophyll a (µg/L)**
SW21 Public Beach	80.58
SW22 North Dock	82.28
SW23 West Docks - N	24.56
SW24 West Docks - S	27.36







10/23/2023

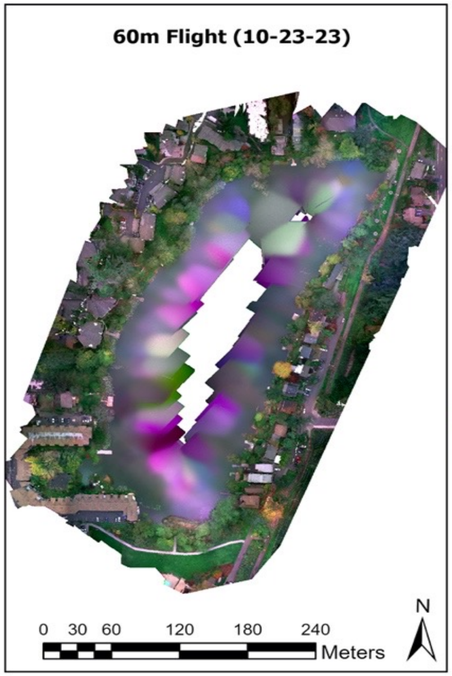

60m Flight (10-23-23)
~10:45am
90m Flight (10-23-23)
~10:20am
120m Flight (10-23-23)
~09:55am
0 30 60 120 180 240 Meters
N
60m Flight (10-23-23) CIVE Index
Legend
CIVE 60m
Value
138.142
-95.341
90m Flight (10-23-23) CIVE Index
Legend
CIVE 90m
Value
133.845
-99.583
120m Flight (10-23-23) CIVE Index
Legend
CIVE 120m
Value
131.368
-103.731

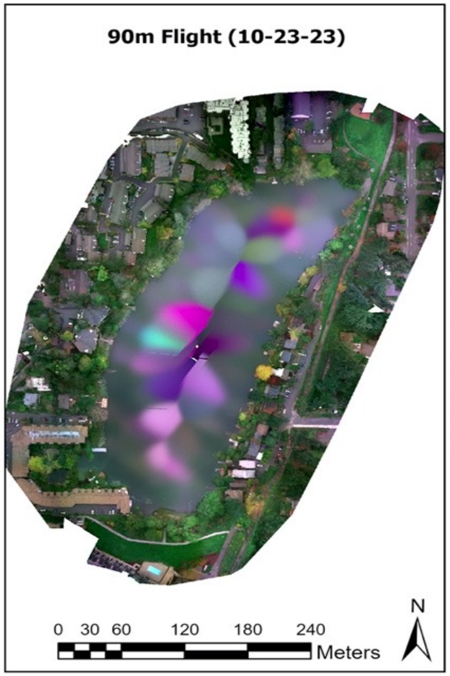
Linear Regression Models - Multispectral VIs

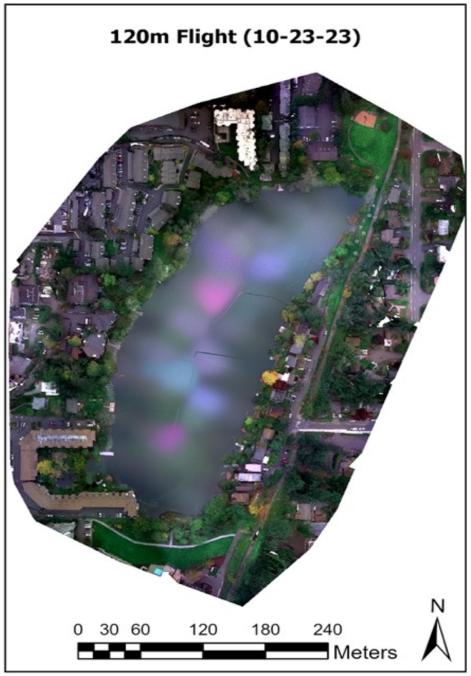
N = 8 (60m and 90m), N = 4 (120m)

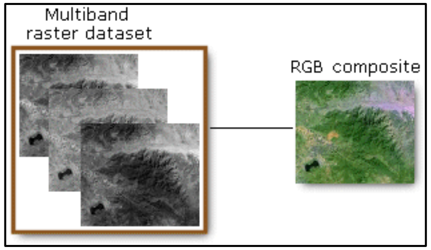
Vegetation Index	Intercept Estimate	Slope Estimate	95% CI	R^2 value (p value)
Flight Altitude	**60m**			
NDVI	2.638	-70.86	[-249.3, 107.5]	0.136 (0.369)
B/G	47.78	-19.90	[-103.3, 63.55]	0.0537 (0.581)
RVI	53.98	-55.29	[-198.5, 87.93]	0.1295 (0.381)
GNDVI	11.80	-41.94	[-143.6, 59.71]	0.1452 (0.352)
EVI2	0.9801	-58.74	[-208.7, 91.25]	0.1327 (0.375)
Flight Altitude	**90m**			
NDVI	-2.397	-85.40	[-346.1, 175.3]	0.0968 (0.453)
B/G	17.76	5.266	[-132.9, 143.4]	0.0014 (0.929)
RVI	59.96	-67.81	[-295.2, 159.6]	0.0815 (0.493)
GNDVI	-1.802	-83.58	[-308.1, 140.9]	0.1215 (0.397)
EVI2	-4.663	-71.30	[-298.8, 156.2]	0.0893 (0.472)
Flight Altitude	**120m**			
NDVI	64.48	97.39	[-453.8, 648.6]	0.2242 (0.527)
B/G	-37.48	65.17	[-143.6, 274.0]	0.4741 (0.311)
RVI	-8.773	81.59	[-373.3, 536.5]	0.2295 (0.521)
GNDVI	19.70	-61.43	[-426.3, 303.4]	0.2079 (0.544)
EVI2	67.92	83.28	[-384.7, 551.3]	0.2267 (0.524)

10/23/2023

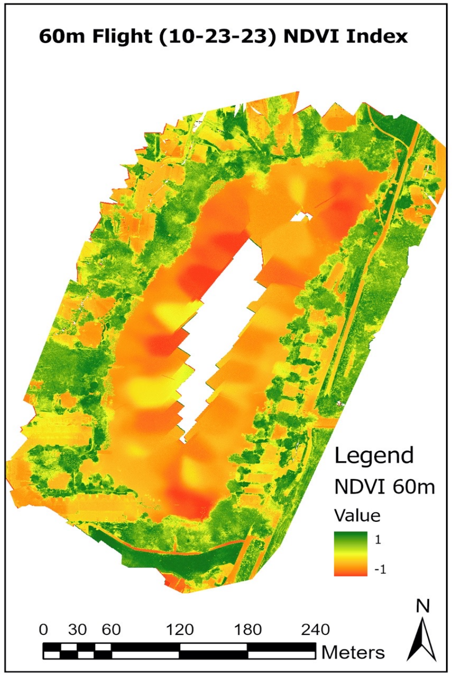


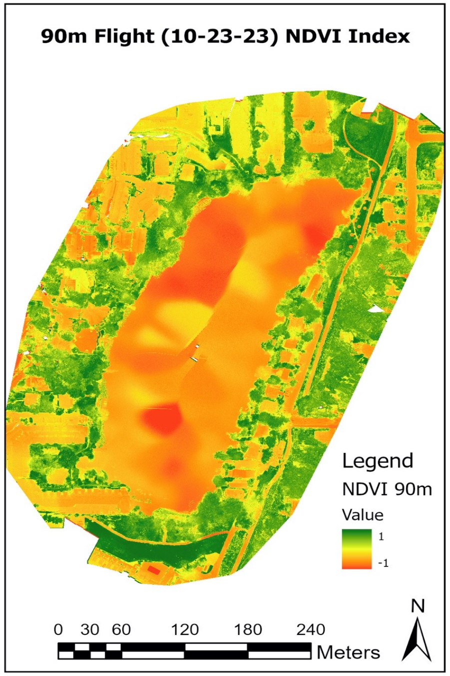


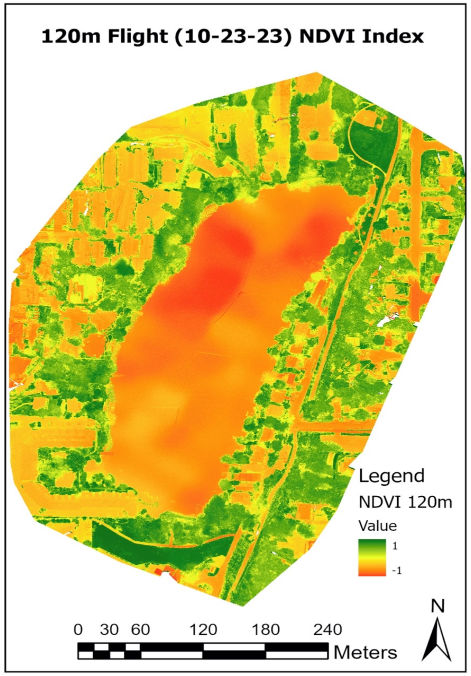




https://pro.arcgis.com/en/pro-app/latest/help/data/imagery/raster-bands-pro-.htm







Discussion

Discussion

> Phantom platform - CIVE 60m index ($R^2 = 0.45$, $p < 0.001$)
  - Comparable results with similar studies
  - More frequent flight data acquisition can enhance monitoring

> Limitations with multispectral platform
  - Lower sample size
  - Costs and scheduling associated with equipment use

> Optimal drone settings and environmental conditions
  - Flight altitude impacts image resolution and consequent chlorophyll a-vegetation index associations
  - Sky conditions

Discussion

- Formation of October HCB
  - Sources and timing
  - Prevention and treatment strategies

- Benefits of incorporating drones
  - Implementation at small scale lakes
  - Accessibility and ease of use, greater lake access
  - Frequent and flexible data collection
  - Relatively lower costs (depending on platform/sensor)

Limitations

Study Limitations

- Possible sample degradation
- Misalignment with water sample collection and imagery
- Interferences (pigments, light angle)
- Drone limitations (weather, sun glint, and shadows)
- Lack of standardized methodology
- Insufficient sample sizes
- Limitations of linear regression models

Concluding Remarks

Concluding Remarks and Future Directions

- Toxic blooms threaten environmental public health outcomes and will worsen with the current climate crisis

- Integration of drones into routine HCB surveillance programs can provide timely information for local public health and environmental resource agencies to act

- Future work can assess different drone platforms, sensors, vegetation indices, lakes of varying sizes and trophic levels, phycocyanin measurements, and collect additional samples for more robust statistical analysis

Acknowledgments

- UW School of Public Health's Population Health Initiative Tier I Pilot Research Grant
- DEOHS

POPULATION HEALTH INITIATIVE
UNIVERSITY of WASHINGTON

SCHOOL OF PUBLIC HEALTH
UNIVERSITY of WASHINGTON

ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES
SCHOOL OF PUBLIC HEALTH
UNIVERSITY of WASHINGTON

Acknowledgments

> Project Collaborators

- Dr. Tania M. Busch Isaksen, PhD, MPH (UW, DEOHS)
- Dr. Scott Meschke, PhD, MS, JD (UW, DEOHS)
- Dr. Gordon Holtgrieve, PhD (UW, School of Aquatic and Fishery Sciences)
- Mr. Stefan Grozev (City of Shoreline)

> Groups

- Echo Lake Neighborhood Association
- UW RAPID Facility
- UW Environmental and Occupational Health Microbiology Laboratory (EOHML)
- UW Collaborative on Extreme Event Resilience (CEER)

References

Almuhtaram, H., Kibuye, F. A., Ajjampur, S., Glover, C. M., Hofmann, R., Gaget, V., Owen, C., Wert, E. C., & Zamyadi, A. (2021). State of knowledge on early warning tools for cyanobacteria detection. *Ecological Indicators, 133*, 108442. https://doi.org/10.1016/j.ecolind.2021.108442.

Arar, E. J. 1997. *Method 446.0: In Vitro Determination of Chlorophylls a, b, c + c and Pheopigments in 1 2Marine And Freshwater Algae by Visible Spectrophotometry*. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/005. Retrieved from https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=309415.

Baird, R. B., Bridgewater, L. L., Eaton, A. D., & Rice, E. W. (2017). *Standard Methods for the Examination of Water and Wastewater (23rd ed., pp. 10-22–10-30).* American Public Health Association.

Benson, J., Hanlon, R., Seifried, T. M., Baloh, P., Powers, C. W., Grothe, H., & Schmale, D. G. (2019). Microorganisms Collected from the Surface of Freshwater Lakes Using a Drone Water Sampling System (DOWSE). *Water, 11*(1), Article 1. https://doi.org/10.3390/w11010157.

Bunyon, C. L., Fraser, B. T., McQuaid, A., & Congalton, R. G. (2023). Using Imagery Collected by an Unmanned Aerial System to Monitor Cyanobacteria in New Hampshire, USA, Lakes. *Remote Sensing, 15*(11), Article 11. https://doi.org/10.3390/rs15112839.

DJI. (2019 June). *Matrice 200 Series V2 M210 V2 / M210 RTK V2 User Manual V1.4*. https://dl.djicdn.com/downloads/m200_v2/20190617/M210_V2_M210_RTK_V2_User_Manual_v1.4_EN.pdf.

DJI. (2020 July). *Phantom 4 RTK User Manual v2.4*. https://dl.djicdn.com/downloads/phantom_4_rtk/20200721/Phantom_4_RTK_User_Manual_v2.4_EN.pdf.

Graham, J.L., Loftin, K.A., Ziegler, A.C., & Meyer, M.T. (2008). *Guidelines for Design and Sampling for Cyanobacterial Toxin and Taste-And-Odor Studies in Lakes and Reservoirs*. U.S. Geological Survey Scientific Investigations Report 2008–5038. https://pubs.usgs.gov/sir/2008/5038/pdf/SIR2008-5038.pdf.

Graham, C. T., O'Connor, I., Broderick, L., Broderick, M., Jensen, O., & Lally, H. T. (2022). Drones can reliably, accurately and with high levels of precision, collect large volume water samples and physio-chemical data from lakes. *Science of The Total Environment, 824*, 153875. https://doi.org/10.1016/j.scitotenv.2022.153875.

Fernandez-Figueroa, E. G., Wilson, A. E., & Rogers, S. R. (2022). Commercially available unoccupied aerial systems for monitoring harmful algal blooms: A comparative study. *Limnology and Oceanography: Methods, 20*(3), 146–158. https://doi.org/10.1002/lom3.10477.

Hanlon, R., Jacquemin, S. J., Birbeck, J. A., Westrick, J. A., Harb, C., Gruszewski, H., Ault, A. P., Scott, D., Foroutan, H., Ross, S. D., González-Rocha, J., Powers, C., Pratt, L., Looney, H., Baker, G., & Schmale, D. G. (2022). Drone-based water sampling and characterization of three freshwater harmful algal blooms in the United States. *Frontiers in Remote Sensing, 3*. https://doi.org/10.3389/frsen.2022.949052.

Kataoka, T., Kaneko, T., Okamoto, H., & Hata, S. (2003). Crop growth estimation system using machine vision. *Proceedings 2003 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2003), 2*, b1079-b1083 vol.2. https://doi.org/10.1109/AIM.2003.1225492.

King County. (2002). *Volunteer Lake Monitoring Results for the Water Year 2001. King County Lake Monitoring Report: Volunteer Lake Monitoring Results for Water Year 2000-2001*. https://your.kingcounty.gov/dnrp/library/archive-documents/wlr/waterres/smlakes/LMRep_01.pdf.

King County. (2015, December 15). *Echo-Shoreline Lake. Lake Information Page - King County*. https://green2.kingcounty.gov/smalllakes/LakePage.aspx?SiteID=10.

Lad, A., Breidenbach, J. D., Su, R. C., Murray, J., Kuang, R., Mascarenhas, A., Najjar, J., Patel, S., Hegde, P., Youssef, M., Breuler, J., Kleinhenz, A. L., Ault, A. P., Westrick, J. A., Modyanov, N. N., Kennedy, D. J., & Haller, S. T. (2022). As We Drink and Breathe: Adverse Health Effects of Microcystins and Other Harmful Algal Bloom Toxins in the Liver, Gut, Lungs and Beyond. *Life*, *12*(3), Article 3. https://doi.org/10.3390/life12030418.

Van der Merwe, D., & Price, K. P. (2015). Harmful Algal Bloom Characterization at Ultra-High Spatial and Temporal Resolution Using Small Unmanned Aircraft Systems. *Toxins, 7*(4), Article 4. https://doi.org/10.3390/toxins7041065.

MicaSense, Inc. (2020 June). *MicaSense Altum™ and DLS 2 Integration Guide*. Revision 10, MSPN 900-00021-01. https://support.micasense.com/hc/article_attachments/360073921173/AltumDLS2IntegrationGuideRev10.pdf.

Molecular Devices Corporation. (1997). *SPECTRAmax® PLUS Microplate Spectrophotometer Operator's Manual*. https://mdc.custhelp.com/euf/assets/content/User%20Manual%20-%20Plus.pdf.

NALMS. (n.d.-a). *Chlorophyll Analysis*. Retrieved July, 2023, from http://www.nalms.org/secchidipin/monitoring-methods/chlorophyll-analysis/.

Oklahoma Water Resources Board. (2018). *Standard Operating Procedure for the Collection and Processing of Chlorophyll-a Samples in Lakes*. https://www.owrb.ok.gov/quality/monitoring/bump/pdf_bump/Lakes/SOPs/Collection_of_Water_Quality_Samples.pdf.

Pix4D. (n.d.-a). P*hotogrammetry Knowledge: What is... (a densified point cloud? an orthomosaic? etc.)*. https://support.pix4d.com/hc/en-us/articles/206455126-What-is-a-densified-point-cloud-an-orthomosaic-etc#label2.

Pix4D. (n.d.-b). *Pix4D Documentation: Processing Steps*. https://support.pix4d.com/hc/en-us/articles/115002472186-Processing-steps.

Schaeffer, B. A., Reynolds, N., Ferriby, H., Salls, W., Smith, D., Johnston, J. M., & Myer, M. (2024). Forecasting freshwater cyanobacterial harmful algal blooms for Sentinel-3 satellite resolved U.S. lakes and reservoirs. *Journal of Environmental Management, 349*, 119518. https://doi.org/10.1016/j.jenvman.2023.119518.

Sunoj, S., Hammed, A., Igathinathane, C., Eshkabilov, S., & Simsek, H. (2021). Identification, quantification, and growth profiling of eight different microalgae species using image analysis. *Algal Research, 60*, 102487. https://doi.org/10.1016/j.algal.2021.102487.

Tan, Z., Yang, C., Qiu, Y., Jia, W., Gao, C., & Duan, H. (2023). A three-step machine learning approach for algal bloom detection using stationary RGB camera images. *International Journal of Applied Earth Observation and Geoinformation*, *122*, 103421. https://doi.org/10.1016/j.jag.2023.103421.

USEPA. (2013). *Standard Operating Procedure for Chlorophyll a Sampling Method Field Procedure. LG404, Revision 07*. Retrieved from https://www.epa.gov/sites/default/files/2017-01/documents/sop-for-chlorophyll-a-201303-5pp.pdf.

Wu, D., Li, R., Liu, J., & Khan, N. (2023). Monitoring Algal Blooms in Small Lakes Using Drones: A Case Study in Southern Illinois. *Journal of Contemporary Water Research & Education, 177*(1), 83–93. https://doi.org/10.1111/j.1936-704X.2022.3383.x.

Xue, J., & Su, B. (2017). Significant Remote Sensing Vegetation Indices: A Review of Developments and Applications. *Journal of Sensors, 2017*, e1353691. https://doi.org/10.1155/2017/1353691.

THANK YOU!

- Questions?
- Joey Teresi, MS Student
- jteresi@uw.edu

DEPARTMENT OF ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES

UNIVERSITY of WASHINGTON
School of Public Health