Island Connections: Soils, Water, Vegetation, and Education in a Small Low Island Context

A Dissertation
Presented in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
with a
Major in Water Resources
in the
College of Graduate Studies
University of Idaho
by
Mary S. Engels

Major Professor: Robert Heinse, Ph.D.
Committee Members: Jerry Fairley, Ph.D.; Arjan Meddens, Ph.D.; Hillary Young, Ph.D.
Department Administrator: Matthew Morra, Ph.D.

August 2019

Authorization to Submit Dissertation

This dissertation of Mary S Engels, submitted for the degree of Doctor of Philosophy with a Major in Water Resources and titled "Island Connections: Soils, Water, Vegetation, and Education in a Small Low Island Context" has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ________________________________ Date: ___________
Robert Heinse, Ph.D.

Committee Members: ________________________________ Date: ___________
Jerry Fairley, Ph.D.

________________________________ Date: ___________
Arjan Meddens, Ph.D.

________________________________ Date: ___________
Hillary Young, Ph.D.

Department Administrator: ________________________________ Date: ___________
Matthew Morra, Ph.D.

Abstract

Atoll islands (AI) are home to unique ecosystems found across a wide range of climatic conditions. The remoteness and small size of these islands limits studies about physical and biological relationships that may be important for adaptation and survival of island species. This dissertation combines both physical studies, remote sensing studies, and educational outreach efforts to increase our understanding of AI. Chapter one of this dissertation explores the mechanisms by which *Pisonia grandis*, R. Br., a native island tree species, alters the soil environment with respect to water. Chapter two validates a method for mapping AI island vegetation from moderate-resolution Landsat 7 ETM+ imagery using multiple endmember spectral mixing analysis. Chapter three described a series of data-driven lesson plans developed about the Pacific Marine National Monument system, and chapter four, which focuses on education but not AI, quantifies changes in scientific literacy experienced by students participating in an experiential water focused science program, the Confluence Project, in northern Idaho.

Acknowledgements

This work would not have been possible without significant help from many different sources.

First, I must gratefully acknowledge my committee members and my advisor, Dr. Robert Heinse. Without their help, guidance, and friendship this work never would have happened.

I really also must thank the funding agencies, NSF GK12, NASA NSSSF, and the NOAA Marine National Monument program for believing in my ideas and making it possible for me to live and work as a graduate student.

Third, without the dedicated students and staff of the Sea Education Association this work would never have gotten started, let alone completed. They risked heat exhaustion, sharks, sharp reefs and very dodgy small boat landings to help me with data collection in Kiribati. Thank you!

Thank you to the members of the Confluence Project team: Drs. Brant Miller and Karla Eitel, Audrey Squires, Jyoti Jennewein. They, and the many teachers and students who participated in the Confluence Project, showed me how powerful a local watershed can be for learning about water and how fun education can be when you work with a great team.

Developing a suite of rigorous, data-driven lesson plans is an enormous undertaking. I could not have asked for a better partner in this endeavor than Laura Nelson. Thank you.

Sarah Smith and Tasia North, thank you for all the help collecting and entering lab data.

Dedication

This dissertation is dedicated to those who have been so supportive of me during my graduate tenure. Without my family and friends, and their belief that this long meandering journey would come to successful conclusion someday, none of this would have been possible.

Thank you and I love you all.

In particular I would like to dedicate this dissertation to my father, who started me on the path to studying water and is not here to see. I know he would have been thrilled.

Thank you, Dad, I miss you and love you.

Table of Contents

Authorization to Submit Dissertation ... ii

Abstract ... iii

Acknowledgements ... iv

Dedication ... v

Table of Contents ... vi

List of Tables ... viii

List of Figures ... ix

Statement of Contribution ... xi

Chapter 1: Vegetation Mediated Capillary Barrier Effect in Pacific Atoll Soils ... 1

Abstract ... 1

1.1 Introduction ... 1

1.2 Methods and Materials ... 2

1.3 Results ... 8

1.4 Discussion ... 16

1.5 Conclusions ... 18

Literature Cited ... 19

Chapter 2: Mapping Atoll Island Vegetation using Landsat 7 ETM+ MESMA Informed by QuickBird ... 22

Abstract ... 22

2.1 Introduction ... 22

2.2 Materials and Methods ... 25

2.4. Results ... 33

2.5 Discussion ... 35

2.6 Conclusions ... 38

Literature Cited ... 39

Chapter 3: Pacific Marine National Monuments: Dynamic systems for educating the next generation of stewards ... 45
Abstract ... 45
3.1 Introduction ... 45
3.2 Lesson Development ... 46
3.3 Lesson Examples ... 48
Literature Cited ... 49
Chapter 4: The Confluence Approach: Developing scientific literacy through project-based learning and place-based education in the context of NGSS ... 50
Abstract ... 50
4.1 Introduction ... 50
4.2 Methods and Materials ... 56
4.3 Results and Discussion ... 61
4.4 Limitation ... 69
4.5 Recommendations ... 70
4.6 Conclusions ... 70
Literature Cited ... 72
Appendix A - Hydrus-1D Modelling Results Matrix ... 77
Appendix B - Pacific Marine National Monument Lesson Plans ... 81

List of Tables

Table 1-1: HYDRUS-1D boundary conditions 8
Table 1-2: Species proportion in different canopy layers for Palmyra Atoll (P, n=70) and Nikumaroro Atoll (N, n=11) as defined in the methods. 9
Table 1-3: MANOVA results by soil traits. For soil traits that vary significantly by canopy type (P <0.1) colors denote the range of the variable from high (orange) to mid-range (white) to low (blue). 10
Table 1-4: Van Genuchten model fitting parameters for a mineral (KAU-ST2) and an organic soil (DUD-PG1), both from Palmyra. Model fitting parameters are used to characterize soil hydraulic characteristics in HYDRUS-1D modelling. 14
Table 2-1: Acquisition Characteristics for imagery used in this study 28
Table 2-2: Spectral Libraries and Endmembers tested in MESMA. 34
Table 2-3: Percentage of successfully unmixed pixels and classification accuracy by library, fraction threshold, and model constraint scenario at an RMSE threshold of 10%. Grey bar highlights the best combination. 34
Table 2-4: Confusion matrix for all pixels with at least 70% homogeneity, as unmixed by the best performing library-constraint-unmixing combination (2_3_IES_10 _-5_105), and the AQB imagery. 34
Table 2-5: Overall, Producer's and User's accuracy in percent by class at different levels of dominance for the IES Library when comparing MESMA classification to AQB classification. Note that bold indicates the dominance threshold as fraction of the image pixel. 35
Table 4-1: The Confluence Approach Participant Counts and Demographic Data for 2014-15 57
Table 4-2: Survey Questions and Five-point Likert-scale Response Options 58
Table 4-3: Codebook for qualitative analysis of the open-ended survey questions 60
Table 4-4: Codes, Code Frequency Changes, and Representative Quotes elated to RQ1. 64
Table 4-5: Codes, Code Frequency Changes, and Representative Quotes Related to RQ2. 66
Table 4-6: Results from the Mann-Whitney-Wilcoxon Tests 67
Table 4-7: Results from Exploratory Factor Analysis 68

List of Figures

Figure 1-1: Location of study atolls. White boxes show the boundaries of the marine protected areas. Palmyra Atoll is part of the Pacific Remote Island Marine National Monument (PRIMNM) and Nikumaroro is part of the Phoenix Island Protected Area (PIPA). 3

Figure 1-2: pH and Organic Carbon (OC) by canopy type. Ellipses indicate the 95% confidence interval for each canopy type. No ellipses are drawn for canopy types with less than 8 samples. 11

Figure 1-3: Percentage of soil retained on each sieve. Pan fraction is any soil that in less than 0.053 mm in size. 12

Figure 1-4: Volumetric water content versus organic carbon percentage of soils at different three different saturation states: Saturation, 0 MPa, Field Capacity, 0.03 MPa, Permanent Wilting Point, 1.5 MPa. 13

Figure 1-5: Amount of water by percent held between SAT and PWP for each soil type. 13

Figure 1-6: Measured soil water retention data for an organic soil (DUD-PG1) and a mineral (KAU-ST2) soil. Curves combine data from three different methods of measuring soil water content in order to cover the range of pressures in which plant roots operate. pF is the log of head in cm. 14

Figure 1-7: Comparison of amount of water stored in the organic cap, or in the upper 30 cm of the soil profile where there is no organic cap, and the time until the upper 10 cm of the soil profile reaches PWP. The depth of the organic cap is indicated by marker colors, the intensity of rainfall events is indicated by marker shades, and the annual precipitation for different islands is indicated by marker size. The amount of water stored at saturation is indicated by horizontal red lines in each depth class. In general, increasing organic cap depth and increasing rainfall intensities results in more water in storage and longer time till dry down. This is pattern holds true across the range of annual precipitation. 15

Figure 2-1: A- Worldview 2 satellite view of Palmyra Atoll vegetation types. B- Landsat 8 satellite view of Palmyra Atoll vegetation types 23

Figure 2-2: Study Area Location showing (A) the Pacific Ocean context with the location of the US Pacific Marine National Monuments (white polygons), and the location of the Pacific Remote Island Marine National Monument (PRIMNM), and (B) Palmyra Atoll. 26

Figure 2-3: Workflow diagram. Colors denote imagery types and products, blue for QuickBird, orange for Landsat 7 ETM+, green for MESMA. Abbreviations are normalized difference vegetation index (NDVI), endmember (EM), multiple endmember spectral mixing analysis (MESMA), and root mean squared error (RMSE). 29

Figure 2-4: Classification maps by technique: Maximum likelihood classification of high resolution QB data (A), aggregated high resolution QB classified by simple fractional majority (B), and classification of MESMA fractions by simple majority (C)...36

Figure 4-1: Conceptual model of The Confluence Approach (TCA) to enhancing scientific literacy. 51

Figure 4-2: The Confluence Approach continuum through an academic year.....................................55

Statement of Contribution

My coauthor for the published lesson plans in Chapter 3 is Laura Nelson. The generation of the lesson concepts, structure, and design was a joint effort, and primary lesson content development was split between Laura and myself. The lesson example shown in this dissertation is my work. Funding for this project was jointly secured from NOAA by both authors.

Coauthors for the submitted work in Chapter 4 are Dr. Brant G. Miller, Audrey Squires, Jyoti Jennewein, and Dr. Karla Eitel. Dr. Brant G Miller and Audrey Squires originally conceptualized the project and the methodology for completed work was a combined effort by all the co-authors. Dr. Brant G. Miller, Audrey Squires and Jyoti Jennewein coded all student responses, and Jyoti Jennewein completed the quantitative analysis. I completed the analysis of the qualitative data and created the manuscript for submission, with review and editing help from all the other authors.

Chapter 1: Vegetation Mediated Capillary Barrier Effect in Pacific Atoll Soils

Abstract

Atoll islands occur across a wide precipitation gradient. In order to be successful on these atolls terrestrial plants have developed a range of water management strategies. The island native tree *Pisonia grandis,* Robert Brown, 1851, is thought to exploit organic rich “Jemo” soils (Fosberg, 1954) that develop in association with this species as part of its water management strategy. In this study I hypothesize that the presence of the organic soils is fundamentally altering the soil infiltration and percolation dynamics under *P. grandis*. To test this hypothesis, I analyzed and modeled soil and environmental data collected from under a variety of canopy types on two atolls in the central Pacific Ocean. Results indicate that highly organic soils are strongly, though not exclusively, associated *P. grandis*, and that soil characteristics and water holding capacities are distinctly different between organic and mineral soils. Modelling results indicate the development of a capillary barrier where organic soils overlie coarse carbonate sands, and this barrier effect results in the organic cap retaining significantly more water than the underlying sands. The presence of excess water in the organic layer results in greater water availability to *P. grandis* and helps explain how this species can exist on both very wet and very dry atolls.

1.1 Introduction

Pacific tropical atoll islands (AI), an island or a chain of islets connected by a coral reef surrounding a central lagoon, are found across a wide precipitation gradient, with mean annual precipitation values from as low as 50 cm/yr up to as high as 500 cm/yr (Mueller-Dombois & Fosberg, 1998). Freshwater in these systems is entirely precipitation derived. Depending on the size and shape of the island water delivered to the island surface and infiltrates ends up in storage either in the soils or as part of a freshwater lens that floats on denser seawater at depth. Because of very high hydraulic conductivities in the coarse carbonate sands and coral rubble which make up the bulk of the island (Bailey, Jenson, & Olsen, 2010), most of the freshwater storage on the islands is in the freshwater lens, which may be out of reach of some plant species.

Mueller-Dombois and Fosberg (1998) have identified a suite of plants characteristic to AI which can be found across the precipitation gradient. These plants have developed various freshwater management strategies in order to be successful under a wide range of precipitation and soil moisture conditions. Some plant, such as *Cocos nucifera* L., *Tournefortia argentea* L. f., and *Scaevola taccada* Vhal may have roots that are deep enough to directly access the freshwater lenses (Carr, 2011; R. B.

Walker & Gessel, 1991). Salt tolerance and brackish water utilization are other common strategies, especially among those that are common in the strand vegetation (Cole, Gessel, & Held, 1961; Mueller-Dombois & Fosberg, 1998). However, none of these strategies are used by the iconic island native *Pisonia grandis* R. Br. Known for its exceptionally shallow roots (T. Walker, 1991) and salt intolerance (Mueller-Dombois & Fosberg, 1998), it is thought that this tree might instead limit its water extraction to near surface soil water storage from the highly organic Jemo soils (Fosberg, 1954) that form in association with this species.

To date little work has been done to understand this potential freshwater management strategy by *P. grandis.* In this study I are interested in understanding the physical mechanisms driving water storage in these organic soils, and the implications of this storage for *P. grandis* adaptation across the precipitation gradient. I hypothesize that the presence of the organic soils is fundamentally altering the soil infiltration and percolation dynamics under *P. grandis* and that this is driving increased water storage in the organic layer. The test this hypothesis I combine environmental, physical, and modeling data from two atolls, one wet and one dry, in the central Pacific Ocean.

1.2 Methods and Materials

1.2.1 Study sites

Palmyra Atoll National Wildlife Refuge (PANWR), located at 5°53′1″N 162°4′42″W, is part of the Pacific Remote Island Marine National Monument and is both protected and minimally inhabited (Fig. 1-1). Currently the atoll is under very strict management by the US Fish and Wildlife Service (USFWS) and The Nature Conservancy (TNC), who limit access to the Atoll. There is a well-established research station on the island run by the Palmyra Atoll Research Consortium. All water (including potable water) used in support of research and management activities comes from rainfall collection and so ecohydrological dynamics on the atoll are not complicated by groundwater pumping.

Palmyra is a small coral atoll formed of coral rubble and sand sourced from the surrounding fringing reef complex. It is composed of a series of small vegetated islets surrounding two central lagoons. While it was being used as a U.S. Naval Air Station during WWII many of the islets were modified and connected to create a single continuous island rim. In addition, a few new islets (e.g., Strawn, Sand, Fighter) were created from dredge material removed during the creation of a deep-water channel. Since WWII natural processes have undone many of the human modification, and the island rim is gradually separating back into distinct islets. Total exposed land area is about 2.5 km^2 (Collen, Garton, & Gardner, 2009), most of which is forested. Islets range from less than a hectare to ~100 ha in size, with a maximum of two meters vertical relief (Hathaway, McEachern, & Fisher, 2011).

Palmyra Atoll is home to both *Coconut* and *P. grandis*, which exist in monodominant and mixed communities on various islets, including the islets created from dredge spoils (Young, Raab, McCauley, Briggs, & Dirzo, 2010).

Average reported annual rainfall in Palmyra is over 400 cm a year, comparable with other wet islands, particularly those in the western Pacific (Mueller-Dombois & Fosberg, 1998). Recent historical records show periods of days and weeks with no rainfall, which is sufficient time, given the high hydraulic conductivities (50-400 m day^{-1}), to force plants to extract water from a limited freshwater lens if they are able (Meehl, 1996).

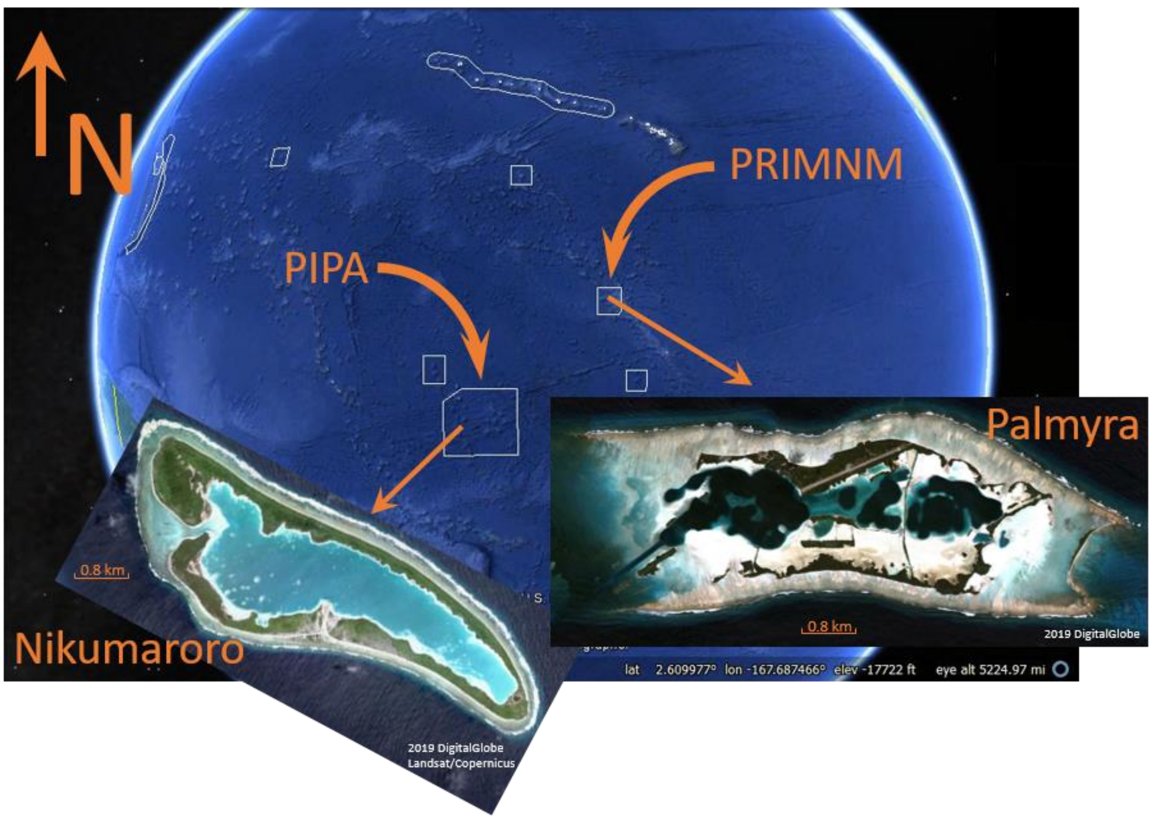


Figure 1-1: Location of study atolls. White boxes show the boundaries of the marine protected areas. Palmyra Atoll is part of the Pacific Remote Island Marine National Monument (PRIMNM) and Nikumaroro is part of the Phoenix Island Protected Area (PIPA).

Nikumaroro Atoll (4°40′32″S 174°31′4″W), also known as Gardner Isle, is one of eight islands that make up the Phoenix Island Protected Area (PIPA), one of the largest marine reserves in the world. PIPA is part of the Small Island Developing State (SIDS) nation of Kiribati and forms the central part of the country, sandwiched between the more populated Gilbert Islands to the West and the Line

Islands to the East. Except for Kanton, which hosts a small community of government employees and their families, the islands of PIPA are currently uninhabited.

Nikumaroro Atoll is a triangular shaped, small (7.5 km x 2.5 km) atoll, with a total vertical relief of less than two meters. The atoll is oriented NW-SE and unlike Palmyra, the atoll rim is intact in all but two locations. Access to the atoll and its lagoon is extremely restricted as the atoll is ringed by a wide, shallow, fringing reef complex. The island rim is composed of coral rubble and sand sourced from the surrounding reef and central lagoon. Total exposed land area is 4.3 km^2, and the land surface is covered by a mix of native atoll vegetation, including large monospecific stands of *P. grandis,* and abandoned coconut plantations.

Human settlement on Nikumaroro has been very limited. Coconuts were first commercially planted on the island in 1892 and sporadic attempts at copra production continued until the mid-1960s at which time settlement attempts were abandoned due to limited fresh water supplies. Commercial coconut production focused on the western end of the island and today there remain large monospecific stands of *Coconut* on that side of the island.

PIPA lies at the edge of the Pacific equatorial dry zone, between the Intertropical Convergence Zone and the South Pacific Convergence Zone. Precipitation is variable and strongly correlated with El Niño, but on average the area gets 50-100 cm of rain a year depending on the ENSO phase (Mueller-Dombois & Fosberg, 1998). Nikumaroro is on the western edge of the PIPA and may get more precipitation than islands further to the east. The abundant forest cover on the island, unlike its eastern neighbors supports this.

1.2.2 Soil sampling and site characterization

In order to characterize the infiltration and percolation dynamics of the island soils I recorded a suite of *in situ* environmental characteristics and removed soil samples for laboratory analysis. On each atoll I selected sample locations (11 on Nikumaroro, 72 on Palmyra) to ensure adequate characterization of soil environments under different canopy types, across productivity gradients, and across the range of islets sizes. Where accessibility remained difficult, particularly in Nikumaroro, I only sampled a portion of the island. Data collected at each site included: photos of ground and canopy cover and soil samples of the top 20 cm of soil.

<u>Canopy Cover:</u> In the field I collected both digital photos and field notes on canopy cover, which were transcribed post hoc to determine canopy classification. Data collected from each photo included percentage alive vs dead canopy cover and orientation of the photograph (ground, horizon, canopy). I further classified the living canopy cover by estimating the percentage of dominant six tree

species, three ground cover species. Canopy layers were determined from photographs and classified into ground cover, understory, middle story and overstory vegetation. Based on photo classification a Simpson's diversity index (SDI) value was calculated for each image and averaged to generate a site value. Sites with 75% coverage or greater (SDI value of 0.375 or smaller) were classified as single species dominated. All others were classified as mixed coverage sites. The dominant tree species at each site was determined by normalizing the mean value of each tree species present by the number of photos in which those species occur.

<u>Soil Samples:</u> After removing leaf litter I collected soil samples from the upper 20 cm of the surface profile and, where present, the O horizon, as "Jemo" soils (Fosberg, 1954) may be classified as an O horizon. Because of the very coarse textured nature of atoll soils traditional measures of *in situ* volume were not possible. Instead, I followed the water method described by Page-Dumroese, Jurgensen, Brown, and Mroz (2010), which determines sample volumes by lining the sample hole with a thin plastic layer and recording the volume of water needed to fill the hole to the reference surface. Due to lack of refrigeration, samples were air dried after collection and returned to the lab for further analysis.

1.2.3 Laboratory Analyses

Preparation for laboratory analysis of soil samples started with sieving soils to separate samples into greater and less than 2 mm fractions following soil processing convention (Staff, 2014). The gravel fraction (>2 mm) was hand sorted into organic, inorganic, and anthropogenic classes, while the remaining fine earth fraction (SSC, <2 mm) was analyzed to determine soil size, nutrient contents, and water retention characteristics.

<u>Soil Size:</u> Soil texture was determined by sieving and the fraction less than 0.053 mm for most samples was not large enough to warrant further analysis using the sedimentation method.

<u>Nutrient contents:</u> Subsamples of each soil were sent to Brookside Laboratories Inc. (New Bremen, OH) for comprehensive nutrient analysis using their Standard Soil Assay with Bray 1 (S001PN) and their Carbon Nitrogen Ration test (S202). Analyses included determinations of carbon nitrogen ratios, total exchangeable cations, pH, organic matter content, and amount of macro (sulfur, phosphorus, calcium, magnesium, potassium, sodium, nitrogen (and ammonia)) and micro (boron, iron, manganese, copper, zinc, aluminum) nutrients. Additional measures of organic matter and pH were determined in house for cross verification purposes. Organic matter characterization followed Dean's method (1974) for determination of organic matter in carbonate soils, and pH was determined using

the saturated paste method described by the NRCS Soil Survey manual (Staff, 2014). pH standards were read every 4th sample to insure calibration.

Water Retention Characteristics: A combination of methods were used to determine the water retention characteristics of these soils. Critical measurement pressures for modelling the water retention profile of the soils and calculating plant available water were saturation (SAT, 0 MPa), field capacity (FC, -0.033 MPa), and permanent wilting point (PWP, -1.5 MPa).

Saturation: I determined saturation water content of soils using an array of Bruckner funnels connected to a Mariotte bottle filled with DI water. Sample material was placed in the funnels to a depth of ~1 cm of dry material and then was slowly saturated from the bottom via the Mariotte bottle with a head reference above the soil surface. Once completely saturated the head reference in the Mariotte bottle was dropped to the same level as the frit on the bottom of the Bruckner funnels. After 24 hours sample were removed from the funnels, weighed, dried for 24 hrs in a 105°C oven and then re-weighed. 25% of the samples were dried for an additional 24 hrs and then re-weighed to ensure that the 24 hr dry time was enough. Replicate saturation measurements were made for only 7% of the samples due to limited sample volume. Gravimetric water content was calculated as the difference in weight between the wet and oven dry samples and converted to volumetric water content using bulk density. Volumetric water content was not determined directly because of significant volume uncertainties associated with the swelling of highly organic soils.

Field capacity: Pressure plates were used to determine water retention at 0.03 MPa following methods NRCS soil survey standard methods (Staff, 2014).

Permanent Wilting Point: The dry end of water retention curve was characterized using a Meter WP4 relative humidity sensor (Meter, Pullman, WA). Oven dry soils were mixed with triple distilled, dionized water to prescribed gravimetric water contents and measured to determine the water potential in MPa. The number of samples varied by soil and additional samples were mixed as necessary in order to ensure multiple sample measurements in the range of water potentials between -1 MPa and -1000 MPa. Interpolation of the water content at the PWP (-1.5 MPa) then followed methods described by Campbell (2012?). The osmotic potential, calculated as 0.36*EC_e (Or, Wraith, & Tuller, 1997), was subtracted from each WP4 measurement in order to improve comparison between pressure plate and WP4 data.

Hyprop: Water content measurements made using saturation and pressure plate method were validated for several representative samples using a Hyprop sensor (UMS GmbH, Munich, Germany), which characterizes the wet end of the water retention curve. Methods followed UMS (UMS GmbH, 2015), except that samples were re-packed into sampling ring using damp < 2 mm soil prior to saturation. Water retention curves were developed by adding saturation, pressure plate and EC corrected WP4 data points to the Hyprop data and fitting the data using Mualem-van Genuchten model (van Genuchten, 1980).

EC adjustment: Electrical conductivity ($EC_{1:5}$) of soil pore water was measured using shaking methods described by He, Desutter, Hopkinds, Jia, and Wysocki (2013). Samples with insufficient head space due to organic matter expansion were diluted in a 1:5 ratio before measuring. $EC_{1:5}$ measurements were converted to an equivalent extracted EC (EC_e) using relationships developed by He, Desutter, Hopkins, Jia & Wysocki (2013).

1.2.4 Statistical Analysis and Modelling

Statistics: Soil attributes were first analyzed by descriptive statistics (minimum, maximum, mean, standard deviation, and standard error). To verify differences among soil samples by canopy type I used a MANOVA. PCA analysis was used to determine which of the ?? soil variables are most important for understanding soil differences across the islands. Only variables with a high percentage of explanation, defined as absolute values within 10% of the highest value (Pereira et al., 2018) were retained for geostatistical analysis. Pearson correlation coefficients were computed for soil attributes retained in the PCA. All statistics were computed in R v3.5.3 (Team & R Development Core Team, 2016) using an alpha of 0.05.

Modelling: Vadose zone water potentials and water flows were modeled using HYDRUS-1D (Šimůnek, Sejna, Saito, Sakai, & van Genuchten, 2008). All model runs consist of a 200 cm soil column with a static freshwater lens at 150 cm. Model discretization was 2 cm and soil hydraulic characteristics are parameterized using values from the Mualem-van Genuchten model (van Genuchten, 1980) as follows:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_\Gamma}{[1 + |\alpha h|^n]} m & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (1)$$

$$K_{(h)} = K_s S_e^{0.5} \left[1 - \left(1 - S_e^{0.5/m}\right)^m\right]^2 \qquad (2)$$

$$m = 1 - {}^{1}/_{n} \quad n > 1 \qquad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

where h is the pressure head (cm), θ_r is the residual water content ($cm^3\ cm^{-3}$), θ_s the saturated water content ($cm^3\ cm^{-3}$), α and *n* are empirical parameters, where α is related to the air-entry pressure value and n is related to the pore size distribution. *M* is dependent on *n* and is the water retention curve shape parameter. K_s is saturated hydraulic conductivity ($cm\ h^{-1}$), and S_e is the relative soil saturation.

Mualem-van Genuchten values (θ_r, θ_s, α, and *n*) were determined by fitting curves to laboratory derived water content and potentials of representative "organic" and "mineral" soils using the SWRC fit (Seki, 2007) and Hyprop ((UMS GmbH, 2015). Other boundary conditions and their sources can be found in Table 1-1. Rooting demand in the model decreases linearly from the surface to a maximum rooting depth of 10 cm, which is typical for *P. grandis* (Walker, 1991).

Model sensitivity analysis was run on each of the individual parameters to determine which factors had the greatest control system dynamics.

Table 1-1: HYDRUS-1D boundary conditions

Variable	Unit	Values	Sources
Annual Precipitation, ***AP***	cm/yr	50, 200, 400	(Mueller-Dombois & Fosberg, 1998)
Soil hydraulic parameters	various	θr, θs, α, n and K_s	See Table 1-2
Organic Soil Depth	cm	0, 14, 30, 50	(Fosberg, 1954, Pers comms Young)
Rooting depth	cm	10	(Christophersen, 1927)
Evapotranspiration, ***ET***	cm/day	0.5	(Krauss, Duberstein, Cormier, Young, & Hathaway, 2015)
Precipitation Intensity, ***PI***	cm/day	1,5,10	(Krauss et al., 2015)
Precipitation Duration, ***PD***	days	0.5	
Precipitation Frequency, ***PF***	days	PF= AP/(365*PI*PD)	Calculated

1.3 Results

1.3.1 Soil sampling and site characterization:

<u>Data collection:</u> A total of 11 sites were sampled for soil on Nikumaroro during the summers of 2014 and 2015. The six samples from north of the lagoon channel (SEDS1-SEDS6) represent a transect starting in the remnant *P. grandis* dominated forest to the north and ending in the abandoned coconut plantation to the south. The other five sample locations were all from the abandoned coconut plantation region south of the lagoon channel and spanned width of the island from the lagoon to the

shore. On Palmyra 72 soil samples and infiltration measurement were collected during the fall of 2016.

Canopy Cover: The most prominent overstory tree in Palmyra is coconut (Table 1-2), even in sites where the lower stories are dominated by other species. The next most common overstory tree in is *P. grandis*. Both trees form monospecific stands about a third of the time. *T. argentea*, and *P. fischerianus*, are not as widespread in the overstory but are common in the middle story. *Hibiscus sp.* is rare on the island and that is reflected in its limited occurrence in the canopy at any level. *S. taccada* did not dominate in the overstory at any sampling location, though it is present in both the middle and understory. Coconut was also the most dominate species in the lower canopies, particularly in the understory (46%). At 22 of 72 sites (30.5%) the entire canopy was composed of a single species and at four sites (5%) there was no canopy at all.

Table 1-2: Species proportion in different canopy layers for Palmyra Atoll (P, n=70) and Nikumaroro Atoll (N, n=11) as defined in the methods.

Canopy Position	Island	*P. grandis*	*C. nucifera*	*T. argentea*	*Hibiscus* sp.	*P. fischerianus*	*S. taccada*	*P. scolopendria*	*A. nidus*	Grass	Other	Mixed	No Cover
Overstory	*P*	21%	40%	14%	3%	7%	0%	0%	0%	0%	0%	7%	7%
	N	***27%***	***36%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***9%***	***27%***
Middlestory	*P*	17%	21%	14%	4%	17%	3%	0%	0%	0%	0%	9%	14%
	N	***36%***	***27%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***18%***	***18%***
Understory	*P*	7%	46%	1%	1%	1%	7%	0%	0%	0%	0%	9%	27%
	N	***36%***	***18%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***27%***	***18%***
Ground Cover	*P*	0%	0%	0%	0%	0%	0%	43%	1%	6%	1%	0%	49%
	N	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***0%***	***9%***	***91%***

On Nikumaroro the two tree species that dominate the canopy (over, middle and understory) are coconut and *P. grandis.* Where *P. grandis* occurs, it forms large monospecific stands with very little understory or groundcover, and the transition from this forest type to the Coconut dominated forests is abrupt. Coconut also forms monospecific stands but is more likely than *P. grandis* to develop mixed canopies. Coconut was also a very common as a middle and understory species. Ground cover on Nikumaroro was only present in a few sites.

1.3.2 Laboratory analyses

Nutrient contents: There are significant differences in 16 of 22 measured soil properties by canopy type (MANOVA, $F_{7,154}$ =1.4066, P=0.01, Table 1-3). The direction and magnitude of changes varies by property and canopy type, but the soils properties vary on a spectrum from *P. grandis* soils at one end and no canopy cover at the other end. Of the soil properties that are significantly different by canopy cover, nine of the soil properties also have a strong correlation (>60%) with the OC percent in soils. Only Boron, Zinc, Sulfur, and the carbon nitrogen ratio did not.

Table 1-3: MANOVA results by soil traits. For soil traits that vary significantly by canopy type (P <0.1) colors denote the range of the variable from high (orange) to mid-range (white) to low (blue).

Soil Trait ± *SE*	P	*P. grandis* (n=15)	*T. argentea* (n=11)	*S. sericea* (n=3)	*P. fischerianus* (n=8)	*H. tiliaceus* (n=3)	*C. nucifera* (n=39)	Mixed Canopy (n=2)	No Canopy (n=2)
ENR*	<0.001	134.73 *± 4.84*	128.91 *± 6.04*	120.33 *± 14.84*	130.62 *± 8.98*	118.67 *± 7.84*	103.36 *± 3.86*	121 *± 4*	79 *± 29*
Mg*	<0.001	743.93 *± 123.62*	743.55 *± 107.89*	411 *± 128.34*	867 *± 134.2*	657.33 *± 155.81*	1359.95 *± 81.18*	1535.5 *± 43.5*	2187.5 *± 1167.5*
OBPer*	<0.001	5.29 *± 0.47*	4.99 *± 0.5*	4.23 *± 0.48*	3.88 *± 0.08*	3.7 *± 0.15*	3.57 *± 0.07*	3.75 *± 0.25*	3.4 *± 0.4*
OC	<0.001	16.7 *± 3.11*	16.14 *± 4.93*	11.63 *± 8.06*	9.84 *± 2.27*	6.34 *± 1.63*	4.4 *± 0.49*	5.37 *± 0.46*	2.35 *± 1.48*
pH*	<0.001	6.45 *± 0.32*	6.68 *± 0.35*	7.13 *± 0.52*	7.53 *± 0.08*	7.7 *± 0.15*	7.83 *± 0.07*	7.65 *± 0.25*	8 *± 0.4*
Pho*	<0.001	842.33 *± 181.89*	473.55 *± 125.14*	722.33 *± 301.53*	190.25 *± 51.73*	128 *± 39.95*	144.49 *± 53.33*	22 *± 4*	172.5 *± 169.5*
Bray1P *	<0.01	649.8 *± 203.5*	174.73 *± 123.18*	706.33 *± 586.3*	25.12 *± 11.94*	11.67 *± 8.84*	52.79 *± 39.77*	1.5 *± 1.5*	98.5 *± 98.5*
Ca*	<0.01	13417 *± 1704.86*	14801.45 *± 1898.46*	14203.67 *± 3384.32*	16326.12 *± 822.89*	17422.67 *± 400.83*	18625.54 *± 478.74*	18089 *± 2550*	22769.5 *± 2094.5*
HPer*	<0.01	15.43 *± 5.71*	12.77 *± 6.15*	4.5 *± 4.5*	0 *± 0*	0 *± 0*	0 *± 0*	0 *± 0*	0 *± 0*
Sul	<0.01	103.8 *± 10.85*	92.09 *± 11.5*	61.67 *± 17.84*	85.88 *± 5.54*	83.33 *± 6.06*	131.13 *± 9.97*	136 *± 42*	242 *± 148*
TEC*	<0.01	90.82 *± 7.19*	94.64 *± 8.33*	80.95 *± 16.1*	94.03 *± 4.62*	97.52 *± 3.48*	111.92 *± 2.97*	113.9 *± 18.38*	148.84 *± 31.22*
Zn	<0.01	32.36 *± 9.21*	15.66 *± 5.02*	72.5 *± 48.75*	6.96 *± 2.25*	6.45 *± 2.06*	9.33 *± 3.89*	2.4 *± 1.28*	8.44 *± 5.22*
CNR	<0.05	17.37 *± 3.46*	24.38 *± 4.28*	27.98 *± 7.41*	29.31 *± 6.95*	30.51 *± 7.35*	55.08 *± 8.37*	30.96 *± 2.12*	99.83 *± 73.03*
NH4N	<0.05	74.31 *± 33.34*	14.37 *± 6.75*	20.97 *± 13.33*	6.95 *± 1.72*	2.63 *± 1.94*	2.82 *± 0.49*	2 *± 1.4*	2.45 *± 1.45*
B	<0.1	1.56 *± 0.24*	1.41 *± 0.17*	1.49 *± 0.29*	1.75 *± 0.12*	1.57 *± 0.12*	2.5 *± 0.25*	2.27 *± 0.11*	2.88 *± 0.11*
Na	<0.1	509.47 *± 134.63*	297.45 *± 44.11*	195.33 *± 12.57*	304.62 *± 40.77*	270.33 *± 25.15*	750.95 *± 198.6*	1344.5 *± 966.5*	2645 *± 2389*
Al		0.6 *± 0.29*	0.27 *± 0.19*	0 *± 0*	0.12 *± 0.12*	0 *± 0*	0.77 *± 0.33*	0.5 *± 0.5*	3 *± 1*
Cu		27.8 *± 25.94*	1.44 *± 0.14*	4.54 *± 1.96*	3.41 *± 1.83*	1.48 *± 0.32*	2.26 *± 0.63*	2.56 *± 0.42*	3.46 *± 2.17*
Fe		3.93 *± 2.68*	1.18 *± 0.64*	13 *± 13*	0 *± 0*	0 *± 0*	2.9 *± 2.54*	0 *± 0*	0 *± 0*
K		136.87 *± 16.79*	101.09 *± 25.58*	73.67 *± 33.23*	84.88 *± 17.16*	54.67 *± 12.17*	90.41 *± 14.38*	192.5 *± 37.5*	126 *± 68*
Mn		3 *± 0.72*	1.55 *± 0.65*	1 *± 0.58*	3.12 *± 1.71*	1.67 *± 0.33*	1.44 *± 0.31*	1.5 *± 0.5*	1 *± 1*
NO3N		54.48 *± 15.27*	156.24 *± 77.72*	15.27 *± 2.17*	34.59 *± 11.44*	7.93 *± 6.22*	28.87 *± 12.88*	4.1 *± 4.1*	12.15 *± 2.55*

* 60% or greater correlation with OC

Organic carbon content ranged from 0.71 % to 51.86% (Fig. 1-2). Samples with the lowest amounts of OC, at 0.71% and 0.73%, are pure beach sand samples. Samples meeting the definition for organic soils, with >20% OC (USDA, 2014), were found in areas with canopy cover dominated by the island natives *P. grandis*, *T. argentea*, and *P. fischerianus*, and in one case from under the non-native invasive *H. tiliaceus.* No samples from areas with Coconut overstory had OC percentages greater than 13.6%, and only two of the Coconut overstory samples, of 39, had OC percentages greater than 10%.

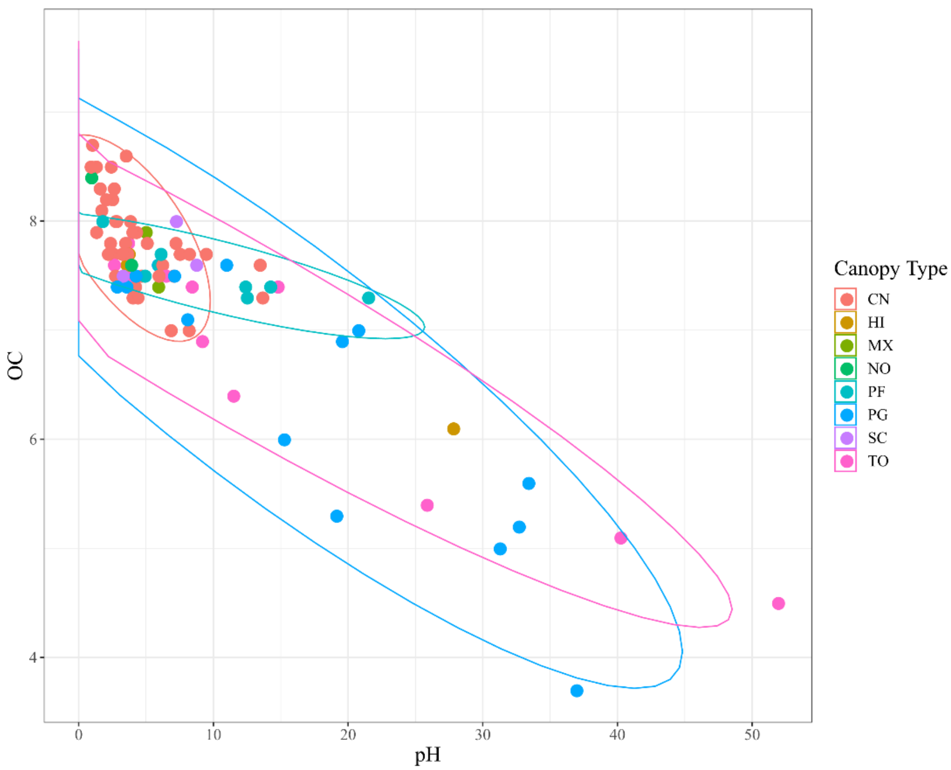


Figure 1-2: pH and Organic Carbon (OC) by canopy type. Ellipses indicate the 95% confidence interval for each canopy type. No ellipses are drawn for canopy types with less than 8 samples.

pH also ranges widely, from 3.7 to 8.7 (Fig. 1-2), and is strongly associated with the OC content of the soils (r2=0.79). Acidic soils with a pH below 7.0 are only found in association with three different canopy cover types; *P. grandis, T. argentea,* and *H. tiliaceus.* Soils from Coconut dominated canopies are the only canopy covered soils in this study with pH values above 8. The other sample with a pH greater than 8 has no canopy cover at all as it is from an area that is flooded regularly at high tide.

<u>Soil size:</u> The size of soils in the <2mm fraction is significantly different (p<0.05) between the mineral and organic soils, in all size classes except 0.106 mm (p=0.33) (Fig. 1-3). In general, the organic soils had more fine sands and silt/clay sized particles (0.053 mm and pan fraction) and very

coarse sand and gravel size particles (1 mm and 2 mm (not shown)). Mineral soils, however, were dominated by medium and coarse sand sized particles.

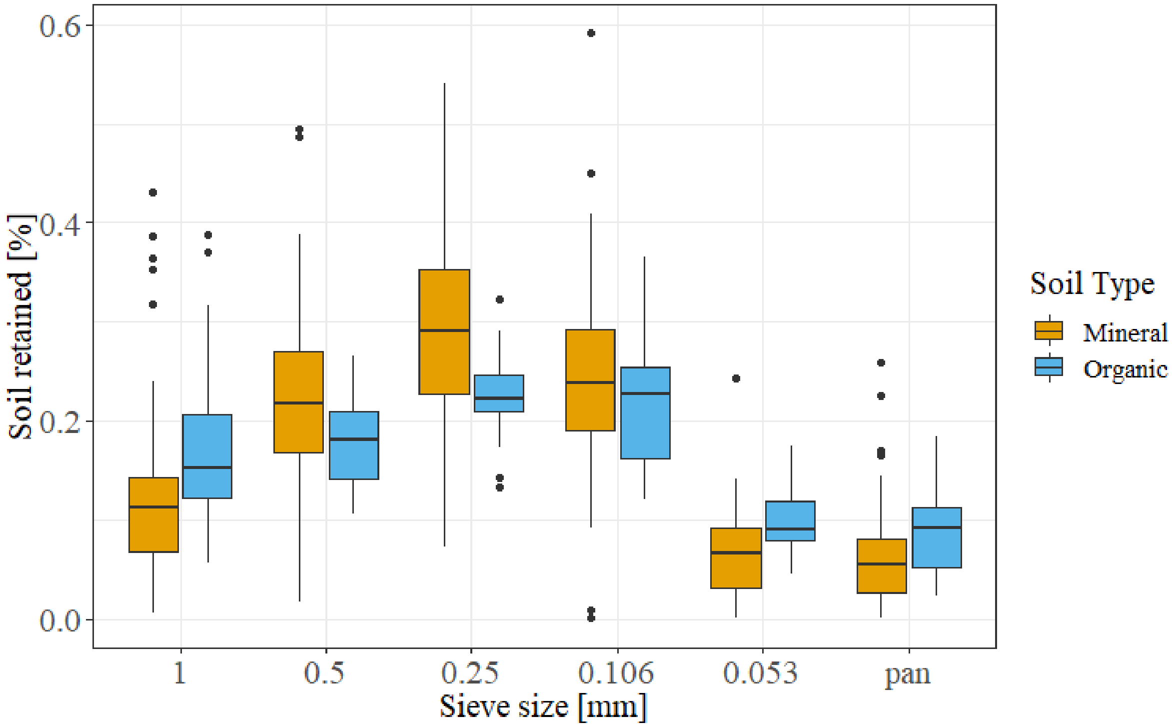


Figure 1-3: Percentage of soil retained on each sieve. Pan fraction is any soil that in less than 0.053 mm in size.

<u>Water Retention:</u> For all soils the range of soil water content at saturation is 50%-80%, at FC is 10%-37%, and at PWP is 2%-25% (Fig. 1-4), with a few outliers. At each measured pressure the VWC is positively correlated with OC content until ~10% OC for at FC and PWP, or ~20% OC at SAT, after which additional increases in OC do not result in greater VWC. Soils with high amounts of organic carbon (>10% OC, hereafter organic soils) on average have the higher VWC at saturation that the mineral soils (<10% OC), but only slightly higher water content at PWP. Thus, the available water in soils between SAT and PWP is significantly different between the organic soils and the mineral soils (Fig. 1-5).

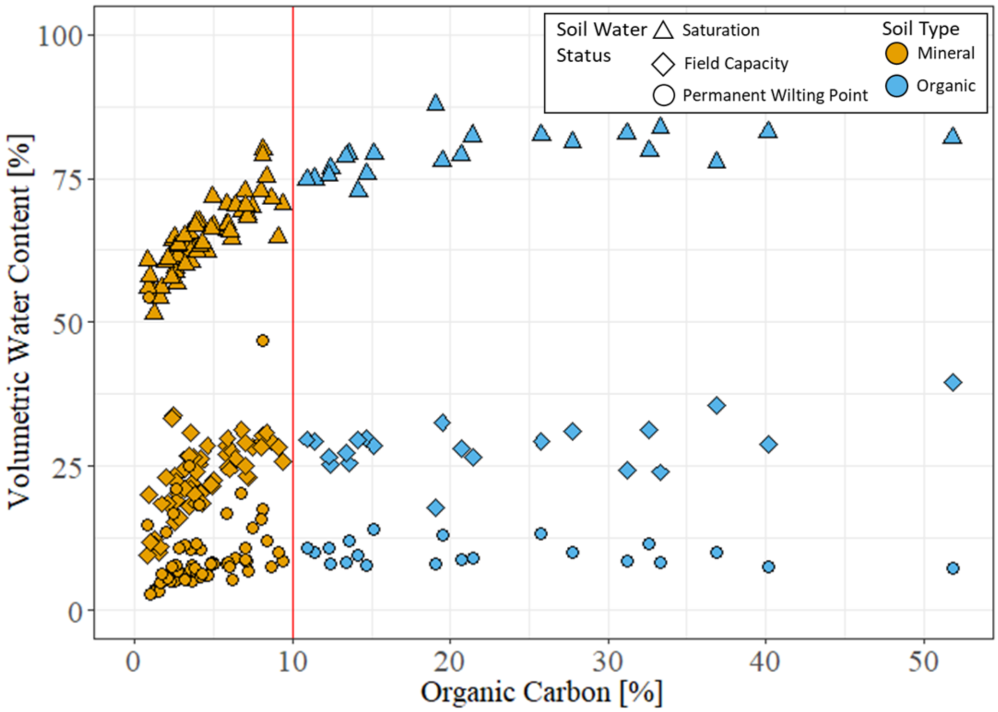


Figure 1-4: Volumetric water content versus organic carbon percentage of soils at different three different saturation states: Saturation, 0 MPa, Field Capacity, 0.03 MPa, Permanent Wilting Point, 1.5 MPa.

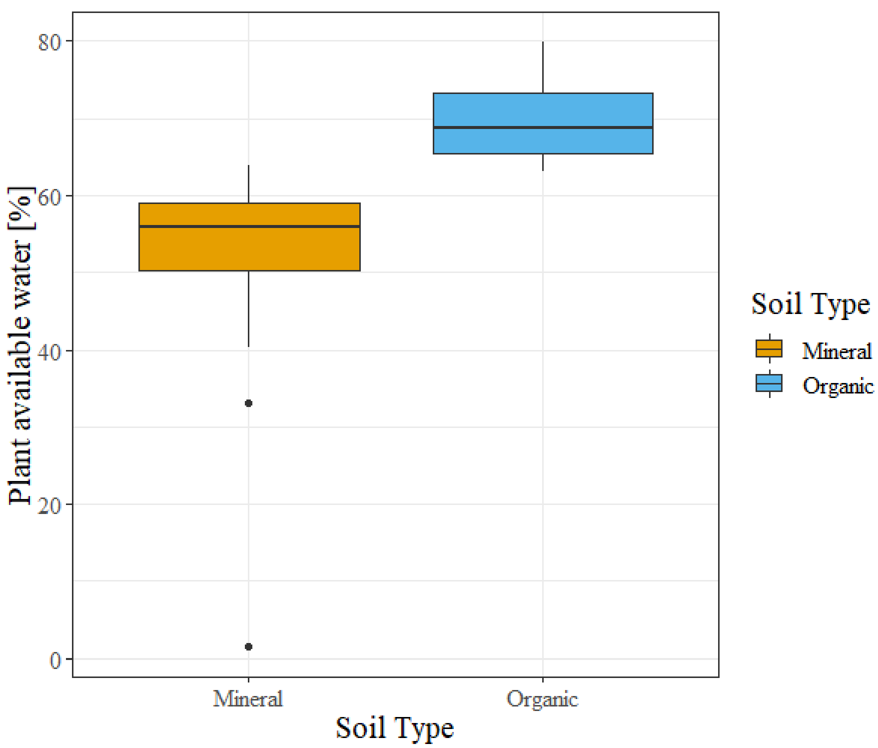


Figure 1-5: Amount of water by percent held between SAT and PWP for each soil type.

Hyprop measured water retention characteristics of two representative soil samples show the similarities and differences between soil types (Fig. 1-6). In both cases ~80% of water is removed from the profile by the time the soil is at FC, and 85% and 94% of the water is lost by PWP for organic and mineral soils respectively. The mineral soil has a distinct flexure point in water content that occurs at 1 pF which is not present in the organic soil, and a less abrupt flexure point at ~1.5 pF.

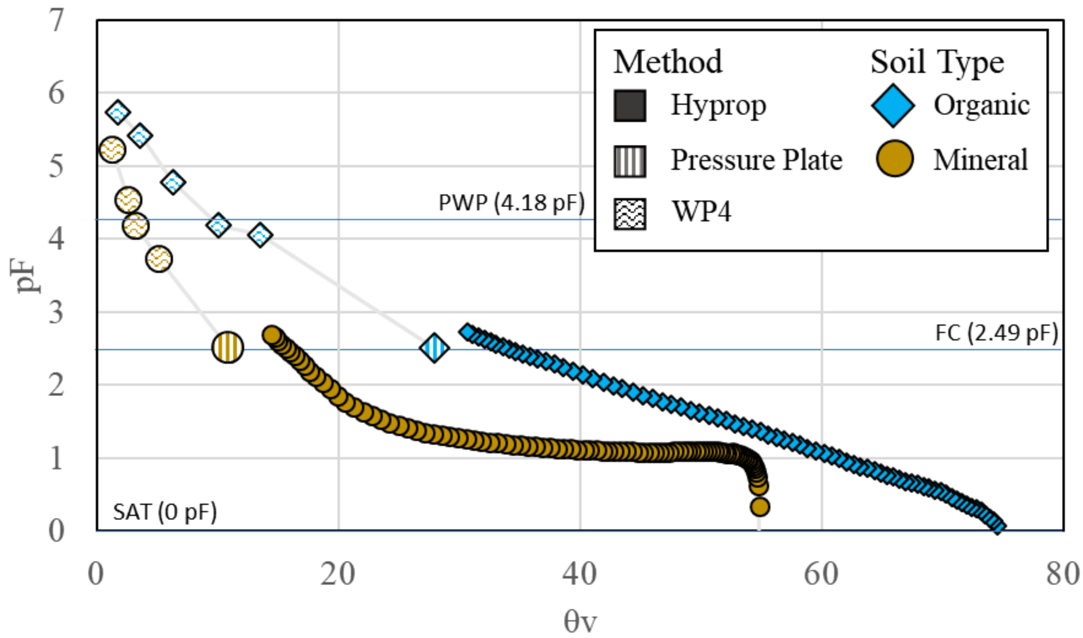


Figure 1-6: Measured soil water retention data for an organic soil (DUD-PG1) and a mineral (KAU-ST2) soil. Curves combine data from three different methods of measuring soil water content in order to cover the range of pressures in which plant roots operate. pF is the log of head in cm.

Van Genuchten-Mualem model fitting parameters (Θ_r, Θ_s, α, n) for the two soils are in Figure 1-6 are shown in Table 1-4. These values are used to parameterize the HYDRUS-1D model. K_s, which is also required for the HYDRUS-1D model, was not well constrained during curve fitting and so was estimated from the literature instead. Fibrous peat, with a K_s of 50 cm/day was used as a proxy for the organic soil hydraulic conductivity (Wong, Hashim, & Ali, 2009), while the estimate of carbonate sand K_s of 5000 cm/day came from Bailey et al (2010).

Table 1-4: Van Genuchten model fitting parameters for a mineral (KAU-ST2) and an organic soil (DUD-PG1), both from Palmyra. Model fitting parameters are used to characterize soil hydraulic characteristics in HYDRUS-1D modelling.

Soil Type	Name	Θ_r ($cm^3\ cm^{-3}$)	Θ_s ($cm^3\ cm^{-3}$)	α (cm^{-1})	*n*	K_s ($cm\ day^{-1}$)
Organic	DUD-PG1	0	0.786	0.2832	1.191	50
Mineral	KAU-ST2	0	0.511	0.107	1.629	5000

1.3.3 Modelling

There was a total of 36 unique HYDRUS-1D model runs resulting from the various combinations of boundary conditions (Table 1), to explore the influence of soil depth, precipitation intensity, and precipitation frequency on water storage in the organic soils (See Appendix A for run combinations and results). In general, increasing organic soil layer depth resulted water being retained in the organic layer over a longer period compared to sand. Figure 1-7 shows all the model runs grouped by soil depth and the time it takes for the upper 10 cm of the soil profile to dry down to PWP. At all soil depths greater annual average precipitation results in longer dry down time. Also, across all soils depths and across the annual precipitation range, higher intensity rainfall events result in longer dry down times.

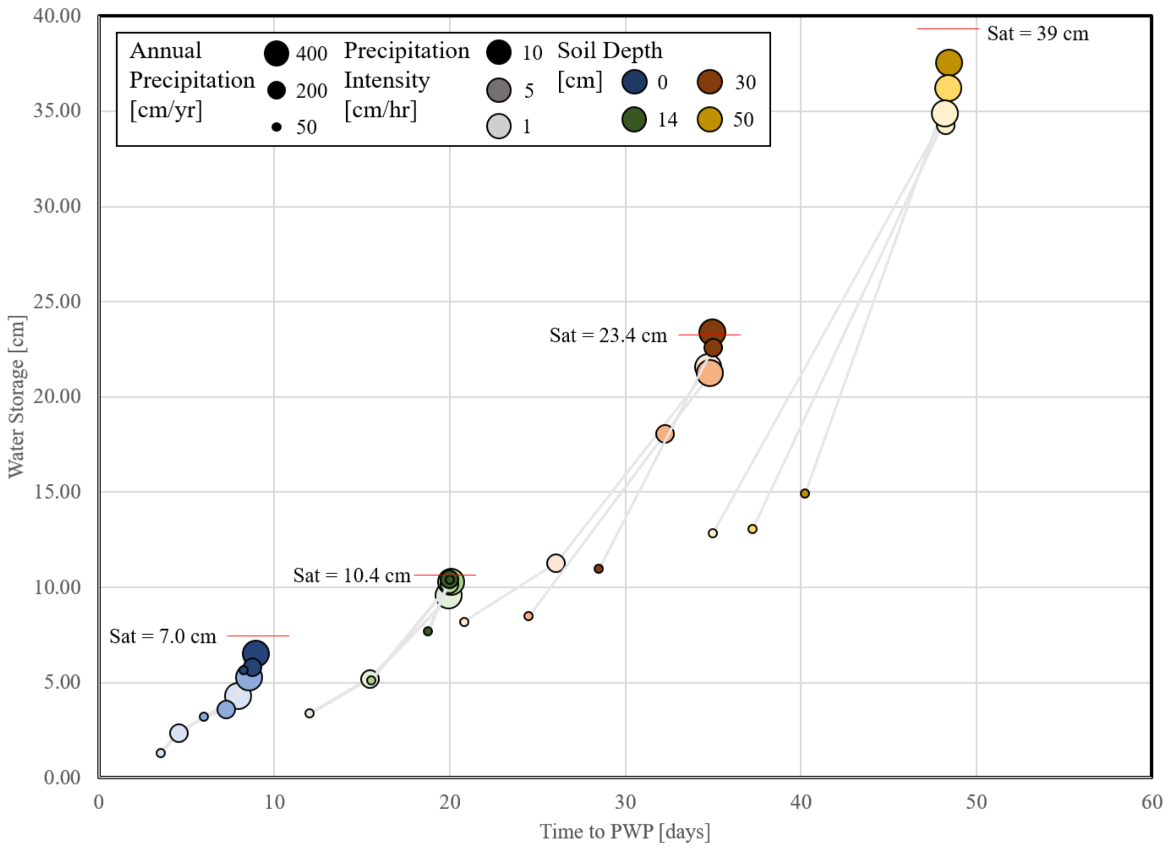


Figure 1-7: Comparison of amount of water stored in the organic cap, or in the upper 30 cm of the soil profile where there is no organic cap, and the time until the upper 10 cm of the soil profile reaches PWP. The depth of the organic cap is indicated by marker colors, the intensity of rainfall events is indicated by marker shades, and the annual precipitation for different islands is indicated by marker size. The amount of water stored at saturation is indicated by horizontal red lines in each depth class. In general, increasing organic cap depth and increasing rainfall intensities results in more water in storage and longer time till dry down. This is pattern holds true across the range of annual precipitation.

In the 0 cm organic soil case (pure sand), no portion of the profile reaches saturation regardless of rainfall frequency or intensity. The closest this profile comes to saturation is 92 %, on wet islands (400 cm annual precipitation) with a high intensity rainfall event (10 cm/hr). The time to dry down in sand ranges from 3.6 to 9 days.

With a 14 cm organic cap the water stored in the organic layer reaches >90% of saturation under any rainfall intensity on wet islands, and under medium to heavy rainfall intensities (5 cm/hr and 10 cm/hr) on moderately wet islands (200 cm annual precipitation). The time to dry down with a 14 cm organic cap ranges from 12 to 20 days.

Thirty cm deep soils have a similar saturation pattern to the 14 cm soils except in the case of moderately wet islands the soil cap only reaches >90% saturation under heavy rainfall intensities. The time to dry down with a 30 cm organic cap ranges from 20.1 to 35 days.

In area that have an organic cap of 50 cm the soil cap will reach >90% saturation on wet and moderately wet island under heavy rainfall intensity and on wet islands under medium rainfall intensity. The time to dry down with a 50 cm organic cap ranges from 35.0 to 48.5 days.

1.4 Discussion

At our study sites the presence of organic soils is strongly tied to the type of overstory canopy (Fig. Table 1-3), and where present these organic soils significantly increases the volume of water and the duration of storage within the organic layer (Fig. 1-5). The likely mechanism for this is increased water storage the formation of a capillary barrier where fine pores of the organic soils come in contact with the coarser textured carbonate sands and rubble. The textural differences between organic and mineral soils (Fig. 1-3) in this study support this idea, as do the HYDRUS-1D modeling results.

A number of studies have shown that layering of soils can increase plant available water (Huang, Lee Barbour, Elshorbagy, Zettl, & Cheng Si, 2011; Naeth, Chanasyk, & Burgers, 2011), but the situation is unique in this case because the development of the capillary barrier effect appears to be an adaptation strategy for *P. grandis.* The most highly developed organic soils found in this study came from two canopy types, *P. grandis* and *T. argentea*. In this study, while the maximum amount of organic carbon found from soils under each tree type can be comparable, the *P. grandis* soils have much more homogeneous and laterally extensive development of organic soils under their canopies than *T. argentea* (personal communication, August 7, 2015). In fact, highly organic “Jemo” soils associated with *P. grandis* have been known about and described for a long time (Fosberg, 1954; Woodroffe & Morrison, 2001; Young et al., 2010), and are often used to infer the historic presence of this species. As this work demonstrates, the presence of an organic cap may result in three to as much as six times more water for the same volume compared to sand (Appendix A), which would substantially increase water available to the shallow roots of *P. grandis.* This suggests that the development of these organic soils is an important mechanism for overcoming water limitation and is likely an adaptation by *P. grandis* to increase their fitness on atoll islands. Assuming the *P. grandis* roots are able to exploit the full depth of the organic layer, which is unclear, this reserve may help explain why *P. grandis* can survive on very dry atolls like Vaugo Island, where the estimated annual rainfall was as low as 7 cm per year (Bell, 1969).

One thing that is unclear, particularly on dry islands, is how these organic soils develop in the first place. *P. grandis* are known for their large leaves, brittle parenchyma rich wood, and close association with sea birds (Mueller-Dombois & Fosberg, 1998; Walker, 1991), all of which provide source material for the development of organic rich soils. However, soils with significant amounts of OC only occur where the decomposition rate is less than accumulation rate of the organic matter. Usually this is associated environments that limit microbial breakdown of organic matter. In the tropics, where low temperatures are not a factor, microbial activity is primarily limited by the saturation state of soils. High rates of hydraulic conductivity typically found on tropical atolls (Bailey, Jenson, & Olsen, 2009) would normally preclude the accumulation of excess water in the vadose zone, so it is unclear how the organic cap associated with *P. grandis* initially forms. This study demonstrates that the capillary barrier effect can result in the organic layer remaining close to saturation once it is established, which would set up a positive feedback loop resulting in greater accumulations of organic material. However, where the organic cap is discontinuous or very thin, the organic material is likely prone to drying out, and thus, decomposition.

One mechanism that might increase the water content of thin or discontinuous soils is the development of a phosphatic hardpan known to be associated with *P. grandis* and Jemo soils. Fosberg (1994) describes the formation of this hardpan as a result of phosphate in seabird guano being mobilized in the acidic environment of *P. grandis* soils and percolating down the soil profile until it neutralizes and precipitates out at the alkaline calcareous surface. While the hydraulic conductivity of the hardpan is unknown, it is certainly less than underlying carbonate sands and gravels and suggests it could be a restrictive boundary. If this hardpan can develop in small localized areas it may help keep the water content of the overlying soils high enough reduce microbial activity and enhance development of thicker and more continuous organic soil layers.

The effects of hardpan were not modeled as part of this study, in part because they cause model instability, but are an important area for further research. Additionally, it will be important to understand the implications of this barrier effect on recharge of the freshwater lens. Finally, this work indicates that *P. grandis* is not the only island species under which highly organic soils develop so it would be interesting to see if other species are using this novel water management strategy to increase their climatic range.

1.5 Conclusions

In summary, one freshwater management strategy by *P. grandis* appears to be the exploitation of a capillary barrier effect to retain water within its root zone. The contrast in soil characteristics between the highly organic soils created by *P. grandis* and the sand and rubble beneath alters the infiltration and percolation dynamics of the organic soil resulting in soils that remain above field capacity for longer periods of time. This water reserve has important implication for the distribution of *P. grandis* and may explain why this species is found across such a wide precipitation gradient.

Literature Cited

Bailey, R T, Jenson, J. W., & Olsen, A. E. (2009). Numerical modeling of atoll island hydrogeology. *Ground Water*, *47*(2), 184–196. https://doi.org/10.1111/j.1745-6584.2008.00520.x

Bailey, Ryan T., Jenson, J. W., & Olsen, A. E. (2010). Estimating the Ground Water Resources of Atoll Islands. *Water*, *2*(1), 1–27. https://doi.org/10.3390/w2010001

Bell, H. L. (1969). Recent Papuan Breeding Records. *Emu - Austral Ornithology*, *69*(4), 235–237. https://doi.org/10.1071/MU969235a

Christophersen, E. (1927). Vegetation of Pacific equatorial islands. *Bishop Museum Bulletin*, *44*(2), 57–61. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Vegetation+of+Pacific+Equatorial+Islands#0

Collen, J. D., Garton, D. W., & Gardner, J. P. a. (2009). Shoreline Changes and Sediment Redistribution at Palmyra Atoll (Equatorial Pacific Ocean): 1874–Present. *Journal of Coastal Research*, *25*(3), 711–722. https://doi.org/10.2112/08-1007.1

Dean, W. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *Journal of Sedimentary Petrology*, *44*(1), 242–248. https://doi.org/10.1128/JCM.01030-15

Fosberg, F. R. (1954). Soils of the Northern Marshall Atolls, with special reference to the Jemo Series. *Soil Science*, *78*(2), 99–108. Retrieved from http://journals.lww.com/soilsci/Fulltext/1954/08000/SOILS_OF_THE_NORTHERN_MARSHALL_ATOLLS,_WITH.4.aspx

Fosberg, F. R. (1994). COMMENTS ON ATOLL PHOSPHATE ROCK. *Atoll Research Bulletin*, *396*(February).

Hathaway, S. A., McEachern, K., & Fisher, R. N. (2011). Terrestrial Forest Management Plan for Palmyra Atoll. *U.S. Geological Survey Open File Report*, *2011–1007*, 1–87.

He, Y., Desutter, T., Hopkins, D., Jia, X., & Wysocki, D. A. (2013). Predicting EC e of the saturated paste extract from value of EC 1 : 5. https://doi.org/10.4141/CJSS2012-080

Huang, M., Lee Barbour, S., Elshorbagy, A., Zettl, J., & Cheng Si, B. (2011). Water availability and forest growth in coarse-textured soils. *Canadian Journal of Soil Science*, *91*(2), 199–210. https://doi.org/10.4141/cjss10012

Krauss, K. W., Duberstein, J. a., Cormier, N., Young, H. S., & Hathaway, S. A. (2015). Proximity to encroaching coconut palm limits native forest water use and persistence on a Pacific atoll. *Ecohydrology*, n/a-n/a. https://doi.org/10.1002/eco.1601

Meehl, G. A. (1996). Vulnerability of freshwater resources to climate change in the tropical pacific region. *Water, Air, and Soil Pollution*, *92*(1–2), 203–213. https://doi.org/10.1007/BF00175566

Mueller-Dombois, D., & Fosberg, F. R. (1998). *Vegetation of the Tropical Pacific Islands*. New York: Springer-Verlag.

Naeth, M. A., Chanasyk, D. S., & Burgers, T. D. (2011). Vegetation and soil water interactions on a tailings sand storage facility in the athabasca oil sands region of Alberta Canada. *Physics and Chemistry of the Earth*, *36*(1–4), 19–30. https://doi.org/10.1016/j.pce.2010.10.003

Or, D., Wraith, J. M., & Tuller, M. (1997). *Agricultural and environmental soil physics*. *Logan: Utah State University*.

Page-Dumroese, D. S., Brown, R. E., Jurgensen, M. F., & Mroz, G. D. (2010). Comparison of Methods for Determining Bulk Densities of Rocky Forest Soils. *Soil Science Society of America Journal*, *63*(2), 379. https://doi.org/10.2136/sssaj1999.03615995006300020016x

Pereira, A. B., Thomazini, A., Schünemann, A. L., Schaefer, C. E. G. R., Francelino, M. R., & Mendonça, E. S. (2018). The spatial variability structure of soil attributes using a detailed sampling grid in a typical periglacial area of Maritime Antarctica. *Environmental Earth Sciences*, *77*(18), 1–15. https://doi.org/10.1007/s12665-018-7818-3

Seki, K. (2007). SWRC fit – a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. *Hydrology and Earth System Sciences Discussions*, *4*(1), 407–437. https://doi.org/10.5194/hessd-4-407-2007

Šimůnek, J., Sejna, M., Saito, H., Sakai, M., & van Genuchten, M. T. (2008). “The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 4.08. HYDRUS Softw. Ser. 3. *Dep. of Environ. Sci., Univ. of Calif., Riverside.* https://doi.org/10.1007/SpringerReference_28001

Staff, S. S. (2014). Soil Survey Field and Laboratory Methods Manual. In Burt & S. S. Staff (Eds.). U.S. Department of Agriculture, Natural Resources Conservation Service.

Team, R. D. C., & R Development Core Team, R. (2016). R: A Language and Environment for Statistical Computing. *R Foundation for Statistical Computing*. https://doi.org/10.1007/978-3-540-74686-7

UMS GmbH. (2015). HYPROP: Operation Manual. *Umwelt Monitoring Systeme GmbH, Munich, Germany*.

USDA. (2014). Keys to soil taxonomy. *USDA*.

van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils1. *Soil Science Society of America Journal*, *44*(5), 892. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Walker, T. (1991). Pisonia islands of the Great Barrier Reef. *Atoll Res Bull*, (350), 1–23. Retrieved from http://www.sil.si.edu/digitalcollections/atollresearchbulletin/issues/00350.01.pdf

Wong, L. S., Hashim, R., & Ali, F. H. (2009). A review on hydraulic conductivity and compressibility of peat. *Journal of Applied Sciences*, *9*(18), 3207–3218. Retrieved from http://scialert.net/qredirect.php?doi=jas.2009.3207.3218&linkid=pdf

Woodroffe, C. D., & Morrison, R. J. (2001). Reef-island accretion and soil development on Makin, Kiribati, central Pacific. *Catena*, *44*(4), 245–261. https://doi.org/10.1016/S0341-8162(01)00135-7

Young, H. S., Raab, T. K., McCauley, D. J., Briggs, A. a., & Dirzo, R. (2010). The coconut palm, Cocos nucifera, impacts forest composition and soil characteristics at Palmyra Atoll, Central Pacific. *Journal of Vegetation Science*, *21*(6), 1058–1068. https://doi.org/10.1111/j.1654-1103.2010.01219.x

Chapter 2: Mapping Atoll Island Vegetation using Landsat 7 ETM+ MESMA Informed by QuickBird

Abstract

Vegetation on atoll islands is changing due to the introduction of the common coconut (*Cocos nucifera* L.). The extent of this change is often unknown because few vegetation maps exist for atoll islands. Remote sensing provides an opportunity to map vegetation communities, but high-resolution imagery for small remote islands may not exist, and where it does, it can be prohibitively expensive for time series analysis. The goal of this study is to examine and evaluate the potential of multiple endmember spectral mixing analysis (MESMA) on moderate resolution Landsat 7 ETM+ to provide accurate maps of atoll island vegetation assemblages. The study area is Palmyra atoll, a heavily forested, protected atoll in the central Pacific Ocean that is part of the Pacific Remote Islands Marine National Monument. I identified potential MESMA endmembers by classifying high resolution QuickBird imagery and identifying homogeneous regions of each forest class. These target regions guided endmember spectral extraction from the Landsat imagery. The results indicate that 2- and 3-endmember models perform best when unmixing this Landsat scene. Overall accuracy when unmixing all the pixels is low (54.3%), but the accuracy improves as the homogeneity of the target pixels increases, with 85% accuracy when target pixels are 80% homogeneous. Visual evaluation of the classified maps suggests that MESMA may perform better than is suggested by the quantitative analysis because of data loss in the reference classification that occurs during aggregation. Future directions for this work include evaluating alterative reference materials and increasing the suite of possible endmembers. To my knowledge this study is the first use of MESMA in an atoll island setting.

2.1 Introduction

Atoll islands (AIs) are the most numerous of all islands in the Pacific Ocean (Mueller-Dombois & Fosberg, 1998), are home to hundreds of thousands of people and are some of the most climatically endangered eco-hydrological systems in the world today (Barnett & Adger, 2003; Goldberg, 2013; UNEP, 2011). One prominent way that AIs are changing is through the introduction and propagation of the common coconut (*Cocos nucifera* L.) by humans. Coconut has been introduced for both subsistence and commercial purposes across the tropics from its native region of Southeast Asia, and is currently established in over 80 countries around the world (Harries, Baudouin, & Cardeña, 2004).. This has been particularly true on AIs, where native forests have been cleared to make room for coconut plantations (Burger, 2005; Niering, 1963; Walker, 1991; Woodroffe & Morrison, 2001). However, the extent of this change is not clear as few data and vegetation maps exist for many AIs, which are often remote and hard to access. Thus, mapping the extent of native and coconut dominated ecosystems is important to understanding how AI ecosystems are changing.

Remote sensing techniques have already been used extensively on atolls to map shoreline changes and the distribution of marine resources (Collen et al., 2009; Jost & Andréfouët, 2006; Lee, 1984; Mann & Westphal, 2014; Rankey, 2011), and land use and land cover changes (Fallati, Savini, Sterlacchini, & Galli, 2017). However, little work has been done on mapping vegetation at the assemblage or species level. Very high-resolution data (<2 m) from airborne or spaceborne sensors is especially suited for accurate mapping of vegetation (Fig 2-1A) because of the fine spatial resolution allows for determination of individual species. However, these products are not freely available and may be prohibitively expensive, particularly for evaluation of time series data. In contrast, moderate resolution imagery, such as Landsat, is free, temporally robust, and has shown utility for mapping vegetation from a variety of contexts (Peña & Brenning, 2015; Rapinel, Bouzillé, Oszwald, & Bonis, 2015; Rembold, Leonardi, Ng, Gadain, & Meroni, 2015). However, with emergent land areas of less than 100 km^2 and widths less than 3 km on many AIs, 30 m x 30 m Landsat data do not have the spatial resolution needed to resolve island vegetation features on a per-pixel basis ((Kelman & West, 2009; Fig. 2-1B).

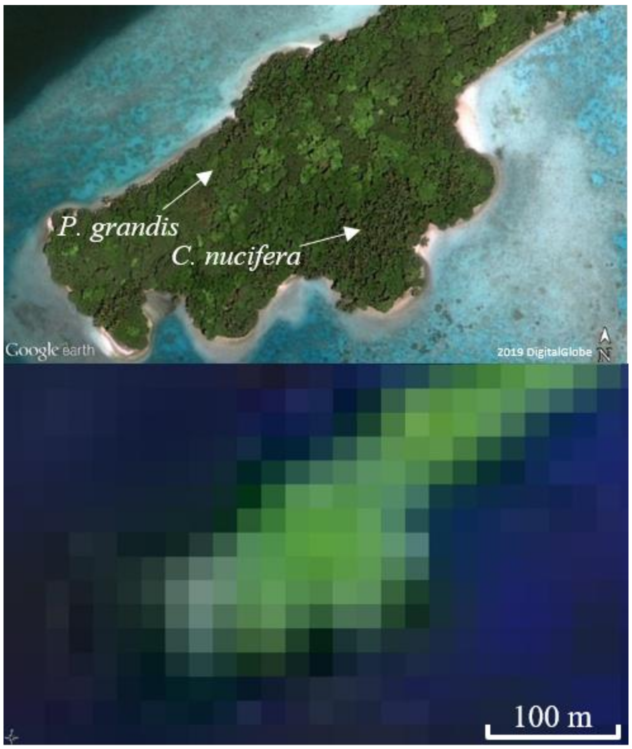


Figure 2-1: A- Worldview 2 satellite view of Palmyra Atoll vegetation types. B- Landsat 8 satellite view of Palmyra Atoll vegetation types

Fortunately Multiple Endmember Spectral Mixing Analysis (MESMA) allows for fractional determination of assemblages and species specific information at a sub-pixel resolutions (Roberts et al., 1998), although this has not been tested in the AI context. Other authors have successfully used this technique in a variety of contexts to map vegetation from moderate resolution imagery (Palaniswami, Upadhyay, & Maheswarappa, 2006; Somers & Asner, 2014a; Youngentob et al., 2011), suggesting that it may work well on AI. The goal of this study is to examine and evaluate the potential of MESMA to provide accurate maps of atoll island vegetation assemblages. To our knowledge this study is the first use of MESMA in an atoll island setting.

2.1.1 Background: Sub-pixel Analysis

Traditional image classifying techniques result in binary states for classified pixel data, i.e. presence or absence of a class. This binary approach does not account for the reality that most pixels represent a mixture ground cover features with different spectral characteristics. This is less of a problem when pixel resolution is very high relative to the size of the ground cover features, but as pixel resolution decreases traditional methods for classification may lead to information loss and reduced classification accuracy (Myint, 2006; Phinn, 1998).

To address this issue a variety of sub-pixel methods have been developed, each with its own set of strengths and weaknesses ((Ichoku & Karnieli, 1996; Myint, 2006). One very common method is the linear spectral mixing analysis (SMA). In this technique pixel reflectance in any band is modeled as the summation of the fractional contributions of reflectance from reference endmember spectra, where endmember spectra are assumed to represent the spectra of a single ground cover feature or class.

SMA (Eq. 1) can be expressed mathematically as:

$$R_i = \sum_{k=1}^{n} f_k R_{ik} + e_i \tag{1}$$

Where

R_i = Spectral reflectance of a pixel in band i

n = number of endmembers

f_k = fraction of an endmember k within a pixel

R_{ik} = spectral reflectance of endmember k within the pixel in band i

e_i = error term for band i

Model fit is often assessed using a root mean square error (RMSE) metric (Eq. 2):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{m}(e_i)^2}{m}} \tag{2}$$

Where *m* = the number of bands in the image (Dennison, Halligan, & Roberts, 2004).

Typically, applications of this method include constraints such that:

$$\sum_{k=1}^{n} f_k = 1 \; and \; 0 < f_k < 1. \tag{3}$$

A result of these constraints is that in standard SMA the number of endmembers cannot exceed the number of bands and every endmember must be represented in each pixel. These constraints limit the utility of this method for classifying complex ground cover features from imagery few bands, such as QuickBird, Ikonos, Landsat, etc. Additionally, for complex landscapes it is unrealistic to expect that every type of ground cover is present in every pixel, and SMA under these constraints may over-represent rare ground cover features (Dennison & Roberts, 2003a). Finally, since only single endmembers are allowed for each class there is no flexibility in modelling ground cover features with a range of spectral responses (Myint & Okin, 2009).

MESMA is an extension of SMA developed to address some of the limitations of the traditional method (Roberts et al., 1998). In this approach the number of endmembers and the type of endmembers can vary on a per pixel basis. Only one endmember per class is allowed, but multiple endmembers representing the same class can be evaluated for the best fit. The added flexibility comes with computational costs (Roberts et al., 1998), but provides greater capacity for mapping large numbers of spectrally distinct types of ground cover. This method has been successfully applied to wide variety of mapping objectives and sensor data types including: vegetation mapping (AVIRIS, HYMAP, Hyperion, Landsat TM, WorldView-2; Li, Ustin, & Lay, 2005; Njenga, 2016; Roberts et al., 1998; Schaaf, Dennison, Fryer, Roth, & Roberts, 2011; Somers & Asner, 2014b; van der Sluijs, 2014; Youngentob et al., 2011), burned area mapping (Hyperspectral, Landsat TM; Lewis et al., 2017; Quintano, Fernández-Manso, & Roberts, 2013), urban landscape mapping (Landsat ETM+; Myint & Okin, 2009; Powell, Roberts, Dennison, & Hess, 2007), and flood mapping (HJ-1B; Feng, Gong, Liu, & Li, 2015). To our knowledge this technique has not been applied on AI, but the relative simplicity of AI vegetation (Mueller-Dombois & Fosberg, 1998), and the linearity of the vegetation classes similar to urban landscapes suggests the technique is highly suitable for this environment.

2.2 Materials and Methods

2.2.1 Study Area

Palmyra, located at 5°53′1″N 162°4′42″W, is a small atoll formed of coral rubble and sand sourced from the nearby fringing reef complex. It is composed of a series of small vegetated islets surrounding two central lagoons. Total exposed land area is about 2.5 km^2 (Collen, Garton, &

Gardner, 2009), most of which is forested. Soils on AIs tend to be thin and poorly developed (Mueller-Dombois & Fosberg, 1998) except under certain native trees and shrubs, such as *Pisonia grandis* R. Br., *Tournefortia argentea* L.f., and *Scaevola sericea* Vhal (Fosberg, 1954). Islets range from less than a hectare to ~100 ha in size, with a maximum of two meters vertical relief (Hathaway, McEachern, & Fisher, 2011). Average reported annual rainfall in Palmyra is over 400 cm a year, comparable with other wet islands, particularly those in the western Pacific (Mueller-Dombois & Fosberg, 1998). Air temperature averages 29˚C year-round. This atoll is similar to hundreds of other atolls found across the Pacific Ocean.

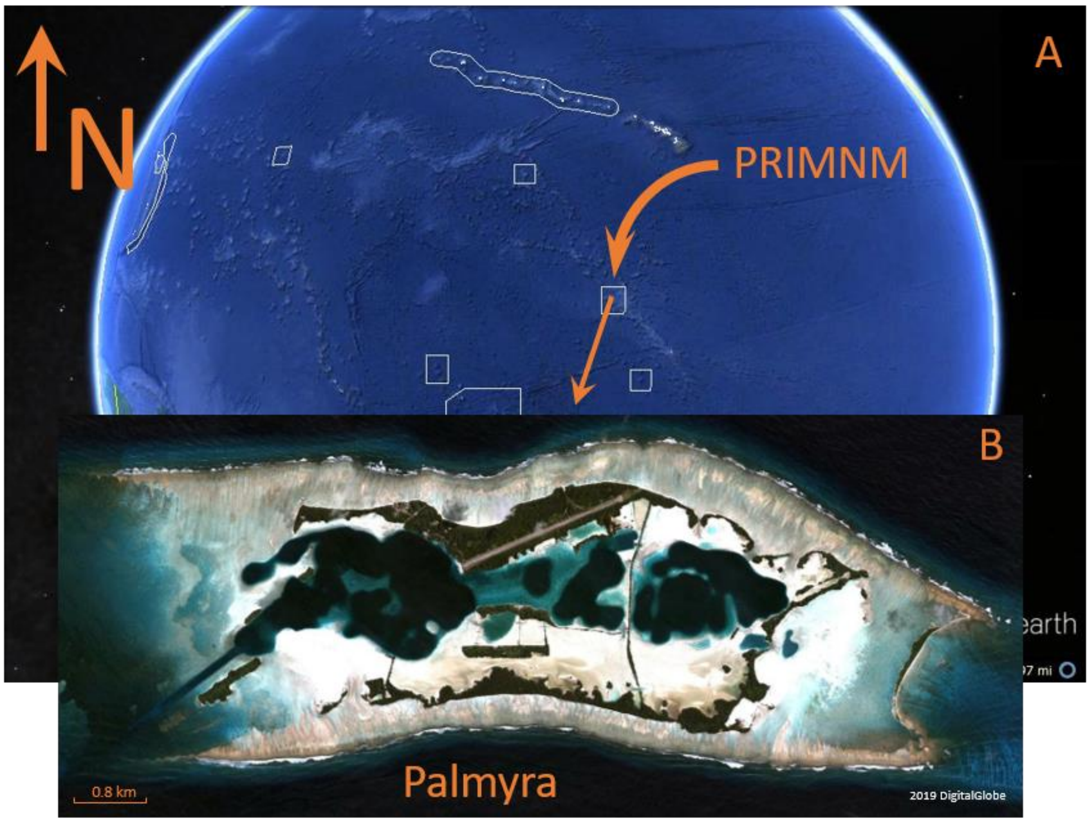


Figure 2-2: Study Area Location showing (A) the Pacific Ocean context with the location of the US Pacific Marine National Monuments (white polygons), and the location of the Pacific Remote Island Marine National Monument (PRIMNM), and (B) Palmyra Atoll.

Palmyra Atoll National Wildlife Refuge (PANWR) is part of the Pacific Remote Island Marine National Monument (Fig. 2-2) and is both protected and minimally inhabited, except by a handful of visiting scientists and a few full-time caretakers. Currently PANWR is under very strict management by the US Fish and Wildlife Service (USFWS) and The Nature Conservancy (TNC), who limit access to the refuge. There is a well-established research station on the island run by the Palmyra Atoll Research Consortium which maintains the runway, a lab facility, and the living quarters on the main islet.

There are three dominant vegetation communities on Palmyra; a tall *P. grandis* forest, a short coastal strand forest composed of a mix of *S. sericea* and *T. argentea*, and a tall coconut palm forest (Hathaway et al., 2011). The proportion of the coconut forest on the island has been increasing while the proportion of *P. grandis* forest is decreasing due to attacks by invasive scale insects (Hathaway et al., 2011) and competition from encroaching coconut palm forests (Krauss et al., 2015). Sea-bird use both the *P. grandis* forest and the coastal strand forest types extensive, but appear to avoid the coconut palm forest (McCauley et al., 2012).

2.2.2 Data Sets

To help identify potential endmember spectra and to assess the accuracy MESMA-derived classifications and vegetation fractions, I acquired a September 17th, 2007 QuickBird-2 (QB) image of Palmyra from the National Geospatial-Intelligence Agency (NGA) via their partnership with DigitalGlobe.

Analysis in this study focused on a single Landsat 7 ETM+ (ETM+) image (L1G product of path 65 and row 56, obtained from EarthExplorer [earthexplorer.usgs.gov]) with a 30 m spatial resolution and 8 bands (Table 2-1). This level-1 image was further processed to level-2 specifications by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software, which applies atmospheric correction routines to Landsat level-1 data to produce surface reflectance data products (U.S. Geological Survery, 2018). The optional vegetation indices from LEDAPS were acquired as well. Those indices include Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), Modified Soil Adjusted Vegetation Index (MSAVI), Normalized Difference Moisture Index (NDMI), Normalized Burn Ratio (NBR), and Normalized Burn Ratio 2 (NBR2). The image data were acquired over Palmyra atoll under cloud-free conditions on August 27th, 2005. All available spectral and indices bands were used in this analysis except the thermal band (band 6) and the panchromatic band (band 8).

Table 2-1: Acquisition Characteristics for imagery used in this study

Study Area	Palmyra Atoll	
Sensor	QuickBird-2	Landsat 7 ETM+
Catalog id	9010010053CA3B00	LE07_L1GT_065056_ 20050827_20170114_01_T2
Processing Level	ORStandard2A	LEDAPS Level 2
Acquisition date	9/17/2007	8/27/2005
No. of spectral bands	5	8
Solar elevation (˚)	73.9	60.8
Sun azimuth (˚)	102.6	80.3
Mean off nadir angle (˚)	21.9	-
In track view angle (˚)	-21.7	-
Cross track view angle (˚)	4.4	-

2.3.1 Pre-processing

I merged, aligned and pansharpened QB data in QGIS (see workflow diagram in Figure 2-3). Image tiles were merged using the merge module from the Geospatial Data Abstraction Library (GDAL), and multispectral bands (2.5 m resolution) were pansharpened using the panchromatic band (0.6 m resolution) and the *"superimpose sensors"* and *"pansharpen (rcs)"* algorithms from the OrfeoToolBox (CNES, 2018). The final composite QB image had 4 multispectral bands with a 0.6 m spatial resolution. From the pansharpened QB I also calculated NDVI and 3x3 moving window variance of the NIR band, which have been shown to improve classification accuracy of trees in QB imagery (Lin, Popescu, Thomson, Tsogt, & Chang, 2015). Finally, I co-registered QB and ETM+ data, subset the imagery to extent of the atoll (upper left UTM 820095 x 652275, lower right UTM 827775, 649755 [UTM Zone 3 North, WGS 84), and masked water pixels using a pixel mask created from negative NDVI values in both sets of imagery. This ensured that I included only non-water pixels common to both sets of imagery for further analysis.

2.3.2 Potential Endmember Identification

The accuracy of unmixing image fractions by SMA requires a robust suite of reference endmembers (Dennison & Roberts, 2003a; van der Sluijs, 2014). Since field collection of reflectance spectra in this case was not feasible, and there are complexities associated with greenhouse growth studies (Hogewoning, Douwstra, Trouwborst, Van Ieperen, & Harbinson, 2010), I chose instead to select representative pixels of homogeneous classes (vegetation and other) directly from the ETM+ image. This has been shown to be an effective method for determining vegetation endmember spectra (Bateson, Asner, & Wessman, 2000; Dennison & Roberts, 2003b) and has advantages because endmembers contain the same systematic errors as the image they unmix.

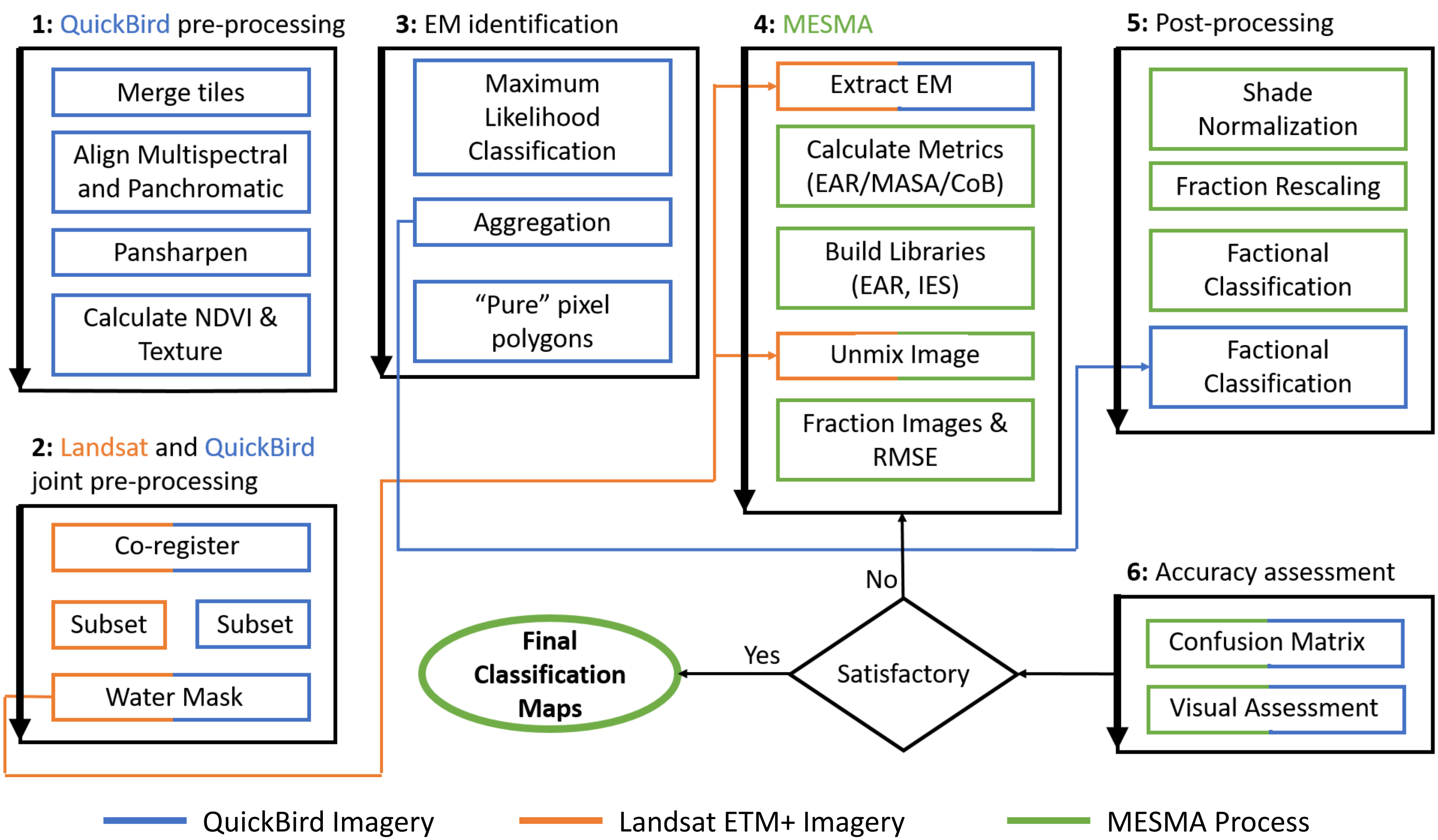


Figure 2-3: Workflow diagram. Colors denote imagery types and products, blue for QuickBird, orange for Landsat 7 ETM+, green for MESMA. Abbreviations are normalized difference vegetation index (NDVI), endmember (EM), multiple endmember spectral mixing analysis (MESMA), and root mean squared error (RMSE).

I selected four endmember classes which include the three dominant forest types on Palmyra atoll: 1) The “Native” class includes the native *P. grandis* forest and a few other full canopied trees such as *Terminalia catappa* and *Hibiscus tiliceus*, which are non-native but have similar crown shapes to *P. grandis*.. 2) The “Coconut” class includes only the coconut forest type, 3) The “Shrub” class is made up the coastal strand forest ecotype, and 4) an “open” class is any non-forested area, including sand, bare soils, pavement, buildings, and grass. While grass is spectrally different than other features in the open class it has been included here because the focus of this analysis is differentiation between forest types the low canopy of the grass makes it marked different from all the other vegetation classes.

In order to identify homogeneous regions of the four different classes I classified the QB data using a supervised maximum likelihood classification (MLC). MLC is a parametric classifier frequently used for land cover classifications and species level vegetation discrimination (Clark, Roberts, & Clark, 2005; Meddens, Hicke, Vierling, & Hudak, 2013; L. Wang, Sousa, Gong, & Biging, 2004)).

I identified training and testing regions by visually interpretation QB imagery and digitizing polygons of each class. For running the MLC I used the *“superclass”* function in R. After classification the QB data were aggregated to the ETM+ scale. This created a fractional image with a 30 m x 30 m pixel resolution, which I hereafter refer to as aggregated QuickBird (AQB). Any pixel of the AQB with >80% of a single class type I then identified as a region of interest for potential endmember selection. These pixels where converted to polygons and overlaid on the ETM+ data to identify target pixels.

2.3.3 Endmember Assessment Metrics

ViperTools (Roberts, Halligan, & Dennison, 2007), a free add-on for ENVI (Version 5.1, Harris Geospatial, 2013), allows for the creation and curation of endmember libraries in addition to performing MESMA. The software calculates three different assessment metrics for all potential endmember spectra and provides three different ways to interpret the assessment metrics in order to develop optimal spectral libraries.

The assessment metrics include Endmember Average RMSE (EAR) (Dennison & Roberts, 2003a), Minimum Average Spectral Angle (MASA) (Dennison et al., 2004), and Count Based Endmember Selection (CoB) (Dennison & Roberts, 2003a), which all provide slightly different information about how well potential endmember spectra model the other spectra in the library, and thus presumably spectra of the features of interest in the target image.

EAR (Eq 4) is calculated from the equation:

$$EAR_i = \frac{\sum_{j=1}^{n} RMSE_{i,j}}{n-1} \tag{4}$$

Where *N* is the number of endmembers, *i* is an endmember, *j* is spectrum being modeled, and *n* is the number of modeled spectra. One is subtracted from *n* to account for the case of the endmember spectra modelling itself. Since EAR can be influenced by albedo affects (excessive brightness or darkness) I partially constrained endmember fractions to decrease the likelihood that very light, or very dark spectra would be selected as the best representatives of their class. In the partially constrained fraction condition, fraction thresholds (0% and 100%) and an RMSE threshold (2.5%) were set for the EAR calculation. Endmembers that are above or below the fraction constraint thresholds have RMSE calculated at the fraction constraint threshold, resulting in an increased in RMSE. If the resulting RMSE is above the RMSE constraint that endmember was excluded from further analysis. If it is below the RMSE threshold it was considered partially constrained and was included in further analysis. This allows for some flexibility in the inclusion of light and dark endmembers but eliminates very bright or very dark endmembers.

MASA (Eq 5) is calculated in a similar fashion to EAR but with a spectral angle instead of RMSE.

$$MASA_i = \frac{\sum_{i=1}^{n} \theta_{i,j}}{n-1} \tag{5}$$

The spectral angle (Eq 6) is calculated as:

$$\theta = cos^{-1}\left(\frac{\sum_{\lambda=1}^{M} \rho_\lambda \rho'_\lambda}{L\rho L\rho'}\right) \tag{6}$$

Where ρ_λ is the reflectance of a test spectra, ρ'_λ is the reflectance of the reference spectra, $L\rho$ is the length of the endmember vector and $L\rho'$ (Eq 7) is the length of the modeled spectrum vector, calculated as:

$$L_{\rho'} = \sqrt{\sum_{\lambda=1}^{M} \rho_\lambda^2} \tag{7}$$

MASA is like EAR in that it is designed to select the spectra with the best average fit within a given class. Unlike EAR, however, MASA is quite sensitive to small spectral differences in dark objects, but less sensitive to spectral differences in bright objects. The opposite is true for EAR (Dennison & Roberts, 2003a). Because of this both these metrics are useful, though not perfect, in identifying potential spectra for inclusion in an endmember library.

Count Based Endmember (CoB) selection is a different approach to endmember selection. CoB determines the number of spectra that a potential endmember models within its own class (InCoB) and the number of spectra it models outside its own class (OutCoB) using the given fraction and RMSE constraints. Spectra with the highest InCoB and the lowest OutCoB are considered good potential endmember candidates (D. A. Roberts et al., 2003).

2.3.4 Development of model libraries

I used two of the three different approaches supported by ViperTools for building an endmember library; the interactive human approach, and a semi-automated Iterative Endmember Selection (IES) approach (Roth, Dennison, & Roberts, 2012). The third approach, Constrained Reference Endmember Selection (D. A. Roberts, Smith, & Adams, 1993), requires *a priori* knowledge of the green vegetation, soil, and non-photosynthetic vegetation fractions, which I do not have from Palmyra.

For the human centered endmember library, I selected the top three spectra according to the calculated metrics (EAR, MASA, and CoB). Any spectra that were the same between categories were only selected once and I did not select more than half of the spectra in any given class. This yielded a starting library of 30 endmember spectra. From this starting library I iteratively added or subtracted additional spectra in order to achieve the highest overall and class accuracy when unmixing the ETM+ imagery.

The IES approach to endmember library creation, as first proposed by Schaaf et al. (2011) and updated by Roth, Dennison, and Roberts (2012), is an automated selection process which selects spectra with the best overall accuracy when a potential endmember spectra models all other potential endmembers spectra (see Roth et al. (2012), for more details). These libraries typically have significantly more spectra included than the human centered libraries.

This left us with two initial endmember libraries, a human created, EAR/MASA/CoB informed library (henceforth EAR library) and an IES library. I further optimized the selected libraries by determining the best combination of RMSE (0%, 2.5%, 5%, and 10%), fraction (-5%:105%, or 0%:100%), and model (2, 2-3, 2-4, or 2-5 endmembers per pixel) constraints that successfully unmixed the greatest number of target pixels while yielding the highest overall and class unmixing accuracy. Model constraints allow for the number of endmembers representing a pixel to vary, so each pixel of the ETM+ imagery is modeled by some number of class spectra (1, 2, 3, or 4) and a shade endmember. At the most restrictive each pixel is only modeled by one spectral endmember and one shade endmember, resulting in a classification output. Partially constrained unmixing (2-3, and 2-4 endmembers) allow for greater representation of different classes, but only in the unconstrained condition could a pixel be unmixed such that all four endmember classes are represented, as is the case in our AQB data. For a given model constraint MESMA selects the model with the lowest RMSE value and assigns that to the pixel.

2.3.5 Post-processing

In order to compare MESMA-derived fractions to AQB fractions I post-processed the MESMA fractions by shade normalizing and rescaling the output data. Shade normalization divides individual non-shade fractions by the total percent cover of all non-shade fractions (1-shade fraction) on a per pixel basis. This allows for a more direct comparison with the AQB in which there is no explicit shade fraction. Additionally, as necessary I re-scaled MESMA-fractions to 0%:100% to facilitate comparison with the AQB fraction.

For determination of classification accuracy, I converted both the fractional MESMA bands, post shade normalization and rescaling, and the fractional AQB bands to classification maps by assigning pixels to the class corresponding to the largest fraction present in any given pixel. I evaluated the classification accuracy at four levels of increasing class dominance (greater than 50%, 60%, 70%, 80%) using a confusion matrix.

2.4. Results

2.4.1 Library Performance

Our results indicate that the IES library, with 116 total endmembers (Table 2-2), an RMSE constraint of 10% (data not shown), fractional constraints of -5%:-105%, and at all model constraints is the most successful at unmixing the greatest number of image pixels (97.1%) and has the highest overall classification accuracy (54%) for those unmixed pixels of any of the library-constraint combinations (Table 2-3). The EAR library, with 27 endmembers, under any set of constraint conditions unmixes about 20% fewer pixels than the IES library, and since there are only 3,098 pixels total representing Palmyra in the ETM+ image, this is an unacceptably large reduction in unmixing power.

Table 2-2: Spectral Libraries and Endmembers tested in MESMA.

Class	Potential EM	IES Library **(IES)**	EAR/MASA/CoB Library **(EAR)**
Native	56	14	7
Coconut	271	17	6
Shrub	11	3	6
Open	190	82	8
Total	**528**	**116**	**27**

Table 2-3: Percentage of successfully unmixed pixels and classification accuracy by library, fraction threshold, and model constraint scenario at an RMSE threshold of 10%. Grey bar highlights the best combination.

Library-Condition	2-3 EM Models		2-4 EM Models		2-5 EM Models	
	Image Fraction	Accuracy	Image Fraction	Accuracy	Image Fraction	Accuracy
IES All 0-100	0.97	0.53	0.97	0.50	0.97	0.49
IES All -5-105	0.97	0.54	0.97	0.51	0.97	0.52
EAR 0-100	0.78	0.50	0.78	0.50	0.78	0.51
EAR -5-105	0.78	0.50	0.78	0.51	0.78	0.51

While the IES 10% -5%:105% library-constraint combination performed well in all unmixing scenarios, it performed best in 2-3 EM model constraint scenario. This is in keeping with work by others (Powell & Roberts, 2008; J. J. Wang, Zhang, & Bussink, 2014), who have suggested that MESMA performs best in unbuilt environments when using 2- and 3- endmember models.

Table 2-4: Confusion matrix for all pixels with at least 70% homogeneity, as unmixed by the best performing library-constraint-unmixing combination (2_3_IES_10 _-5_105), and the AQB imagery.

		Reference: 70% homogeneous pixels from AQB						
	Class	Coconut	Native	Open	Shrub	Total	Comm. error	User acc.
Prediction:	Coconut	303	18	5	2	328	7.6%	92.4%
MESMA	Native	88	138	8	11	245	43.7%	56.3%
	Open	5	1	213	0	219	2.7%	97.3%
	Shrub	31	27	5	16	79	79.7%	20.3%
	Total (pixels)	427	184	231	29	**871**		
	Omis. error	29.0%	25.0%	7.8%	44.8%		**Overall Accuracy**	**76.9%**
	Prod. acc.	71.0%	75.0%	92.2%	55.2%			

Table 2-4 shows the full confusion matrix for this library and constraint combination where the QB reference pixels are at least 70% homogeneous, and Table 2-5 has the producer's and user's accuracy for this library-constraint combination at the different levels of class dominance. Hereafter I refer to this best performing library-constraint-EM scenario as the IES library.

Table 2-5: Overall, Producer's and User's accuracy in percent by class at different levels of dominance for the IES Library when comparing MESMA classification to AQB classification. Note that bold indicates the dominance threshold as fraction of the image pixel.

AQB Single Class Dominance	**Image Fraction**	**Overall Accuracy**	**Producers Accuracy by class**				**User Accuracy by class**			
			Native	Coco	Shrub	Open	Native	Coco	Shrub	Open
Mode	1.00	0.54	0.39	0.58	0.38	0.81	0.60	0.66	0.15	0.53
0.50	0.57	0.64	0.54	0.66	0.47	0.84	0.62	0.75	0.17	0.85
0.60	0.40	0.70	0.60	0.68	0.49	0.89	0.59	0.84	0.17	0.93
0.70	0.28	0.77	0.75	0.71	0.55	0.92	0.56	0.92	0.20	0.97
0.80	0.17	0.85	0.93	0.76	0.73	0.97	0.50	0.99	0.27	1.00

2.5 Discussion

2.5.2 Visual map evaluation

The quantitative evaluation of library performance is one way to assess mapping accuracy, but visual inspection of the classified maps also reveals important information. Visual assessment of the sequence of our classification maps (Fig.2-4A-C) suggests the mapping accuracy of MESMA is not as poor as is implied by the quantitative data.

In general, the island pattern of coconut dominated islets to the south and native forest dominated islets to the north comes through clearly, though these trends are more heterogeneous in the MEMSA map than in the AQB map. In the AQB map there are a couple locations north of the runway where single pixels of coconut or shrub can be seen surrounded by the native class, but these intermixed pixels are not common. By contrast, intermixed pixels are quite common in the MESMA (Fig 2-4C) classification map. One reason for this discrepancy may be that the AQB is underrepresenting the actual variability on the landscape, and that this variability is being picked spectrally by MESMA. This idea is supported by looking at the original high resolution QB (Fig. 2-4A), which reveals significantly more heterogeneity than is implied by the AQB. This loss of landscape complexity is an

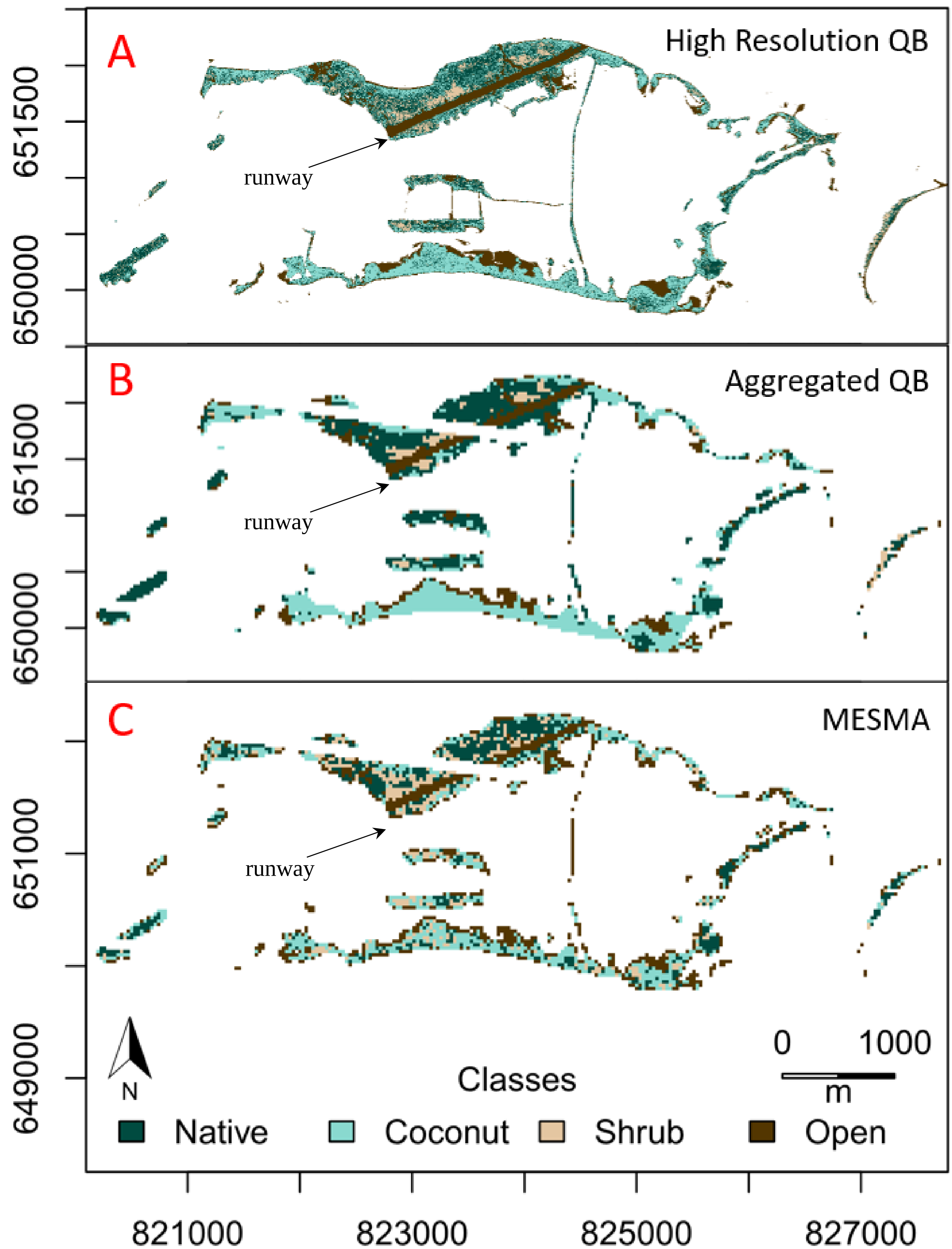


Figure 2-4: Classification maps by technique: Maximum likelihood classification of high resolution QB data (A), aggregated high resolution QB classified by simple fractional majority (B), and classification of MESMA fractions by simple majority (C).

artifact of the aggregation process, whereby the entire 30 m x 30 m pixel is assigned to the class with the greatest fractional representation in the pixel, even if that is only a bare majority. Thus, If the fractional representation of different classes in a pixel are similar, there is a good probability that MESMA will select the wrong class, especially if the spectral separability between classes is poor (Roberts et al., 2003; Somers & Asner, 2014b). One way to address this issue may be to evaluate MESMA classification accuracy by comparison with point locations from either the high resolution QB classification or ground truth points, instead of comparing to the AQB.

MESMA appears to over map the shrub class relative to the AQB classification, particularly around the runway on the north side of the atoll. Here again the heterogeneity of the high resolution QB data suggests that MESMS is likely doing a reasonable job picking out the spectral signature of the shrub class where it exists on the landscape. This is interesting because the whole diversity of the shrub class in the IES library is represented by only three endmembers. These endmembers do a good job covering the spectral range within the shrub class, as indicated by a high users' accuracy, but also appear to model spectra outside their own class as can be seen by the low producers' accuracy. Visual inspection of the map, confirmed by the confusion matrix, indicates that the greatest area of class confusion is between shrub and the native class. This is not surprising as they both have similar canopy shapes and colors.

Finally, the locations of the open class correspond well between the two maps, though the MESMA map has more edge pixels mapped as open class than does the AQB map. This edge confusion occurs in the coconut class as well. A good example of this can be seen on the three small islets at the western edge of the atoll. I suspect that the presence of shallow water and/or bright sands may be affecting the spectral signatures recorded by ETM+ in these locations. For future analyses an edge buffer to remove potential water affected pixels may help improve classification accuracy.

2.5.3 Limitations

There are several complicating factors in this analysis that may contribute to the limited accuracy I encountered. First, the unmixing is only as good as the endmembers that are selected (Dennison & Roberts, 2003a; Roberts et al., 1998; Roth et al., 2012), and the semi-automated way I selected potential endmembers means that limitations associated with the classification of the high resolution QB imagery (MLC overall accuracy of 80%) could result in marginal endmembers being selected for MESMA. For the future to improve confidence in our endmember pool I will complement our selection process calculation of "pixel purity index" (Dennison & Roberts, 2003a; D. A. Roberts et al., 1998; Roth et al., 2012).

Access to *in situ* spectra information specific to these island ecosystems to be included in the endmember libraries would also likely improve the accuracy of the MESMA. Since many of the species on this island are found on other atoll islands across the pacific, collection of *in situ* spectral information from one of these islands might significantly improve the classification accuracy for this island, and perhaps expand the applicability to other islands as well.

Finally, having high-resolution imagery and moderate-resolution imagery that are co-incident in time would be very helpful. Since this island is mostly un-inhabited the land cover is not changing rapidly due to the presence of humans, but there are other disturbances like weather events and scale insect invasions, that may alter vegetation patterns. Two-year gap between the images used in this study is certainly a limitation and undoubtedly introduces error in the analysis.

2.6 Conclusions

In this study I demonstrated that MESMA can be used to successfully map AI vegetation communities where pixels are dominated by a single class. In addition, I found that some of the limited accuracy may be a function of how the reference data were classified after aggregation, suggesting that the MESMA mapping on AI may be more accurate than is implied by this study. Future directions for this work include assessing the accuracy of this MESMA library across time, on Palmyra, and across space on other atoll islands. Additionally, I would like to improve the MESMA endmember library by refining endmember selection techniques adding *in situ* AI vegetation spectra.

Literature Cited

Barnett, J., & Adger, W. N. (2003). Climate Dangers and Atoll Countries. *Climatic Change*, *61*(3), 321–337. https://doi.org/10.1023/B:CLIM.0000004559.08755.88

Bateson, C. A., Asner, G. P., & Wessman, C. A. (2000). Endmember bundles: a new approach to incorporating endmember variability into spectral mixture analysis. *IEEE Transactions on Geoscience and Remote Sensing*, *38*(2), 1083–1094. https://doi.org/10.1109/36.841987

Burger, A. E. (2005). Dispersal and germination of seeds of Pisonia grandis, an Indo-Pacific tropical tree associated with insular seabird colonies. *Journal of Tropical Ecology*, *21*(3), 263–271. https://doi.org/10.1017/S0266467404002159

Clark, M. L., Roberts, D. A., & Clark, D. B. (2005). Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. *Remote Sensing of Environment*, *96*(3–4), 375–398. https://doi.org/10.1016/j.rse.2005.03.009

CNES. (2018). OTB Software Guide. Retrieved from www.orfeo-toolbox.org

Collen, J. D., Garton, D. W., & Gardner, J. P. a. (2009). Shoreline Changes and Sediment Redistribution at Palmyra Atoll (Equatorial Pacific Ocean): 1874–Present. *Journal of Coastal Research*, *25*(3), 711–722. https://doi.org/10.2112/08-1007.1

Dennison, P. E., Halligan, K. Q., & Roberts, D. A. (2004). A comparison of error metrics and constraints for multiple endmember spectral mixture analysis and spectral angle mapper. *Remote Sensing of Environment*, *93*(3), 359–367. https://doi.org/10.1016/j.rse.2004.07.013

Dennison, P. E., & Roberts, D. A. (2003a). Endmember selection for multiple endmember spectral mixture analysis using endmember average RMSE. *Remote Sensing of Environment*, *87*(2–3), 123–135. https://doi.org/10.1016/S0034-4257(03)00135-4

Dennison, P. E., & Roberts, D. A. (2003b). Endmember selection for multiple endmember spectral mixture analysis using endmember average RMSE. *Remote Sensing of Environment*, *87*(2–3), 123–135. https://doi.org/10.1016/S0034-4257(03)00135-4

Fallati, L., Savini, A., Sterlacchini, S., & Galli, P. (2017). Land use and land cover (LULC) of the Republic of the Maldives: first national map and LULC change analysis using remote-sensing data. *Environmental Monitoring and Assessment*, *189*(8). https://doi.org/10.1007/s10661-017-6120-2

Feng, Q., Gong, J., Liu, J., & Li, Y. (2015). Flood mapping based on multiple endmember spectral mixture analysis and random forest classifier-the case of yuyao, China. *Remote Sensing*, *7*(9), 12539–12562. https://doi.org/10.3390/rs70912539

Fosberg, F. R. (1954). Soils of the Northern Marshall Atolls, with special reference to the Jemo Series. *Soil Science*, *78*(2), 99–108. Retrieved from http://journals.lww.com/soilsci/Fulltext/1954/08000/SOILS_OF_THE_NORTHERN_MARSHALL_ATOLLS,_WITH.4.aspx

Goldberg, J. (2013). Drowning Kiribati. *Bloomberg Businessweek*, 1–17. Retrieved from http://www.businessweek.com/articles/2013-11-21/kiribati-climate-change-destroys-pacific-island-nation

Harries, H., Baudouin, L., & Cardeña, R. (2004). Floating, boating and introgression: molecular techniques and the ancestry of coconut palm populations on Pacific islands. *Ethnobotany Research and Applications*, *2*(800), 37–53. Retrieved from http://scholarspace.manoa.hawaii.edu/handle/10125/137

Harris Geospatial. (2013). Environment for Visualizing Images. Retrieved from https://www.harrisgeospatial.com/Software-Technology/ENVI

Hathaway, S. A., McEachern, K., & Fisher, R. N. (2011). Terrestrial Forest Management Plan for Palmyra Atoll. *U.S. Geological Survey Open File Report*, *2011–1007*, 1–87.

Hogewoning, S. W., Douwstra, P., Trouwborst, G., Van Ieperen, W., & Harbinson, J. (2010). An artificial solar spectrum substantially alters plant development compared with usual climate room irradiance spectra. *Journal of Experimental Botany*, *61*(5), 1267–1276. https://doi.org/10.1093/jxb/erq005

Ichoku, C., & Karnieli, A. (1996). A Review of Mixture Modeling Techniques for Sub-Pixel Land Cover Estimation. *Remote Sensing Reviews*, *13*(3–4), 161–186. https://doi.org/10.1080/02757259609532303

Jost, C. H., & Andréfouët, S. (2006). Long-term natural and human perturbations and current status of Clipperton Atoll, a remote island of the Eastern Pacific. *Pacific Conservation Biology*, *12*(3), 207–217. Retrieved from https://doi.org/10.1071/PC060207

Kelman, I., & West, J. J. (2009). Climate Change and Small Island Developing States : A Critical Review. *Ecological and Environmental Anthropology*, *5*(1), 1–16. Retrieved from http://www.ilankelman.org/articles1/eea2009.pdf

Krauss, K. W., Duberstein, J. a., Cormier, N., Young, H. S., & Hathaway, S. A. (2015). Proximity to encroaching coconut palm limits native forest water use and persistence on a Pacific atoll. *Ecohydrology*, n/a-n/a. https://doi.org/10.1002/eco.1601

Lee, M. a. B. (1984). Biogeography and ecology of atoll plants. *Progress in Physical Geography*, *8*(4), 509–522. https://doi.org/10.1177/030913338400800402

Lewis, S. A., Hudak, A. T., Robichaud, P. R., Morgan, P., Satterberg, K. L., Strand, E. K., … Lentile, L. B. (2017). Indicators of burn severity at extended temporal scales: A decade of ecosystem response in mixed-conifer forests of western Montana. *International Journal of Wildland Fire*, *26*(9), 755–771. https://doi.org/10.1071/WF17019

Li, L., Ustin, S. L., & Lay, M. (2005). Application of multiple endmember spectral mixture analysis (MESMA) to AVIRIS imagery for coastal salt marsh mapping: a case study in China Camp, CA, USA. *International Journal of Remote Sensing*, *26*(23), 5193–5207.

Lin, C., Popescu, S. C., Thomson, G., Tsogt, K., & Chang, C. I. (2015). Classification of tree species in overstorey canopy of subtropical forest using QuickBird images. *PLoS ONE*, *10*(5), 1–23. https://doi.org/10.1371/journal.pone.0125554

Mann, T., & Westphal, H. (2014). Assessing long-term changes in the beach width of reef Islands based on temporally fragmented remote sensing data. *Remote Sensing*, *6*(8), 6961–6987. https://doi.org/10.3390/rs6086961

McCauley, D. J., Desalles, P. a, Young, H. S., Dunbar, R. B., Dirzo, R., Mills, M. M., & Micheli, F. (2012). From wing to wing: the persistence of long ecological interaction chains in less-disturbed ecosystems. *Scientific Reports*, *2*, 409. https://doi.org/10.1038/srep00409

Meddens, A. J. H., Hicke, J. A., Vierling, L. A., & Hudak, A. T. (2013). Evaluating methods to detect bark beetle-caused tree mortality using single-date and multi-date Landsat imagery. *Remote Sensing of Environment*, *132*, 49–58. https://doi.org/10.1016/j.rse.2013.01.002

Mueller-Dombois, D., & Fosberg, F. R. (1998). *Vegetation of the Tropical Pacific Islands*. New York: Springer-Verlag.

Myint, S. W. (2006). Urban vegetation mapping using sub-pixel analysis and expert system rules: A critical approach. *International Journal of Remote Sensing*, *27*(13), 2645–2665. https://doi.org/10.1080/01431160500534630

Myint, S. W., & Okin, G. S. (2009). Modelling land-cover types using multiple endmember spectral mixture analysis in a desert city. *International Journal of Remote Sensing*, *30*(9), 2237–2257. https://doi.org/10.1080/01431160802549328

Niering, W. A. (1963). Terrestrial Ecology of Kapingamarangi Atoll, Caroline Islands. *Ecological Monographs*, *33*(2), 131–160.

Njenga, G. W. (2016). Multiple Endmember Spectral Mixture Analysis (MESMA) on multi-temporal VHR images for weed detection in smallholder farms ., 116. Retrieved from http://www.itc.nl/library/papers_2016/msc/gfm/njenga.pdf

Palaniswami, C., Upadhyay, A. K., & Maheswarappa, H. P. (2006). Spectral mixture analysis for subpixel classification of coconut. *Current Science*, *91*(12), 1706–1711.

Peña, M. A., & Brenning, A. (2015). Assessing fruit-tree crop classification from Landsat-8 time series for the Maipo Valley, Chile. *Remote Sensing of Environment*, *171*, 234–244. https://doi.org/10.1016/j.rse.2015.10.029

Phinn, S. R. (1998). A framework for selecting appropriate remotely sensed data dimensions for environmental monitoring and management. *International Journal of Remote Sensing*, *19*(17), 3457.

Powell, R. L., & Roberts, D. A. (2008). Characterizing variability of the urban physical environment for a suite of cities in Rondônia, Brazil. *Earth Interactions*, *12*(13), 1–32. https://doi.org/10.1175/2008EI246.1

Powell, R. L., Roberts, D. A., Dennison, P. E., & Hess, L. L. (2007). Sub-pixel mapping of urban land cover using multiple endmember spectral mixture analysis: Manaus, Brazil. *Remote Sensing of Environment*, *106*(2), 253–267. https://doi.org/10.1016/j.rse.2006.09.005

Quintano, C., Fernández-Manso, A., & Roberts, D. A. (2013). Multiple Endmember Spectral Mixture Analysis (MESMA) to map burn severity levels from Landsat images in Mediterranean countries. *Remote Sensing of Environment*, *136*, 76–88. https://doi.org/10.1016/j.rse.2013.04.017

Rankey, E. C. (2011). Nature and stability of atoll island shorelines: Gilbert Island chain, Kiribati, equatorial Pacific. *Sedimentology*, *58*(7), 1831–1859. https://doi.org/10.1111/j.1365-3091.2011.01241.x

Rapinel, S., Bouzillé, J. B., Oszwald, J., & Bonis, A. (2015). Use of bi-Seasonal Landsat-8 Imagery for Mapping Marshland Plant Community Combinations at the Regional Scale. *Wetlands*, *35*(6), 1043–1054. https://doi.org/10.1007/s13157-015-0693-8

Rembold, F., Leonardi, U., Ng, W., Gadain, H., & Meroni, M. (2015). Mapping areas invaded by Prosopis juliflora in Somaliland with Landsat 8 imagery. *Proceedings of SPIE*, *9637*, 1–12. https://doi.org/10.1117/12.2193133

Roberts, D. A., Dennison, P. E., Gardner, M. E., Hetzel, Y., Ustin, S. L., & Lee, C. T. (2003). Evaluation of the Potential of Hyperion for Fire Danger Assessment by Comparison to the Airborne Visible/Infrared Imaging Spectrometer. *IEEE Geoscience and Remote Sensing Letters*, *41*(6), 1297–1310. https://doi.org/10.1080/00207233.2013.862468

Roberts, D. A., Smith, M. O., & Adams, J. B. (1993). Green Vegetation, Nonphotosynthetic Vegetation, and Soils in AVIRIS Data. *Remote Sensing of Environment*, *44*, 255–269.

Roberts, D., Halligan, K., & Dennison, P. (2007). VIPER Tools User Manual V 1.5.

Roberts, Gardner, M., Church, R., Ustin, S., Scheer, G., & Green, R. O. (1998). Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment*, *65*(3), 267–279. https://doi.org/10.1016/S0034-4257(98)00037-6

Roth, K. L., Dennison, P. E., & Roberts, D. A. (2012). Comparing endmember selection techniques for accurate mapping of plant species and land cover using imaging spectrometer data. *Remote Sensing of Environment*, *127*, 139–152. https://doi.org/10.1016/j.rse.2012.08.030

Schaaf, A. N., Dennison, P. E., Fryer, G. K., Roth, K. L., & Roberts, D. A. (2011). Mapping Plant Functional Types at Multiple Spatial Resolutions Using Imaging Spectrometer Data. *GIScience & Remote Sensing*, *48*(3), 324–344. https://doi.org/10.2747/1548-1603.48.3.324

Somers, B., & Asner, G. P. (2014a). Tree species mapping in tropical forests using multi-temporal imaging spectroscopy: Wavelength adaptive spectral mixture analysis. *International Journal of Applied Earth Observation and Geoinformation*, *31*(1), 57–66. https://doi.org/10.1016/j.jag.2014.02.006

Somers, B., & Asner, G. P. (2014b). Tree species mapping in tropical forests using multi-temporal imaging spectroscopy: Wavelength adaptive spectral mixture analysis. *International Journal of Applied Earth Observation and Geoinformation*, *31*(1), 57–66. https://doi.org/10.1016/j.jag.2014.02.006

U.S. Geological Survery. (2018). Landsat 4-7 Surface Reflectance (Ledaps), (December), 41.

UNEP. (2011). *Freshwater under threat - Pacific Islands. Vulnerability Assessment of Freshwater Resources to Environmental Change*. Nairobi: United Nations Environment Program. https://doi.org/ISBN: 978-92-807-3132-3

van der Sluijs, J. (2014). *Characterizing Tree Species in the Northwest Territories Using Spectral Mixture Analysis and Multi-Temporal Satellite Imagery*. University of Lethbridge.

Walker, T. (1991). Pisonia islands of the Great Barrier Reef. *Atoll Res Bull*, (350), 1–23. Retrieved from http://www.sil.si.edu/digitalcollections/atollresearchbulletin/issues/00350.01.pdf

Wang, J. J., Zhang, Y., & Bussink, C. (2014). Unsupervised multiple endmember spectral mixture analysis-based detection of opium poppy fields from an EO-1 hyperion image in helmand, afghanistan. *Science of the Total Environment*, *476–477*, 1–6. https://doi.org/10.1016/j.scitotenv.2014.01.006

Wang, L., Sousa, W. P., Gong, P., & Biging, G. S. (2004). Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. *Remote Sensing of Environment*, *91*(3–4), 432–440. https://doi.org/10.1016/j.rse.2004.04.005

Woodroffe, C. D., & Morrison, R. J. (2001). Reef-island accretion and soil development on Makin, Kiribati, central Pacific. *Catena*, *44*(4), 245–261. https://doi.org/10.1016/S0341-8162(01)00135-7

Youngentob, K. N., Roberts, D. A., Held, A. A., Dennison, P. E., Jia, X., & Lindenmayer, D. B. (2011). Mapping two Eucalyptus subgenera using multiple endmember spectral mixture analysis and continuum-removed imaging spectrometry data. *Remote Sensing of Environment*, *115*(5), 1115–1128. https://doi.org/10.1016/j.rse.2010.12.012

Chapter 3: Pacific Marine National Monuments: Dynamic systems for educating the next generation of stewards

Mary Engels and Laura Nelson

Available at https://www.fisheries.noaa.gov/resource/outreach-and-education/using-scientific-data-collected-marine-national-monuments

Abstract

The Pacific Marine National Monuments (MNM) are relatively unknown to the general public. This lack of understanding about valuable marine resources means that garnering support and funding for NOAA's critical management, preservation, and educational mandates is difficult. One way to increase understanding about the MNM is to leverage the educational mission of NOAA to increase awareness of these resources. To that end we developed 11 lessons for grades 7-12 focused on the MNM and highlighting the ongoing research occurring within the MNM. Lessons are written in such a way that they can be used in sequence to form a complete unit on a particular subject, or so that they can be used individually to enhance existing curricula. Not only will these lessons familiarize the next generation of decision makers with the MNM, but students will also be able to share this newly learned information with parents and other community members through projects, presentations, and informal discussions.

3.1 Introduction

There is an old African proverb that goes: "You protect what you love. You love what you know. You know what you're taught." The US Marine National Monuments are areas of great environmental, cultural, economic, and aesthetic value, yet most people will never get a know these places in person. If we are to protect and preserve these places, the inherent beauty, environmental, and human value of these monuments needs to be better publicly communicated so that there is support and understanding for the preservation mission.

In order to enhance public appreciation of MNM and to educate students about interconnected systems and ecosystem services they provide, between 2013 and 2016 my colleague, Laura Nelson, and I developed 11 lessons for students grades 7-12 highlighting ongoing research within the monuments. The incredible diversity contained within the MNM means that lessons developed about these areas have applicability to a wide range of topics, from the natural sciences like biology, chemistry, ecology, and oceanography, to social science like environmental science, marine management and marine policy.

The overall goals of these lessons are to introduce students to the MNM and the concept of protected areas, and to help them expand their appreciation and understanding of these areas by using the scientific data being collected in these regions. Helping students connect the ecosystem services provided by these monuments to those they receive from their local environment extend these lessons and give them local relevance.

3.2 Lesson Development

The lessons were created such that they can be used sequentially to form a cohesive unit, or they can be used singly to enhance existing curricula. All the lessons were developed using the 5E learning cycle model (Bybee et al., 2006), they conform to NOAA's Ocean Literacy Essential Principles (Roth et al., 2012) and Fundamental Concepts, and they align with the Next Generation Science Standards (Council, 2013) and Common Core standards for math and literacy (Common Core State Standards Initiative, 2010). All lessons were reviewed and revised based input from both NOAA education professionals, relevant scientific content experts, and practicing educators.

Each series of lessons begins with an introduction to the specific Monument in which the lessons are set. This includes an organizational overview of the associated lessons. Lessons materials consist of a series of separate files, all named according to the monument and topic they cover. All lessons include a Lesson Plan file that provides teachers with background, teaching tips, materials lists, alignment with Next Generation Science Standards and the Ocean Literacy principles, and the lesson overview. Most lessons also have a student worksheet or similar activity, relevant answer keys, and other supplementary materials. The lessons by Monument and topic are:

3.2.1 Pacific Remote Islands Marine National Monument

<u>Seabird Biology</u> In this lesson students learn about the islands and atolls that are a part of the Pacific Remote Islands Marine National Monument, get a basic introduction to the location and size of the islands and atolls, and examine some of the requirements for seabird living and reproducing within the monument.

<u>Guano and Nutrient Cycling</u> This lesson introduces students to the Pacific Remote Islands Marine National Monument through the lens of seabird guano. Students will use mapping exercises to determine island locations and climates, develop food and nutrient webs for seabird communities, and calculate rate of guano development to determine the sustainability of this resource.

<u>Ocean Currents</u> This lesson examines some of the interactions between the natural environment and human exploration. Students learn about ocean currents, historical exploration in the region of the Pacific Remote Islands and plan their own sailing voyage using the information they have learned.

3.2.2 Rose Atoll Marine National Monument

Sea Turtles: Students learn about the importance of Rose Atoll as a sea turtle nesting area and complete an exercise using data and maps from sea turtles that have been tagged with satellite tags while nesting at Rose Atoll.

Coral Reefs: This lesson introduces students to the life history of coral reefs and the health of coral reefs throughout the United States. Students do a virtual dive on the reef at Rose Atoll and model coral reef growth.

Marine Protected Areas: Students completing this lesson will learn about what it means to be a marine protected area and how NOAA works to manage our marine protected areas. They will learn about the characteristics and goals of marine protected areas and design their own protected area.

3.2.3 Papahānaumokuākea Marine National Monument

Marine Debris: This lesson explores the issue of marine debris and why it is a problem in Papahānaumokuākea MNM. Students complete a modeling exercise on drifting debris and a hand on activity on plastic density.

Biodiversity: In this lesson students investigate some of the unique biodiversity found in the Monument. Students research a plant or animal from the Monument and complete a mathematical exercise to model measuring biodiversity.

Science and Technology: This lesson serves as an introduction to Papahānaumokuākea Marine National Monument and scientific tools and techniques that are used to help scientists understand this unique environment.

3.2.4 Mariana Trench Marine National Monument

Tectonic Evolution: In this lesson student use the bathymetry of the ocean floor as a guide to understanding the tectonic history of the region. They use a combination of physical data and model simulations to develop an understanding of how the physical features of the Marianas Trench region formed over millions of years, and to predict how the region might continue to change with time.

Island Fish: This lesson focus on reef fish populations found around both the young and old islands within the Marianas Trench Marine National Monument and nearby waters. Students use survey data from the NOAA CRED to develop an understanding of the distribution and population status of reef fish, and how proximity to human settlements impact fish populations.

3.3 Lesson Examples

One example lesson is included in Appendix B. The full suite of lessons can be accessed at https://www.fisheries.noaa.gov/resource/outreach-and-education/using-scientific-data-collected-marine-national-monuments.

Literature Cited

Bybee R, Taylor JA, Gardner A, Van Scotter P, Carlson J, Westbrook A, Landes N (2006). “The BSCS 5E Instructional Model: Origins and Effectiveness.” Colorado Springs, CO: BSCS.

Common Core State Standards Initiative. (2010). Common Core State Standards Science, and Technical Subjects. Development. https://doi.org/10.1378/chest.119.3.926

Council, N. R. (2013). The Next Generation Science Standards: For States, By States. Washington, D.C., The National Academies Press. https://doi.org/10.1016/j.endm.2015.07.014

NOAA. (2013). The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages. ocean literacy. https://doi.org/10.1029/2006EO400003.Garrison

Chapter 4: The Confluence Approach: Developing scientific literacy through project-based learning and place-based education in the context of NGSS

Mary Engels, Brant Miller, Audrey Squires, Jyoti Jennewein, Karla Eitel

Submitted to *Electronic Journal of Science Education*

Abstract

This study evaluates the effectiveness of a newly developed educational framework for enhancing scientific literacy in rural high school classrooms. The Confluence Approach (TCA) is a curriculum aligned to the Next Generation Science Standards (NGSS) that utilizes a combination of project-based learning (PrBL) and place-based education (PlBE). TCA educational activities take place in students' local watersheds where they interact with scientific partners and gain experience carrying out science and engineering practices focused on water quality, water quantity, and water use in real world settings. In 2014-15, before and after participation in a year-long TCA program, researchers administered attitudinal surveys to understand the program's impact on two important aspects of scientific literacy; students' perceptions of science as important to society and personal decision-making, and on student ability to carry out scientific practices. Qualitative and quantitative survey results were analyzed using a mixed methods approach, where qualitative data were coded using both *a priori* and grounded theories and quantitative data were analyzed with exploratory factor analysis and Mann-Whitney-Wilcoxon tests to compare pre- and post-survey responses. Results show that completion of a TCA program positively changed students' perceptions of the importance of science, both locally and globally, and it increased their confidence engaging in scientific practices. Recommendations from this work include utilizing local contextual factors as frequently as possible to enhance curriculum relevance for students and to use PrBL curriculum elements to elevate student confidence with scientific practices.

4.1 Introduction

In order to address pressing current and future environmental problems, society needs citizens who understand the nature of scientific knowledge (NGSS Lead States, 2013; Organization for Economic Co-operation and Development [OECD], 2016), and who have well developed critical thinking and problem-solving skills (Hurd, 1998; National Research Council [NRC], 2012; Nargund-Joshi, Liu, Chowdhary, Grant, & Smith, 2013). This concept of a scientifically literate citizenry was first introduced in 1958 by P. DeHart Hurd to encourage discussion of how science education could contribute to the common good (Hurd, 1998). While the definition of scientific literacy continues to evolve, benchmarks include familiarity with scientific tools and practices, the ability to explain phenomena scientifically, and the ability to critically interpret and evaluate scientific data to make informed judgements in human and social contexts (NRC, 1996; Hurd, 1998; Roberts & Bybee, 2014; OECD, 2016).

Research shows that scientifically literate citizens are more likely to be prepared for long-term involvement in science-based issues in their communities (Roth & Lee, 2004), and that public participation in environmental and resource management aids in planning, decision making, and conflict resolution (Diduck, 1999). In addition, developing skills associated with scientific literacy while in high school, such as finding and critically evaluating data, prepares students to be successful in college, in their careers, and as active, engaged members of society (Julien & Barker, 2009).

While the development of scientific literacy is an ongoing process, the primary exposure to scientific topics for many students occurs in formal science classrooms. Science curricula with relevance to students' lives and applicability in the "real world" have a greater likelihood of achieving scientific literacy goals (Hurd, 1998) than curricula disconnected from the students' lived experiences.

In 2013, the Next Generation Science Standards (NGSS) provided a contemporary update to how K-12 scientific literacy is approached in the United States (Bybee, 2013; National Science Teachers Association [NSTA], 2013). One of the guiding assumptions of the standards is: "Science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. Both elements- knowledge and practice are essential" (p. 26, NRC, 2012). By approaching standards in more authentic ways to how science and engineering are practiced, NGSS facilitate scientific literacy in students, preparing them for societal and ecological change through the implementation and integration of science and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012; NGSS Lead States, 2013). It follows that development and evaluation of curriculum aligned with NGSS will help ensure that students are exposed to essential concepts and practices that are the foundational building blocks of scientific literacy.

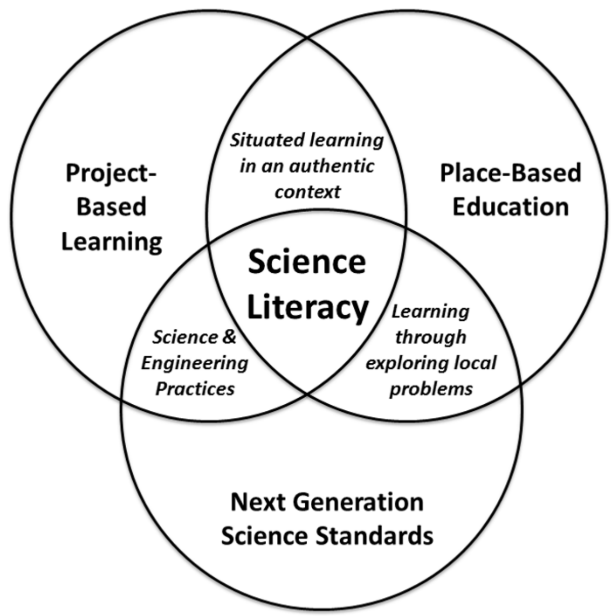


Figure 4-1: Conceptual model of The Confluence Approach (TCA) to enhancing scientific literacy.

The purpose of this study was to evaluate the effectiveness of a collaborative, NGSS-aligned science curriculum approach designed to enhance essential components of scientific literacy for high school students. The Confluence Approach (TCA, Fig. 4-1) is an educational framework focused on promoting watershed science education in rural United States Inland Northwest high school science classrooms. Specifically, we are interested in understanding how the student experience of this TCA curriculum changes students' perceptions of science as important to society and personal decision-making, and how it impacts their ability to utilize scientific practices. This research has the potential to inform other similarly situated educational initiatives interested in enhancing scientific literacy and will provide support for TCA style of student engagement, as described in the following section.

4.1.1 The Confluence Approach

TCA was developed in the context of an established National Science Foundation Graduate STEM Fellows in K-12 Education (GK-12) partnership. It connects NGSS-aligned hands-on curriculum within local watersheds while combining the demonstrated benefits of project-based learning (PrBL) and place-based education (PlBE) (Author, 2015; Author, 2016). Overall, the goals of TCA are to: (1) improve student scientific literacy; (2) improve student motivation and engagement; (3) enhance student environmental awareness and connection to place; and (4) help communities protect and restore local water resources.

<u>Foundations of the TCA Educational Framework:</u>

The NGSS approach differs dramatically from the previous content-focused standards outlined in the 1996 National Science Education Standards (NSES) (NRC, 1996; Reiser, 2013). As such, the established body of curriculum developed for the NSES is not well positioned to address the needs of the new standards. However, several pedagogical approaches show promise as tools for the development of curriculum that aligns with NGSS. Specifically, both PrBL and PlBE present potential pathways for conceptualizing new ways to enact NGSS.

PrBL pedagogical approaches support students in carrying out science and engineering practices by engaging them in tasks similar to those of adult professionals, and by providing them opportunities to apply knowledge to answer meaningful questions (Krajcik & Blumenfeld, 2006). PrBL learning environments tend to have five common features: (1) a driving question; (2) authentic, situated learning; (3) collaborative elements; (4) learning scaffolds for students; and (5) tangible products (Blumenfeld et al., 1991; Krajcik, Blumenfeld, Marx, & Soloway, 1994; Krajcik, Czerniak, & Berger, 2002). These pedagogical features align well with the eight science and engineering practices at the core of the NGSS framework, which include: (1) asking questions and defining problems; (2) developing and using models; (3) planning and carrying out investigations; (4)

analyzing and interpreting data; (5) using mathematics and computational thinking; (6) constructing explanations and designing solutions; (7) engaging in argument from evidence; and (8) obtaining, evaluating and communicating information (Bybee, 2011; NRC, 2012). Thus, PrBL as a pedagogical approach can support efforts to implement NGSS in meaningful ways.

PlBE, which often includes elements of PrBL, provides students with opportunities to engage in learning that utilizes the context of the local environment (Smith, 2002). This is in contrast to the conventional school environment that often presents content that is disconnected from students' lived experiences. PlBE seeks to connect students to local knowledge and issues while providing an authentic context to engage students in learning. As a whole, PlBE helps engage *all* students in STEM learning by using the students' lived experiences and local environment as a learning resource. Within this context, students have relevant expertise and can enhance their communities by proposing solutions to local ecological and social problems.

Both these approaches are informed by situated learning theory (Lave & Wenger, 1991) which posits that the most effective learning occurs when students are engaged with activities and experiences that are authentic to local contexts, and interacting with real-world issues (Krajcik & Shin, 2014). Thus, students participating in TCA are effectively engaging in legitimate peripheral practice which is the cornerstone of situated learning. Legitimate peripheral practice is defined as opportunities for participants to use language and practices associated with a community of practice, initially engaging in "low risk" tasks and then taking on tasks with more complexity and risk as they move from "novice" to "expert" (Lave & Wenger, 1991). In this case, the community of practice is the scientific community and the tasks are those associated with studying and restoring a local watershed. By positioning students for situated learning that espouses PrBL and PlBE programmatic design elements, the legitimate peripheral practice as experienced in their local watershed is hypothesized to have beneficial impacts on students' scientific literacy.

Individually, both PlBE and PrBL have shown significant positive impacts on student learning. For example, Harris et al. (2015) used a randomized controlled trial to test a PrBL curriculum in 72 sixth grade classrooms – 46 treatment and 26 comparison classrooms – located in a single urban school district. Results from this assessment demonstrated that sixth grade students who experienced a PrBL curriculum outperformed students that used more traditional approaches. At the high school level, Mioduser and Betzer (2007) compared the learning outcomes of 60 technology students in PrBL structured classrooms with 60 technology students in traditionally structured classrooms. They found that students in PrBL classrooms increased their formal knowledge, expanded their technical knowledge, and had a positive change in attitude toward technology and technological studies compared to their traditionally structured counterparts. These attitude changes are similar to findings seen by Barak and Asad (2012) when looking at the influence of PrBL on 9th grade student interest in learning technical computing skills.

PlBE has also been found to improve performance on standardized-tests (Lieberman & Hoody, 1998; Bartosh, 2004) and yield growth in critical thinking skills (Ernst & Monroe, 2004), which is an important facet of scientific literacy. A recent meta-analysis also found that learning certain kinds of science concepts outdoors in a PlBE context was more effective than learning these concepts indoors, and that learning outdoors enhanced students' attitudes and interest in science and their environment (Ayotte-Beaudet, Potvin, Lapierre, & Glackin, 2017).

Thus, while PrBL pedagogical approaches are applicable in many learning environments and have been shown to improve student critical thinking and problem-solving skills, their benefits may be synergistically enhanced when they are tied to authentic, situated learning contexts through PlBE. As such, drawing on the strengths of both of these pedagogies is a natural fit for development of NGSS-aligned curriculum that will enhance scientific literacy.

TCA Framework in Practice

In practice, TCA framework connects high school students to their local watersheds throughout the school year (Fig. 4-2) through a series of field investigations which integrate PlBE experiences with PrBL practices both in and out of the classroom. Field investigations focus on one of three themes: (1) water quality, (2) water quantity, and (3) water use (with emphasis on agriculture, forestry, and/or watershed restoration). Through these field investigations, students gain experience carrying out science and engineering practices in real world settings. Students collect water quality, snowpack, and soil data, and learn to analyze and interpret these data in the 'big picture' of resource management in their communities. Program partners support these field investigations by facilitating in-class pre- and post-lessons and working closely with students while in the field. This framing of field investigations with classroom-based lessons helps students become more invested in what they are learning and supports students' development of an integrated picture of the science, environmental issues, and resource interests in their watersheds.

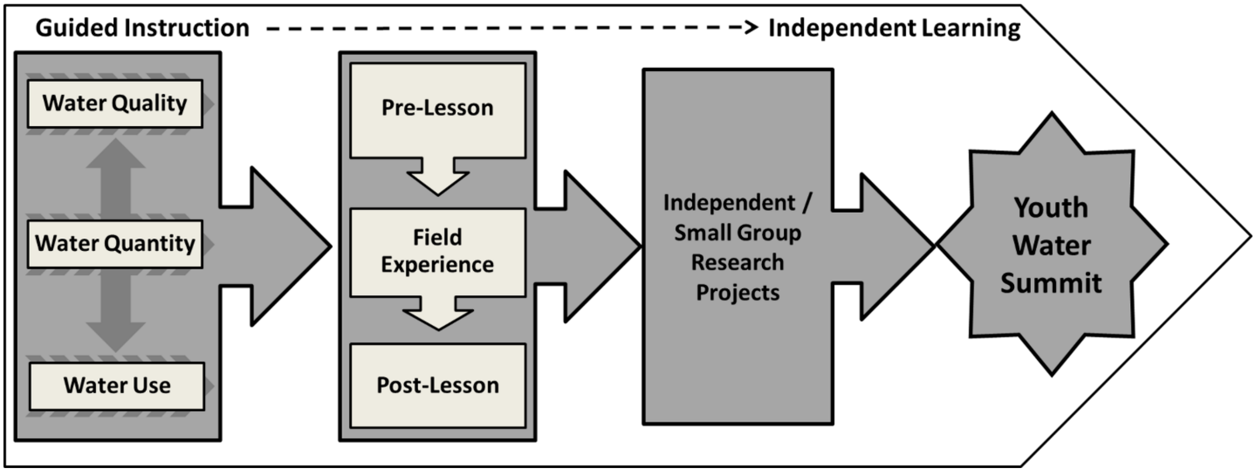


Figure 4-2: The Confluence Approach continuum through an academic year

Before each field experience, as part of a series of classroom-based pre-lessons, students are exposed to pertinent science content, explore the issues present at local field sites, read relevant scientific literature, and design the research they will carry out in the field. During the field investigation, students participate in data collection framed and facilitated by program partners. These partners are an essential element of the program because they provide students with an opportunity to collaborate with and learn from a wide variety of professionals and community leaders who provide important perspectives on natural resource management, local policy, and diverse community cultural understandings of the environment. After each field investigation, as part of the classroom-based post-lessons, students analyze their data and use the results to discuss how to address the problems they encountered in their watershed.

Program partners and teachers help guide the process at the beginning of the academic year with the goal that students will be able to conduct their own community-based research projects by the end of the academic year. Students are challenged to creatively communicate the findings of their individual or group research projects, including both the scientific results and their proposed solutions to the watershed issues, at a regional Youth Water Summit (Author, 2015; Author, 2016). Because students investigate topics of their choosing, projects presented at the Youth Water Summit are diverse and unique. For example, projects have ranged from designing off-site watering operations that remove cattle from local creeks, to creating water color paintings with different quality lake water to highlight sediment contamination issues, to working with local water extension agents on the design of a storm water filtering apparatus to reduce the impact of road runoff in local waterbodies.

4.2 Methods and Materials

Due to the rich history of scientific literacy there are myriad definitions for the concept (Laugksch, 2000). For the purpose of this research, we broadly define scientific literacy in three parts: (1) the knowledge and understanding of scientific concepts and processes; (2) how science relates to society and personal decision-making; and (3) the ability to carry out scientific practices (NRC, 1996; Hurd, 1998; Laugksch, 2000; Blake, 2017). In order to assess if participation in a TCA program positively impacts students' scientific literacy, we focused this investigation primarily on the latter two parts of this definition, specifically:

> **Research Question 1 (RQ1):** How does participation in a TCA program impact students' perceptions of science as important to society and personal decision-making?
>
> **Research Question 2 (RQ2):** How does participation in a TCA program impact student ability to carry out scientific practices?

To answer the research questions, we utilized a mixed methods approach (Creswell, 2017), in a pre- and post-TCA program survey. Qualitative data were obtained from short answer questions based on desirable or undesirable science experiences. Quantitative data were derived from a series of five-point Likert-type scale questions based on student concern for local environmental issues, perceptions of science as it relates to their lived experiences, confidence in conducting scientific practices, and ability to use science as a tool to solve problems. We used "between methods" triangulation to evaluate the internal consistency of the data (Jick, 1979).

4.2.1 Participants

This study focuses on U.S. high school students (grades 10-12) who participated in a TCA classroom. Students were enrolled in a variety of science classes at high schools across eight different Inland Northwest communities (Table 4-1). The communities were diverse in size and type of economy, including both urban and rural areas and with economies based on mining, agriculture, manufacturing, timber, and tourism. The schools were selected based on their relative proximity to the researchers and the presence of school administrators and teachers interested in participating in the program.

A pre/post program survey was administered to students (n=230 for pre-survey, n=207 for post-survey). Difference in participation between the pre- and post-surveys was due to changes in student enrollment throughout the year, absences when surveys were administered, and scheduling conflicts with survey administration.

Table 4-1: The Confluence Approach Participant Counts and Demographic Data for 2014-15

Course	**Grade**	**Student Count: Pre- / Post-Survey**	**School Enrollment** *(approximate)*	**Population size of Community**
Advanced Biology	11	17 / 20	175	800
Environmental Science	10	8 / 4	115	872
Wildlife Biology	10	12 / 8	170	882
Honors Biology	10	32 / 20	295	2,333
Various - Alternative HS	10-12	15 / 13	25	24,534
Honors Biology	10	57 / 42	1,500	29,357
Ecology/ Environmental Science	11-12	49[a] / 73	1,000	32,401
AP Environmental Science	11-12	40 / 25	1,500	46,402

Note. [a]Low pre-survey student count due to scheduling conflicts with survey administration

4.2.2 Data Collection

The survey instrument used in this study was initially developed by the researchers in 2013 for program evaluation of the pilot TCA program. We field tested the instrument in the 2013-14 academic year and modified it in 2014-15 to reduce bias and improve clarity of questions, as well as to better inform the updated research questions and program goals. A convenience sample of program participants was used, as the overall population was small enough that our sample size would have included nearly all students to achieve a confidence interval of 0.95.

The survey delivered to students was composed of 20 multiple choice, Likert-type scale questions and three open-ended questions. Some quantitative questions were targeted specifically at program evaluation and were therefore eliminated from consideration in this analysis. The remaining subset of 12 Likert-type scale questions were used to address the research questions pertaining to scientific literacy. All three open-ended questions were coded and then analyzed qualitatively (Table 4-2).

Teachers and graduate students in the program administered the surveys to high school participants during class time after receiving both student assent and parental consent for participation in TCA and the surveys. Pre-surveys were administered in September before the first TCA field

Table 4-2: Survey Questions and Five-point Likert-scale Response Options

CATEGORY	QUESTION	RESPONSES
INTEREST IN SCIENCE AND NATURE *(Used to address RQ1)*	Q1: Is what you learn in science class useful in your everyday life?	Not at all useful → Very useful
	Q2: Do the concepts and processes you learn in science class help you understand how the natural world works?	Not at all helpful → Very helpful
	Q3: Are you concerned about ecological problems in your community?	Not at all concerned → Very concerned
	Q4: To what extent can scientific solutions reduce the impact of environmental issues in your community?	Not at all → Very much
	Q5: If it were your choice and not a requirement, would you be interested in taking more science classes?	Not at all interested → Very interested
	Q6: Do you like to spend time in natural settings?	Not at all → Very much
DOING SCIENCE *(Used to address RQ2)*	Q7: How confident are you with using the scientific method?	Not at all confident → Very confident
	Q8: How confident are you with collecting data?	Not at all confident → Very confident
	Q9: How confident are you with analyzing data?	Not at all confident → Very confident
	Q10: How confident are you with presenting your research?	Not at all confident → Very confident
	Q11: How confident are you with communicating and collaborating with other students?	Not at all confident → Very confident
	Q12: How confident are you with communicating and collaborating with adults?	Not at all confident → Very confident
QUALITATIVE QUESTIONS	Q21: What is your favorite aspect of science class?	Open-ended
	Q22: What is your favorite aspect of science class?	Open-ended
	Q23: Describe a time that you felt really engaged in a science lesson.	Open-ended

Note. Questions 13-20 were not analyzed for this research and therefore are not included.

investigation and post-surveys were administered in April and May after completion of the program. Surveys were administered either on paper or via Google Forms, depending on the technological capabilities of the classroom.

4.2.3 Qualitative Analysis

We coded qualitative data from the three open-ended questions: (1) what is your favorite aspect of science class? (hereafter “favorite”); (2) what is your least favorite aspect of science class? (hereafter “least favorite”); and, (3) describe a time that you felt really engaged in a science lesson (hereafter “engaged”). These questions were designed to capture slightly different aspects of student thinking. Both the “favorite” and “least favorite” questions aimed to understand which specific areas of science students perceive as important. By contrast, the “engaged” question looked at what specific scientific experiences promote student learning. We asked students about their experiences with science *class* because, for most students, that is the primary way in which they experience science and formulate attitudes about science (Simpson & Oliver, 1990; Maltese & Tai, 2010). All of these questions have direct relevance to scientific literacy as we have defined it because scientifically literate citizens are more interested and engaged in scientific topics and issues (OECD, 2016).

Our initial codebook was developed *a priori* and kept in mind the lenses of PlBE, PrBL, and NGSS. As coding progressed, we employed a grounded approach to identify further parent codes (indicated by numbers) and child codes (indicated by letters) that emerged in student responses (Schwandt, 2001; Weston et al., 2001; Ryan & Bernard, 2003; Charmaz, 2006).

A three-person research team developed a codebook through an iterative process that consisted of four rounds of coding random subsets of the data to reach an acceptable degree of interrater agreement for each code (Cohen’s kappa > 0.80) (MacQueen, McLellan, Kay, & Milstein, 1998; Weston et al., 2001; Krippendorff, 2004). During each round, each researcher worked with approximately five percent of the data for each of the six questions (three pre-survey and three post-survey). Each researcher independently coded the data and adapted the codebook to their understanding of the data.

After each round of coding, the lead coder calculated the code-specific kappa utilizing GraphPad Software (2016) to determine interrater agreement and then the research team discussed any coding disagreements and refined the codebook (MacQueen et al., 1998). After four rounds of coding, kappa values for 75% of all codes exceeded 0.80 while the average kappa was 0.81, providing confidence that the codes were acceptable (Weston et al., 2001). At that point, the code book was

Table 4-3: Codebook for qualitative analysis of the open-ended survey questions

Parent Code	**Child Code**	**Description**	**Key Points**	**RQ***
1	**-**	**Project-Based Learning (PrBL)**	"Learning by doing and applying ideas" through engaging in "real-world activities that are similar to the activities that adult professionals engage in" (Krajcik and Blumenfeld 2006); typically, longer-term, in-depth activities	**2**
-	*1A*	*Active Construction*	Creating a deeper understanding of the content or processes because of PrBL experiences like engaging in real world activities and problem solving	**2**
-	*1B*	*Situated Learning*	Learning situated in an authentic, real-world context that relates to the PrBL they are engaged in; students see the value and meaning of tasks/activities they perform	**1**
-	*1C*	*Collaborations*	Teachers, students, and community members working together in a situated activity to construct shared understandings	**2**
-	*1D*	*Cognitive Tools*	Using any tool (e.g., computers, lab and field equipment, blogging) that helps amplify and expand learning	**2**
-	*1F*	*Designing Solutions*	Student-driven design of solutions to problems they encounter	**2**
2	**-**	**Application**	Activities that make a connection to students' lived experience or the authentic contexts of the world around them	**1**
-	*2A*	*Place-Based Education (PlBE)*	Learning about/working in/connecting to local environment, watershed, or community, not necessarily connected to a deeper PrBL project	**1**
-	*2B*	*Holistic View*	Understanding processes and functions, learning how the world works, applying/connecting scientific concepts to the real world	**1**
-	*2C*	*Relevance*	Enjoyment of learning when topics are relevant to students' lives, lack of enjoyment or learning when they are not relevant	**1**
3	**-**	**Environment**	Learning about, being in or helping the environment and/or nature	**1**
4	**-**	**Science and Engineering Practices**	Doing science and engineering, not necessarily in a real world or project-based setting	**2**
5	**-**	**TCA Field Investigations**	Mention of specific TCA field investigations	**1**

Note. *Research Question. Parent codes are shown in **bold**, child codes are show in *italics*. Additional codes generated during coding analysis but not relevant to this analysis are not shown finalized through group discussion of the data, then the lead researcher finished coding the remainder of the data.

The full list of codes was pared down to six parent codes and 10 child codes pertinent to the research questions (see Table 4-3 for code definitions). For the remainder of the paper reference to qualitative codes are italicized for convenience. Our qualitative analysis indicated that RQ1 could be best answered using three parent codes and their associated child codes *(2: Application, 3*: *Environment, 5: TCA field investigation)* and one child code *(1B: Situated learning)*. For RQ2, two parent codes and their associated child codes *(1: PrBL learning, 4: Science and Engineering Practices)* were deemed most applicable. Analysis of the qualitative data looked at changes in code frequency from pre- to post-survey in each of the three open-ended survey questions ("favorite," "least favorite," "engaged") across all codes identified as pertinent to the specific research question. For a full description of all qualitative codes and how they were used to address our research questions, refer to Table 4-3.

4.2.4 Quantitative Analysis

Quantitative analyses were conducted using R version 3.3.1 (R Core Team, 2016) and Microsoft Excel (Microsoft, 2010). Of the 12 multiple choice survey questions analyzed (Table 4-3; Table 4-5), six focused on student perceptions of science and were used to answer RQ1, and six focused on student abilities in conducting scientific practices and communicating scientific topics and were used to answer RQ2. Specifically, questions used for RQ2 assessed student confidence in conducting scientific investigations (i.e., collecting and analyzing data, presenting results, and collaborating with peers and adults).

Likert-type scale questions were analyzed using exploratory factor analysis to reduce the number of statistical comparisons made and to determine latent variable structure. An oblique rotation, direct oblimin (delta = 0), was selected because input variables are related to, and correlated with, one another (Fabrigar, Wegener, MacCallum, & Strahan, 1999). Wilcoxon-Mann-Whitney tests (Wilcoxon, 1945; Mann & Whitney, 1947) were then used to compare responses between pre- and post-survey rotated factors. Cronbach's alpha assessed the internal consistency reliability of each rotated factor (Cronbach, 1951), with 0.75 serving as the minimum reliability cut-off.

4.3 Results and Discussion

Several major patterns emerge when examining both the qualitative and quantitative data. First, we present results and discuss the qualitative data as they pertain to each of the two research questions, including pre/post percent change in code frequencies to indicate relative trends and direct quotes to provide insight into student thinking. Subsequently, we present and discuss the quantitative data results and assess how these results support and enhance our qualitative findings.

4.3.1 Qualitative Results

RQ1: How does participation in a TCA program impact students' perceptions of science as important to society and personal decision-making?

When a student answers the questions "What is your favorite/least favorite part of science class" we interpret their response as an indication of which aspects of their science experience are important and relevant to them. Codes related to RQ1 are focused on pedagogical elements of the TCA program that shape the student scientific experience. By looking at changes in code frequency pre- to post-survey in the "favorite" and "least favorite" questions we can begin to build a picture of which pedagogical elements within the TCA program are most important for altering students' perceptions of science as important. In general, we see that after participation in the TCA program, students find science more important to them when it is situated and relevant, applicable in local contexts, and focused on "real world" problems. This can be seen in the code frequency increases in the "favorite" category across all RQ1 codes (Table 4-4). By contrast, these same factors seem to have little to no negative impacts on students' perceptions of science as important, as indicated by the negligible changes in code frequency in the "least favorite" question. *1B: Situated Learning* (authentic "real world" context) was the only code that showed an increase in mentions as part of students' "least favorite" part of science class (1%). Given these limited changes in the "least favorite" question, we will restrict the remainder of the discussion to changes seen the "favorite" and "engaged" questions.

The largest increases in the "favorite" question were seen in both the *1B: Situated Learning* and *2C: Relevance* codes (+6% for both), suggesting science is perceived by students as more important when it is properly contextualized in the "real world" (*1B: Situated Learning*) and when it has explicit relevance to them (*2C: Relevance*) (Table 4-3). Both of these codes speak to the importance of the student-focused experience in a curriculum, and that being able to see themselves and their concerns reflected in their science classes is an important driver of their interest in science. As one student stated:

> When we went on the snow pack field trip, and when we worked on the water summit project, I really felt engaged because I could apply what I was learning to real life situations. It was also really fun and interesting, so I got into it and enjoyed it. When I enjoyed it, I actually learned a lot and I learned how to apply it to real world situations.

Though not apparent in the aggregate data, the *2C: Relevance* code also contains student responses specific to disliking science when it is not relevant to their lives. For example, one student stated, [my least favorite aspect of science is] “probably the really confusing things that have no relevance to everyday life.” While it is unclear from our data if students find science important for making personal decisions, it is clear that they find science that has relevance to their own lives more interesting. This is very much in line with the findings of Åkerblom and Lindahl (2017) where they note that authenticity of science experiences contributes to students’ connection to their local context, and thus, contributes to relevance and interest in the topic of study.

Increases (3%-4%) were also seen in codes related to science in local contexts (*2A: PlBE* and *5: TCA Investigations*) and science as it relates to more global issues (*2B: Holistic View, 3: Environment*), suggesting that among students there is an increased perception of science as important to society after participation in a TCA program. For instance, one student wrote:

> This year in science class we have gained a lot of knowledge. The part that I like the most is going more in depth with all of the concepts we have been learning about for years. We were also able to tie science into our community through the confluence project. This is a lot better than looking at the book and expecting to learn everything without putting it into a real-world situation.

By design, the TCA program attempts to build explicit connections for students between their local community and scientific concepts, so in some ways this is not a surprising finding. However, the fact that students come out of the program with enhanced appreciation for science as a tool that can be used to address problems both locally and globally does indicate that participation in a TCA program is an important instrument for enhancing scientific literacy among students in this study.

In addition to trying to understand which areas of science students find important after participation in a TCA program we were also interested in which specific experiences within the program enhanced student learning related to RQ1. To answer this question, we look at the data about when students felt “engaged.” Changes in code frequencies indicate that the times students really felt “engaged” in science class were strongly related to participation in science activities in their local communities (Table 4-4). Interestingly, increases occurred only in codes related to student experiences of place-based science (*1B: Situated Learning, 2A: Place-based education, 5: TCA field investigation*), but not in codes related to experience of more global scientific issues (*2B: Holistic view, 3: Environment*). This suggests that by providing students hands-on experiences with science in their local community, real opportunities for changing their perceptions of science are realized.

Table 4-4: Codes, Code Frequency Changes, and Representative Quotes elated to RQ1.

Codes	**Change *Favorite***	**Change *Least Favorite***	**Change *Engaged***	**Student Quotes**
1B: *Situated Learning*	**+ 6%**	**+1%**	**+7%**	The whole thing I like about science class is the fact of finding a problem and making a solution to that problem. And the moment comes to where I can use the scientific method to find a solution for that problem is the best part about it.
2A: *Place-based education*	**+ 4%**	0%	**+4%**	During the [water quality and riparian restoration] part of the year I was interested in what happened simply because it affected us locally.
2B: *Holistic view*	**+ 4%**	0%	0%	Learning new things that will help me understand the world better.
2C: *Relevance*	**+ 6%**	0%	0%	My favorite part about science class is learning things that we can take to real everyday situations. Things we do on field trips really help me learn about things we can really do to help our earth. In classroom lessons are hard for me to understand how to use them in everyday life. That's why I like outdoor lessons.
3: *Environment*	**+3%**	0%	0%	[My favorite part of science class is that] we focus on the environment and real-world examples that involve our regional natural habitat.
5: *TCA field investigation*	**+ 3%**	0%	**+17%**	The most engaged I think I've ever been in science is when we went on the snow science field trip to [the ski resort]. I was really interested because while we were collecting scientific data, we were having fun, being active, and being outside.

Because students had not yet participated in any TCA field investigations at the time of the pre-surveys, it is only logical that there would be a positive change in engagement around this code. As expected, the largest pre-post code change we saw was in *5: TCA field investigation* (17%), suggesting that these trips were a demonstratively positive and important experience for many students. For instance, one student wrote, “I felt fully engaged when we did the confluence project. We actually got to be involved and we had to use our brains to find solutions.” Overall student comments indicate that the experience of science situated in a local, real-world, authentic context enhances students’ perceptions of science as important, both at a personal, local scale and at the larger global scale. This change in perception is an important improvement in scientific literacy.

RQ2: How does participation in a TCA program impact student ability to carry out scientific practices?

Codes related to RQ2 are focused on the technical components (or tools) of scientific practice (Table 4-5). These include things such as *1C: Collaborations, 1F: Designing Solutions,* or using *1D: Cognitive Tools.* When analyzing codes related to RQ2, we see that after participation in a TCA program, students more frequently identify these technical components of scientific practice as being either their "favorite" part of science class or a time when they felt "engaged" in class. The increase in frequency with which these practices are mentioned occurred across all codes related to RQ2 in both the "favorite" category (1-4%) and the "engaged" category (2-5%). There was an increase in comments coded as *1A: Active Construction* in the "least favorite" question category (1%) No other code categories related to this research question showed frequency increases in the "least favorite" question and so the "least favorite" question will not be discussed further.

While the changes in code frequencies related to RQ2 are smaller overall than for RQ1, they do still suggest a TCA program positively impacts student engagement with scientific practices (Tables 4-4 and 4-5). In general, increases in code frequency were greater in the "engaged" question than in the "favorite" and "least favorite" questions, indicating that moments which drive student engagement around scientific practices are indeed related to PrBL elements (collaboration, executing scientific experiments, or designing solutions) of the TCA program (refer to Table 4-4 for code definitions). These experiences, while engaging, seem to only have a modest positive impact on how students feel about executing the mechanics of science (Table 4-5). In a way this makes sense, since feeling engaged when testing water quality is more likely to lead to an appreciation of the importance of water quality (*2C: Relevance*) than to an appreciation of how to test water quality. However, since there are positive changes with regard to these PrBL codes in the "favorite" question (Table 4-5), we can say that there is some greater appreciation among students for the technical components of science. This is born out when looking at student statements about their favorite aspects of science class. For example, one student wrote, "My favorite aspect of science class is the whole process that you have to go through trying to find the results or research of what we are doing in class at the time." Another student focused on the actual use of scientific equipment and doing science in the field: "When we were learning water quality and we went to [the field site] and we learned to use all of the tools and actually walked in the creek and it was very hands on and I enjoyed it very much." These comments indicate that after participating in a TCA program, students were more confident and engaged in activities related to carrying out scientific procedures, a key form of scientific knowledge that is foundational to scientific literacy (OECD, 2016).

Table 4-5: Codes, Code Frequency Changes, and Representative Quotes Related to RQ2.

Codes	**Change *Favorite***	**Change *Least Favorite***	**Change *Engaged***	**Student Quotes**
1A: *Active Construction*	**+ 1%**	**+1%**	**+2%**	Writing about the results, I'm a kinda technical person so I really like getting into detail about what I've done and what's happened in the experiment.
1C: *Collaborations*	**+ 2%**	0%	**+5%**	I felt really engaged in class when we are able to get into groups and put our knowledge together to get our projects or our work done.
1D: *Cognitive Tools*	**+ 1%**	0%	**+4%**	In the beginning of this year, [a program partner] came to our school with a stormwater model. We got to experiment with the model and see what different materials did to our "aquifer." It was really fun, and it was a great, creative way to get us all engaged in a real life example of a problem.
1F: *Designing Solutions*	**+ 4%**	0%	**+2%**	The whole thing I like about science class is the fact of finding a problem and making a solution to that problem, and the moment comes to where I can use the scientific method to find a solution for that problem is the best part about it.
4: *Science and Engineering Practices*	**+2%**	0%	**+5%**	During labs and experiments I always feel engaged because I get to actually do the work instead of hearing about it.

4.3.2 Quantitative Results

Results of the rotated pattern matrix from the exploratory factor analysis of quantitative data revealed three factors (Table 4-6). Thematically, factor one contains questions related to students' perception of science and its efficacy to solve real world issues, as well as student connection to natural settings and view of local ecological problems. Therefore, factor one was named "relevance of science." Questions in factor two were related to confidence in the initial components of scientific investigation – designing research, collecting and analyzing data. Therefore, factor two was named "mechanics of science." Factor three included questions associated with communication with peers and adults as well as confidence with presenting results. Hence, factor three was named "communication and collaboration." All factors had acceptable internal consistency reliability (i.e., Cronbach's alpha ≥ 0.75), and the rotated factor solution explained 49% of the variance (Table 4-6). Interestingly this exploratory factor analysis suggests that "mechanics of science" and "communication and collaboration," both important skill sets for scientifically literate students, are in fact two distinct skill sets and should not be confounded.

We used results from "relevance of science" (rotated factor one) to address RQ1 and "mechanics of science" (rotated factor two) and "communication and collaboration" (rotated factor three) to address RQ2. Factors were tested for pre-/post-survey differences using the Mann-Whitney-Wilcoxon test (Table 4-7). Of the three factors, only "relevance of science" had a statistically significant difference from pre- to post-survey ($p < 0.05$). This supports our qualitative findings that participation in a TCA program does positively change students' perceptions of science as important to society and personal decision-making.

In contrast, the other two factors ("mechanics of science" and "communication and collaboration") were not significantly different from pre- to post-survey. We speculate that students were already reasonably comfortable with scientific practices, which is exemplified in the pre-survey means (Table 4-7) and, therefore, did not experience a significant increase in these skills. However, means for both "mechanics of science" and "communication and collaborations" did increase from pre- to post-survey, which supports our qualitative findings that participation in a TCA program may have an impact, though modest, on students' confidence with scientific practices.

Table 4-6: Results from the Mann-Whitney-Wilcoxon Tests

	Relevance of Science	**Mechanics of Science**	**Communication and collaboration**
Mann-Whitney-Wilcoxon "W"	18838*	21813	21256
Effect size "Z"	2.9348	0.59284	0.9386
Mean pre-survey	3.48	3.43	3.55
Mean post-survey	3.71	3.48	3.61

Note. *$p < 0.05$

4.3.3 Mixed Method Findings

Based on the triangulated responses from qualitative and quantitative results it is clear that students' perceptions of science as important to their lives and community is enhanced when science is tied to place, as it is in a TCA program. This finding is supported by both our qualitative and quantitative analyses and is in line with the findings of Liberman and Hoody (1998) who found that studying the environment as an integrating context increased student engagement. Second, further analysis suggests that this finding is in part because students find the science engaging when it

Table 4-7: Results from Exploratory Factor Analysis

Survey Questions	**Rotated Factor Loadings**			**Communalities**	**Cronbach's Alpha**
	1	**2**	**3**		
Factor 1 – Relevance of science					
Is what you learn in science class useful in your everyday life?	**0.81**	0.02	0.06	0.34	0.80
Do the concepts and processes you learn in science class help you understand how the natural world works?	**0.78**	0.03	0.02	0.36	
If it were your choice and not a requirement, would you be interested in taking more science classes?	**0.69**	0.01	0.10	0.49	
Are you concerned about ecological problems in your community?	**0.42**	0.21	0.03	0.66	
To what extent can scientific solutions reduce the impact of environmental issues in your community?	**0.38**	0.22	0.02	0.69	
Do you like to spend time in natural settings?	**0.34**	0.04	0.30	0.78	
Factor 2 – Mechanics of science					
How confident are you with using the scientific method?	0.17	**0.62**	0.01	0.46	0.85
How confident are you with collecting data?	0.04	**0.93**	0.01	0.19	
How confident are you with analyzing data?	0.17	**0.74**	0.08	0.34	
Factor 3 – Collaboration and communication					
How confident are you with presenting your research?	0.10	0.09	**0.59**	0.64	0.77
How confident are you with communicating and collaborating with other students?	0.01	0.06	**0.76**	0.40	
How confident are you with communicating and collaborating with adults?	0.01	0.03	**0.82**	0.29	
Factor Solution					
Eigen values	4.90	1.77	0.96		
Proportion of total variance explained by factors	0.19	0.16	0.14		
Cumulative variance explained by factors	0.19	0.35	0.49		

Note. 12 Likert-scale quantitative questions ranging from 1-5 were included; direct Oblimin rotation was used; Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) statistic = 0.85; Bartlett's test of sphericity: $X^2 = 1127.528$, df =66, $p<0.01$

is tied to place, and this engagement translates to modest increases in appreciation for the relevance of science both at the local and global scales. According to Hurd (1998), "scientific literacy is seen as a civic competency required for rational thinking about science in relation to personal, social, political, economic problems, and issues that one is likely to meet throughout life" (p. 410). Thus, TCA as designed and implemented gives students experiences that meaningfully contribute to their development as scientifically literate people by engaging them in legitimate peripheral practices (Lave & Wenger, 1991).

4.4 Limitation

There are several limitations to our study. First, teachers and students who participated in this study were by necessity a convenience sample. Teachers within a several hour proximity of the University were recruited to participate in the program but chose to do so because of their own interest and excitement with the TCA curriculum. As such, the classrooms involved in the study consisted of widely varied subjects and grade levels (e.g. AP Environmental Science and 10th grade Biology), and the context for each school was unique (different watersheds, different partner organizations, differing levels of administrative support). Thus, with eight partner schools and a limited population base, it was not feasible to identify or use a representative control group for this study. In the future it may be possible to identify control groups in individual school contexts where one teacher instructs multiple sections of the same course but given the mostly rural context of our setting this is likely to be enrollment dependent.

The second limitation is regarding our survey instrument. Although we based our instrument on previously validated tools, we deemed it necessary to modify the instrument to more closely align with our study context. Although not ideal, modification of the instrument meant that the data collected would align more closely to the research questions we were interested in answering, even if it compromised the strength of the tool used. As we continue this research, validity testing will occur with our modified instrument to shore up this limitation in future iterations of the study. Future student surveys may be altered to a single post-survey that also incorporates a retrospective pre-survey component. This retrospective design addresses "pre-test overestimation," which is a common problem with pre-test/post-test comparisons (Pratt, McGuigan, & Katzev, 2000).

The third and final limitation we would like to discuss is that of pairing pre-/post-surveys to the individual student. Each partner school context presented a unique set of challenges. Given the geographic distances separating schools and the complicated scheduling, it was difficult for the research team to directly oversee data collection. Thus, we relied heavily on our partner teachers to administer the surveys and share the data with us. Unfortunately, in a few instances, miscommunication resulted in student codes not being recorded and reused for the post-surveys. This error ultimately resulted in the inability to pair pre-/post-survey responses to individual students.

4.5 Recommendations

Based on our research, we would like to make a few recommendations to the science education community. The first recommendation is to utilize local contextual factors as frequently as possible within existing curricular structures. Our research shows that by engaging meaningfully in local issues, curriculum can come alive for students and lead to sought after outcomes for student learning, engagement, and changes in perceptions. The second recommendation is to consider more longitudinally-based curricular interventions that allow for an extended interaction with the concepts and experiences, thus giving students more time to acquire confidence around their scientific skills. We found with this research that the relevance and the repetition of working through locally significant issues created an atmosphere that fosters student confidence in their emerging scientific skillset. And finally, we recommend developing strong working relationships with local partners and professionals. Bringing local professionals working on watershed-based issues into the classroom allows students to clearly see the relevance of the activities they are engaging with. This resulted in a more seamless interaction with scientific phenomena in their watersheds and contributed to their development of a more grounded scientifically literate perspective.

4.6 Conclusions

In summary TCA, which links PrBL and PlBE to NGSS, is an approach to science education that enhances student appreciation for the importance of science in their own lives and communities, engages students in practices of science, and increases student confidence in communicating scientific topics. Therefore, we maintain that enacting PrBL, PlBE, and NGSS aligned curriculum in a local context is a successful approach to enhancing scientific literacy in high school-aged students. NGSS, PrBL, and PlBE proved to be engaging aspects for students within TCA’s educational design, which fits with the assertion of Stage, Asturias, Cheuk, Daro, and Hampton (2013) that through the platform of NGSS, students can become more motivated and inspired within the formal education system. This motivation and inspiration enhances students’ ability to learn and increases their desire to persist in continued educational pursuits. At the same time, improving teaching and learning in K-12 science education has become a priority in the U.S. as we seek to prepare students for college and careers within an increasingly competitive global economy and to address the future needs and problems of our society and environment (Hurd, 1998; Nargund-Joshi et al., 2013; OECD, 2016).

We anticipate future research incorporating a stepwise progression that utilizes a design-based implementation research approach that brings the data-driven outcomes into the realities of practice that pave the way for utilizing educational interventions such as TCA to foster real educational change (Fishman, Penuel, Allen, Cheng, & Sabelli, 2013). The beauty of TCA and similarly situated approaches is that the tools for implementation are inherent in the places education is delivered. It is our role as educational researchers to provide the scaffolds to effective implementation and remove barriers to new approaches that have real and lasting results.

Literature Cited

Åkerblom, D., & Lindahl, M. (2017). Authenticity and the relevance of discourse and figured worlds in secondary students' discussions of socioscientific issues. *Teaching and Teacher Education, 65*, 205-214.

Ayotte-Beaudet, J. P., Potvin, P., Lapierre, H. G., & Glackin, M. (2017). Teaching and Learning Science Outdoors in Schools' Immediate Surroundings at K-12 Levels: A Meta-Synthesis. *EURASIA Journal of Mathematics, Science and Technology Education*, *13*(8), 5343-5363.

Barak, M., & Asad, K. (2012). Teaching image-processing concepts in junior high schools: Boys' and girls' achievement and attitudes towards technology. *Research in Science & Technological Education*, 30, 81–105.

Bartosh, O. (2004). Environmental education: Improving student achievement. Master's thesis, The Evergreen State College, Olympia, Washington. Retrieved fromhttp://www.seer.org/pages/research/Bartosh2003.pdf.

Blake, C. (2017). Understanding scientific literacy. Professional Resources. Concordia University Nebraska. Retrieved from http://online.cune.edu/defining-scientific-literacy/.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist*, 26(3-4), 69–398.

Bybee, R. W. (2011). Scientific and engineering practices in K–12 classrooms: Understanding a framework for K–12 science education. *The Science Teacher*, 78(9), 34–40.

Bybee, R. W. (2013). The Next Generation Science Standards and the life sciences. *Science and Children*, 50(6), 7–14.

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative research.* London: Sage.

Creswell, J. W. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.).* Thousand Oaks, CA: Sage.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrica*, 16, 297–334.

Diduck, A. (1999). Critical education in resource and environmental management: Learning and empowerment for a sustainable future. *Journal of Environmental Management*, 57(2), 85–97.

Ernst, J. & Monroe, M. (2004). The effects of environment-based education on students' critical thinking skills and disposition toward critical thinking. *Environmental Education Research*, 10(4), 507–522.

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., & Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychological Methods*, 4(3), 272-299.

Fishman, B. J., Penuel, W. R., Allen, A. R., Cheng, B. H., & Sabelli, N. (2013). Design-based implementation research: An emerging model for transforming the relationship of research and practice. *Teachers College Record*, 115(14), 136–156.

GraphPad Software, Inc. (2016). Quantify agreement with kappa. Retrieved from http://www.graphpad.com/quickcalcs/kappa1/.

Harris, C. J., Penuel, W. R., D'Angelo, C. M., DeBarger, A. H., Gallagher, L. P., Kennedy, C. A., Cheng, B. H., & Krajcik, J. S. (2015). Impact of project-based curriculum materials on student learning in science: Results of a randomized controlled trial. *Journal of Research in Science Teaching*, 52(10), 1362–1385.

Hurd, P. D. (1998). Scientific literacy: New minds for a changing world. *Science Education*, 82(3), 407–416.

Jick, T. D. (1979). Mixing qualitative and quantitative methods: Triangulation in action. *Administrative Science Quarterly*, 24(4), 602–611.

Julien, H. & Barker, S. (2009). How high-school students find and evaluate scientific information: A basis for information literacy skills development. *Library & Information Science Research*, 31(1), 12–17.

Krajcik, J. S., Blumenfeld, P. C., Marx, R. W. & Soloway, E. (1994). A collaborative model for helping middle grade science teachers learn project-based instruction. *The Elementary School Journal*, 94(5), 483–497.

Krajcik, J. S., Czerniak, C., & Berger, C. (2002). *Teaching science in elementary and middle school classrooms: A project-based approach (2nd ed.)*. McGraw-Hill: Boston, MA.

Krajcik, J. S. & Blumenfeld, P. C. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 317–334). Cambridge University Press.

Krajcik, J. S., & Shin, N. (2014). Project-Based Learning. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 275–297) (2nd ed.). Cambridge University Press.

Krippendorff, K. (2004). Reliability in content analysis: Some common misconceptions and recommendations. *Human Communication Research*, 30(3), 411–433.

Laugksch, R. C. (2000). Scientific literacy: A conceptual overview. *Science Education*, 84(1), 71-94.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.

Lieberman, G. A. & Hoody, L. L. (1998). Closing the achievement gap: Using the environment as an integrating context for learning. San Diego: State Education and Environment Roundtable.

MacQueen, K. M., McLellan, E., Kay, K., & Milstein, B. (1998). Codebook development for team-based qualitative analysis. *Cultural Anthropology Methods*, 10(2), 31–36.

Maltese, A. V. & Tai, R. H. (2010) Eyeballs in the Fridge: Sources of early interest in science. *International Journal of Science Education*, 32(5), 669-685.

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, 50-60.

Microsoft. (2010). Microsoft Excel [computer software]. Redmond, Washington: Microsoft

Mioduser, D., & Betzer, N. (2008). The contribution of project-based-learning to high-achievers' acquisition of technological knowledge and skills. *International Journal of Technology and Design Education*, 18, 59–77.

Nargund-Joshi, V., Liu, X., Chowdhary, B., Grant, B., & Smith, E. (2013). Understanding meanings of interdisciplinary science inquiry in an era of Next Generation Science Standards. Presented at the Annual Meeting of the National Association for Research in Science Teaching, Rio Grande, Puerto Rico.

NGSS Lead States. (2013). Next Generation Science Standards: For states, by states. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/18290/next-generation-science-standards-for-states-by-states

National Research Council. (1996). National Science Education Standards. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/4962/national-science-education-standards

National Research Council. (2012). A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/13165/a-framework-for-k-12-science-education-practices-crosscutting-concepts

National Science Teachers Association (NSTA). (2013). Disciplinary Core Ideas in the Next Generation Science Standards (NGSS) Final Release. Retrieved from http://nstahosted.org/pdfs/ngss/20130509/matrixofdisciplinarycoreideasinngss-may2013.pdf.

Organisation for Economic Co-operation and Development (OECD). (2016). PISA 2015 Assessment and Analytical Framework: Science, reading, mathematic and financial literacy. Paris: OECD. Retrieved from http://www.oecd.org/education/pisa-2015-assessment-and-analytical-framework-9789264255425-en.htm

Pratt, C. C., McGuigan, W. M., & Katzev, A. R. (2000). Measuring program outcomes: Using retrospective pretest methodology. *American Journal of Evaluation*, 21(3), 341–349.

R Core Team. (2016). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from http://www.R-Project.org.

Reiser, B. J. (2013). What professional development strategies are needed for successful implementation of the Next Generation Science Standards? Paper presented at the Invitational Research Symposium on Science Assessment. Washington, DC. Retrieved from https://www.ets.org/Media/Research/pdf/reiser.pdf

Rittenburg, R., Miller, B. G., Rust, C., Esler, J., Kreider, R., Boylan, R., & Squires, A. (2015). The Community Connection: Engaging students and community partners in project-based science. The Science Teacher, 82–1(January), 47–52. https://doi.org/10.2505/4/tst15

Roberts, D. A. & Bybee, R. W. (2014). Scientific literacy, science literacy, and science education. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of Research on Science Education* (pp. 545–558). New York, NY: Routledge.

Roth, W. M. & Lee, S. (2004). Science education as/for participation in the community. *Science Education*, 88(2), 263–291.

Ryan, G. W. & Bernard, H. R. (2003). Techniques to identify themes. *Field Methods*, 15(1), 85–109.

Schwandt, T. A. (2001). *Dictionary of qualitative inquiry (2nd ed.).* Thousand Oaks, CA: Sage.

Simpson, R. D. & Oliver, J. S. (1990). A Summary of Major Influences on Attitude toward and Achievement in Science among Adolescent Students. *Science Education*, 74(1), 1-18.

Smith, G. A. (2002). Place-based education: Learning to be where we are. *The Phi Delta Kappan*, 83(8), 84–594.

Squires, A., Jennewein, J., Engels, M. S., Miller, B. G., & Eitel, K. (2016). Integrating Watershed Science in High School Classrooms : The Confluence Project Approach. Clearing, (Fall), 1–10. Retrieved from http://clearingmagazine.org/archives/13145

Stage, E. K., Asturias, H., Cheuk, T., Daro, P. A., & Hampton, S. B. (2013). Opportunities and challenges in Next Generation Standards. *Science*, 340(6130), 276–277.

Weston, C., Gandell, T., Beauchamp, J., McAlpine, L., Wiseman, C., & Beauchamp, C. (2001). Analyzing interview data: The development and evolution of a coding system. *Qualitative Sociology*, 24(3), 381–400.

Wilcoxon, F. (1945). Individual comparisons by ranking methods. *Biometrics Bulletin*, 1(6), 80-83.

Appendix A - Hydrus-1D Modelling Results Matrix

NO ORGANIC SOIL:
(SAND) 0 CM

Model Combination	Annual Precip [cm]	Frequency [d]	Intensity [cm/d]	Duration [d]	Maximum Water Storage [cm]	Water Storage at Event End [cm]	Saturation [%]	Water available in 30 m^2 [L]	Time to dry down [days]
400P-10CMD-0OS	400.00	4.5625	10	0.5	7.01	6.46	0.92	19.4	9
200P-10CMD-0OS	200.00	9.125	10	0.5	7.01	5.84	0.83	17.5	8.75
50P-10CDM-0OS	50.00	36.5	10	0.5	7.01	5.62	0.80	16.9	8.25
400P-5CMD-0OS	400.00	2.28125	5	0.5	7.01	5.22	0.74	15.6	8.6
200P-5CMD-0OS	200.00	4.5625	5	0.5	7.01	3.62	0.52	10.9	7.25
50P-5CDM-0OS	50.00	18.25	5	0.5	7.01	3.18	0.45	9.5	6
400P-1CMD-0OS	400.00	0.45625	1	0.5	7.01	4.27	0.61	12.8	8
200P-1CMD-0OS	200.00	0.9125	1	0.5	7.01	2.36	0.34	7.1	4.53
50P-1CDM-0OS	50.00	3.65	1	0.5	7.01	1.29	0.18	3.9	3.55

SHALLOW SOILS:
14 CM

Model Combination	Annual Precip [cm]	Frequency [d]	Intensity [cm/d]	Duration [d]	Maximum Water Storage [cm]	Water Storage at Event End [cm]	Saturation [%]	Water available in 30 m^2 [L]	Time to dry down [days]
400P-10CMD-14OS	400	4.5625	10	0.5	10.435	10.431	1.00	31.29	20
200P-10CMD-14OS	200	9.125	10	0.5	10.435	10.409	1.00	31.23	20
50P-10CDM-14OS	50	36.5	10	0.5	10.435	7.6645	0.73	22.99	18.75
400P-5CMD-14OS	400	2.28125	5	0.5	10.433	10.258	0.98	30.77	20.1
200P-5CMD-14OS	200	4.5625	5	0.5	10.433	10.177	0.98	30.53	20
50P-5CDM-14OS	50	18.25	5	0.5	10.434	5.1046	0.49	15.31	15.5
400P-1CMD-14OS	400	0.45625	1	0.5	10.432	9.5209	0.91	28.56	20
200P-1CMD-14OS	200	0.9125	1	0.5	10.433	5.1954	0.50	15.59	15.44
50P-1CDM-14OS	50	3.65	1	0.5	10.431	3.3831	0.32	10.15	12.05

MEDIUM SOILS: 30 CM									
Model Combination	Annual Precip [cm]	Frequency [d]	Intensity [cm/d]	Duration [d]	Maximum Water Storage [cm]	Water Storage at Event End [cm]	Saturation [%]	Water available in 30 m^2 [L]	Time to dry down [days]
400P-10CMD-30OS	400	4.5625	10	0.5	23.35	23.335	1.00	70.01	35
200P-10CMD-30OS	200	9.125	10	0.5	23.35	22.588	0.97	67.76	35
50P-10CDM-30OS	50	36.5	10	0.5	23.35	10.97	0.47	32.91	28.5
400P-5CMD-30OS	400	2.28125	5	0.5	23.35	21.207	0.91	63.62	34.85
200P-5CMD-30OS	200	4.5625	5	0.5	23.35	18.046	0.77	54.14	32.25
50P-5CDM-30OS	50	18.25	5	0.5	23.35	8.4904	0.36	25.47	24.5
400P-1CMD-30OS	400	0.45625	1	0.5	23.35	21.535	0.92	64.61	34.75
200P-1CMD-30OS	200	0.9125	1	0.5	23.35	11.256	0.48	33.77	26.03
50P-1CDM-30OS	50	3.65	1	0.5	23.35	8.1931	0.35	24.58	20.8

DEEP SOILS:
50 CM

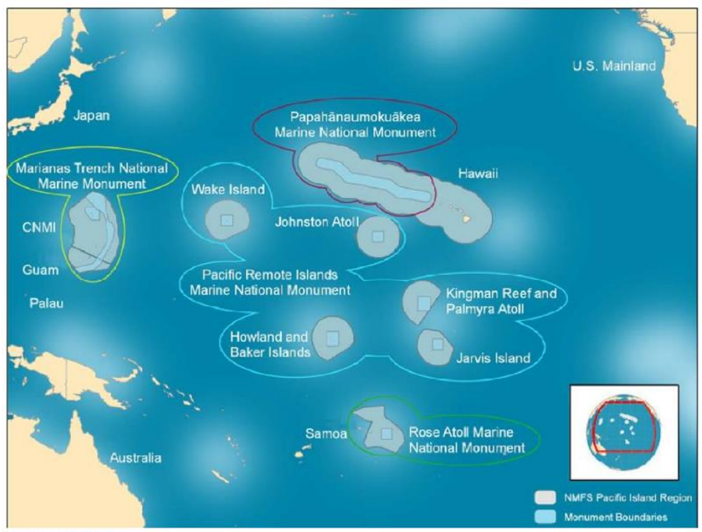
Model Combination	Annual Precip [cm]	Frequency [d]	Intensity [cm/d]	Duration [d]	Maximum Water Storage [cm]	Water Storage at Event End [cm]	Saturation [%]	Water available in 30 m^2 [L]	Time to dry down [days]
400P-10CMD-50OS	400	4.5625	10	0.5	39.007	37.514	0.96	112.54	48.5
200P-10CMD-50OS	200	9.125	10	0.5	39.008	36.01	0.92	108.03	48.375
50P-10CDM-50OS	50	36.5	10	0.5	39.006	14.952	0.38	44.86	40.25
400P-5CMD-50OS	400	2.28125	5	0.5	39.005	36.176	0.93	108.53	48.45
200P-5CMD-50OS	200	4.5625	5	0.5	39.007	34.978	0.90	104.93	48.375
50P-5CDM-50OS	50	18.25	5	0.5	39.008	13.087	0.34	39.26	37.25
400P-1CMD-50OS	400	0.45625	1	0.5	39.006	34.28	0.88	102.84	48.25
200P-1CMD-50OS	200	0.9125	1	0.5	39.008	34.842	0.89	104.53	48.25
50P-1CDM-50OS	50	3.65	1	0.5	39.009	12.858	0.33	38.57	35

Appendix B - Pacific Marine National Monument Lesson Plans

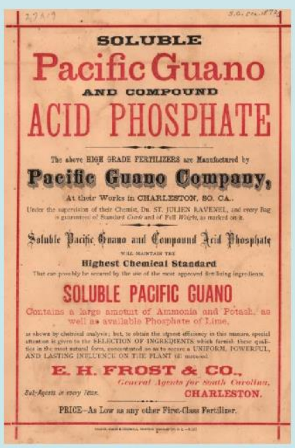
1. Lesson Plan

Pacific Marine National Monuments

Pacific Remote Island Marine National Monument: Guano and Nutrient Cycling



Source: NOAA



Early Guano Advertising Poster Source: Duke Advertising Ephemera Collection

Grade Level

- 7-12

Timeframe

- 2.5 – 3 hours

Materials

- Large blank paper
- Colored pencils
- Sooty tern food web cards
- Sooty tern simulation cards
- "Nutrients" paper/cotton balls
- Containers for holding nutrients

Activity Summary

This lesson introduces students to the Pacific Remote Islands Marine National Monument (PRIMNM) through the lens of seabird guano. Students will orient themselves using a mapping exercise to locate the islands within the PRIMNM. Once oriented they explore nutrient flow through ecosystems by developing a food web for the sooty tern and use that to trace the movement of nutrients from source (the ocean) to sink (islands). This concept will be further reinforced and extended with a physical simulation exercise that introduces the variability of climate as a control on guano development. Students then use climate data from their mapping exercise to make inferences about which islands within the PRIMNM are likely to have the best developed guano resources. Finally they use source data on seabird populations in the past to calculate rates of guano development to determine the sustainability of this resource.

Learning Objectives

Students will be able to:

- Explore the geography of the PRIMNM
- Understand the relationship between food webs and nutrient flows

Key Words

- Guano
- Food web
- Nutrient reservoirs
- Jarvis Island
- Invasive Species

Outline

ENGAGE – Where are we?

EXPLORE – Food Webs and Nutrient Flows

EXPLAIN – Food Webs and Nutrient Flows

ELABORATE- Focus on Jarvis Island, Climate Mapping, Guano Calculations.

EVALUATE- Summary

Vocabulary

BIOAVAILABLE – Compounds and elements that are in a form usable by organisms. For example elemental nitrogen (N_2) is inert but when converted to ammonium (NH_4^+) or nitrate (NO_3^-) via microbial or other processes, it becomes bioavailable.

CARRYING CAPACITY – The maximum population size of a given species that can be sustained indefinitely in a particular environment.

EQUATORIAL DRY ZONE – An arid region near the equator that forms as air masses sink and spread away from each other.

GUANO-The excrement of sea-birds (or bats and others). Under the right environmental conditions guano can form large deposits. These deposits have historically been mined for fertilizer because guano is very high in bioavailable nitrogen and phosphorus.

- Understand how climate helps control resource development
- Use data to calculate resource availability
- Be able to discuss sustainability of natural resources

Background Information

Guano

Source: US Fish and Wildlife

Webster's Dictionary defines guano broadly as "excrement especially of seabirds or bats", but more specifically as "a fertilizer containing the accumulated excrement of seabirds or bats". It is this second definition that explains the historical importance of guano and the US possession of many of the small islands in the Central Pacific.

Increasing populations in the 18th and 19th centuries and the need to maintain productive soils led to a suite of advances in agricultural techniques both in the US and abroad. Among them was the idea of replacing essential nutrients lost during crop production by adding nutrients from another source, a "fertilizer". In the early days of commercial fertilization, one of the most prized types of fertilizer was seabird guano with its high concentrations of nitrate, phosphate and potassium. However, the development of large quantities of seabird guano occurs only in a limited number of locations in the world. This is because in addition to needing a large numbers of seabirds to concentrate marine derived nutrients and long periods of time for accumulations to occur, the climate must be dry. Bioavailable nitrogen, in the form of nitrogen oxides (NOx) or ammonia (NH_3), is incredibly mobile and is easily removed from an environment by leaching, erosion, volatilization or bacterial denitrification. Leaching is also the primary way that phosphorus is removed from the environment, so the best guano for agricultural purposes came from areas with very little rain.

Seabird guano was so essential to US agriculture development that in 1856 the US passed the Guano Act which declared:

"Whenever any citizen of the United States discovers a deposit of guano on any island, rock, or key, not within the lawful jurisdiction of any other government, and not occupied by the citizens of any other government, and takes peaceable

Vocabulary (continued)

RESERVOIRS – Places where essential element/nutrients are stored for long periods of time without being recirculated. For example, coal is a reservoir for carbon and guano deposits are a reservoir for nutrients.

SYNTHETIC FERTILIZERS – Fertilizers with bioavailable nutrients created by laboratory and industrial processes.

Remnants of guano tramway on Jarvis Island with guano stockpiles in the background. Source: Wikipedia

possession thereof, and occupies the same, such island, rock, or key may, at the discretion of the President, be considered as appertaining to the United States." - US Guano Act 1856, 48 U.S. Code § 1411

All of the islands that now make up the PRIMNM, with the exception of Wake Island, became US positions under this Act.

Details of historical ownership are not the only legacy of guano mining on these islands. Rats and mice came to the islands aboard the guano ships and quickly adapted to a diet of seabird eggs and chicks. In addition, domesticated cats introduced in the 1930s to control the rodent populations easily adapted to a bird- based diet once the rodents were exterminated. Ground nesting birds were especially susceptible to predation by rats and cats and many seabird species were extirpated (localized extinction) altogether.

Indeed by 1966 only three species of seabirds remained on Jarvis Island when the Pacific Ocean Biological Survey Program visited. The ecological devastation resulting from these invasive species remains a lasting legacy of the guano mining era and one of the major challenges faced by the managers of the monument today.

Sooty Terns:

Source: US Fish and Wildlife

Sooty terns, with colony sizes in the millions, are a good example of seabirds that helped develop the guano resources on the small remote islands in the PRIMNM. By feeding in the productive waters upwelled around the islands, and returning food to their land bound chicks, nutrients sourced from the sea build up over time on the islands (sources and sinks). These birds also clearly demonstrate the resilience of a species in the face of invasive threats. Locally extirpated from a number of the PRIMNM islands, sooty terns have made a remarkable comeback once the predation and human disturbance pressures were removed. Their breeding colonies again number in the millions.

This lesson plan uses the feeding relationship of Sooty terns to demonstrate how nutrients can flow from source (ocean and atmosphere) to sink (islands). Additionally, students use climate data to make observations about where guano resources might develop, and calculate rates of guano development to investigate the concept of sustainable resources.

Preparation

- Read background.
- Print and cut out Sooty tern food web cards for each student.
- Print student worksheet for each student.
- Print plotting sheets in color, enough for each pair of students.

Learning Procedure

Engage

- Hand out the lat/long coordinates of all seven islands in the PRIMNM (or display on the overhead) without indicating what these locations represent. Ask student to work with a partner to brainstorm where on the planet these places might be and what they might have in common.
- After some discussion time, hand out the student plotting sheets and have students plot the coordinates. After they plot the locations ask them to revise their answers from before.
- After further discussion, introduce them to the Marine National Monument (MNM) in general and the Pacific Remote Islands Marine National Monument specifically (short PowerPoint PRIMNM Guano Monument Overview).
- Have students complete ***Part 1: Where are we?*** on their worksheet.

Explore/Explain – Food Webs and Nutrient Flows

Part 1: Food webs, trophic levels and nutrient flow

This can be done as a whole class brainstorming activity, or with small groups/pairs, or as an individual review. Students should already be familiar with the concept of food webs.

1. As a class briefly discuss the food webs and trophic levels so everyone has a good understanding of the concepts.
2. Present the food web cards, except for the sooty tern chick card, a large sheets of paper and two colored pencils to the each student or group and ask them to create a food web. You may need to introduce phytoplankton as the primary producers in marine food webs if the students are not familiar with marine ecosystems. In one color lightly draw feeding relationships that exist within this food web and label the

trophic levels for each species. Note that some species may occupy more than one trophic level.

3. Now ask the students how these organisms get their nutrients. In a different color trace the nutrient flow into, out of and through the food web. Use the following question to help guide understanding:
   a. Where do the nutrients for the primary producers come from?

      Primarily ocean upwelling of nutrient rich waters, drawdown from the atmosphere, release by decomposers and inputs from land. Note, upwelling is not coved in this lesson and may need to be discussed if the students are not familiar with this concept.

   b. How do those nutrients move through the food web?

      Primary producers extract nutrients from the surrounding waters, and consumers get their nutrients from their food. Students should understand that the food ingested in one form is released as waste in a different form, but that nutrients are present in both forms.

   c. Do organisms use 100% of the nutrients they take in?

      No, large amounts of nutrients are excreted as waste.

   d. Are 100% of nutrients transferred between trophic levels?

      No, most organisms are messy eaters and many of the nutrients are lost during eating and become part of the "marine snow". Other nutrients are lost when animals excrete waste or "fecal pellets".

4. Now introduce the Sooty tern chick card and ask the students to include this in the food/nutrient web. Use the guiding questions to help students:
   a. Where must the chicks be located given that they cannot fly?

      Mostly on islands. Fledging take ~60 days after hatching.

   b. How will nutrients get to them and what will happen to their excess nutrients?

      Chicks must be fed by their parents and excess nutrients from both chicks and parents are excreted and remain on the island rather than falling back into the sea. Over time, nutrients in the waste will start to build up on the islands.

Part 2: Nutrient accumulation simulation

This simulation will show the students how nutrients can be concentrated on oceanic islands. Begin by designating a portion of the classroom as an "island". The area should be large enough to fit a couple of student comfortably. Designate the area all around the island as "ocean". This region should be large enough to fit the majority of students participating in the activity with space for them to move around. Around the edges of the "ocean" designate a couple of places as "atmosphere". Divide the students up using food web cards making sure that there are at least twice as many bacteria, phytoplankton, and zooplankton as squids, anchovies, and terns. Chicks are restricted to the island. Begin by scattering a few nutrients (cotton balls) around the "ocean" region (not on the island) and in several places designated to be "atmosphere". Simulation follows these rules…

1. Bacteria: for every four nutrients you ingest, discard three back into the water as waste. You can get nutrients from the water (by decomposing materials found in the water), or from the atmosphere (some bacteria are nitrogen-fixers).
2. Phytoplankton: for every four nutrients you ingest, discard two as waste into the water. You get your nutrients from the water (nutrients returned to the water by you or other organisms).
3. Zooplankton, Anchovy, Squid: For every four nutrients you "ingest" two must be discarded into the water as waste. You can get your nutrients from eating other animals. Use the relationships on the food web to determine which animals you eat. If you are eaten by another animal, give them all of your nutrients and then start collecting nutrients again.
4. Sooty tern: For every four nutrients you take in, discard two as waste. You can get your nutrients from eating other animals. Use the relationships on the food web to determine which animals you eat. Once you have built up six nutrients in your reserve, go and give three to your chick on the island.
5. Sooty tern chick: for every four nutrients you get, discard two as waste on the island. You get your nutrients from your parent sooty terns.

Run the simulation for two minutes to see what happens.

6. Stop the simulation and ask the students what is happening with the nutrients.
   Students should begin to see an accumulation of nutrients on the island.
7. Run the simulation for several more rounds and then ask what is happening.
   The nutrient accumulation on the island should become bigger with time.
8. Stop the simulation and ask the students what will happen if it rains on the island.
   They should be able to determine that the nutrients on the island will wash back into the ocean.
9. Now introduce a precipitation event that washes most of the nutrients off the island during every two-minute period (you can simulate the effect of precipitation on the accumulation of nutrients on the island by giving one student a broom and instructing them to sweep off the whole "island"

once during the two minute round). Nutrients that run back into the water are fair game again. Run the simulation this way for several rounds.

10. Run the simulation both ways until it is clear to the students that nutrients build up much more slowly when there is rain on the islands. Stop the simulations and have students discuss the different dynamics they observed. Where did the nutrients come from? How hard was it for the higher trophic level organisms to get the nutrients they needed? What were the best sources of nutrients?

End the day by having the students complete **Part 2: Food Webs and Nutrient Flows** of their worksheet.

Elaborate – Jarvis, Climate Mapping, Guano Calculations

This sections asks students to study the environmental consequences of guano mining and to investigate the environmental conditions needed for the development of guano reserves. They will use that information to determine where the largest guano reserves are likely to be and will do some basic calculations to get a better understanding of the sustainability of guano as a harvestable resource.

Part 3: Focus on Jarvis Island

To re-engage students with the lesson have them read ***Part 3: Focus on Jarvis Island*** in their student worksheet. This will give them some background on guano mining operations and the lasting ecological damage resulting from those operations. In addition this short video http://youtu.be/haoqvgPzFsQ of sooty terns on Johnston Atoll gives a good sense of what it is like to be in a sooty tern colony and how the terns feed their young.

Part 4: Climate Mapping

Have students use their map of island locations from **Engage: Part 1 – Where are we?** to determine the monthly average rainfall and to calculate the annual average rainfall for each island in the PRIMNM. They should record their answers in the table provided in their worksheet. Once they have completed the table they should use that information to help them answer the subsequent questions.

Part 5: Poop Calculations

Using published seabird survey numbers, have students calculate the maximum annual rate of guano development for two points in time, before and after invasive cat removal. The follow up questions ask about the time it might take to replace all the guano mined from the islands and serves as a basis for students to think about the sustainability of this resource.

Evaluate – Summary

As a summative assessment have the students answer the short answer questions found in **Part 6: Summary** of their worksheet. As appropriate ask students to share their answer to stimulate a summary discussion around the important topics.

Extending the Lesson

There are numerous options for extension to this lesson.

- In the nutrient accumulation simulation you can add the element of carrying capacity in the system by allowing the organisms to replicate if they are able to get enough nutrients (e.g. six nutrients). Start with only one of each organism and begin by allowing only the bacteria and the phytoplankton to play for one or two rounds. Once there is a pool of these organisms, bring in all the other organisms. After several rounds, it should become clear that those organisms that have many food sources, the ones that are very quick, or the ones with no predators in this simulation (i.e. sooty terns) will come to dominate the scenario. This can lead to an excellent discussion of carrying capacity.

- Nitrogen fixation: both bacteria and blue green algae are able to fix N_2 from the atmosphere. Additionally bacteria are the main decomposers within the system. What happens to the food web and nutrient flow if bacteria are removed from the picture? Run several simulations without the bacteria to get a sense of how important these organisms are to the nutrient cycle. Instead of having discarded nutrients going back into the ocean, have them go into a "undecomposed material container" that is off limits as a nutrient source. Very quickly the students should see that the bacteria are essential to the functioning of the food web.

Connections to Other Subjects

- Math
- Ecology
- Biology
- Oceanography
- Geology

Related Links

Jarvis Island
NOAA Fisheries Pacific Remote Islands MNM
NOAA Fisheries Pacific Islands Regional Office
Guano Islands Act
NY Times article on Guano and Pacific Islands

For More Information

NOAA Fisheries Pacific Islands Regional Office
NOAA Marine National Monument Program
1845 Wasp Blvd., Building 176
Honolulu, HI 96818

(808) 725-5000, (808) 725-5215 (fax) pirohonolulu@noaa.gov

Acknowledgement

This lesson is one in a series exploring the geology, biology, oceanography, and ecology of the Pacific Marine National Monuments. It was developed for the NOAA Fisheries Pacific Islands Regional Office.

This lesson was developed by Mary Engels of the University of Idaho and Laura Nelson of the University of Washington.

All images are from NOAA, Laura Nelson or Mary Engels unless otherwise cited.

Thank you to all the reviewers for their feedback and assistance.

Sources

Advertising Ephemera Collection - Database #B0331
Emergence of Advertising On-Line Project
John W. Hartman Center for Sales, Advertising & Marketing History
Duke University David M. Rubenstein Rare Book & Manuscript Library
http://library.duke.edu/digitalcollections/eaa/

Cushman, Gregory T. Guano and the opening of the Pacific World: A global ecological history. Cambridge University Press, 2013.

Del Hoyo, Josep, Andrew Elliott, and Jordi Sargatal. "Handbook of the birds of the world, 3. Barcelona: Lynx Edicions." Komolphalin, Kamol (1996).

"Guano." Merriam-Webster.com. Merriam-Webster, n.d. Web. 24 Sept. 2014. <http://www.merriam-webster.com/dictionary/guano>.

Wikipedia. Wikimedia Foundation. Web. 8 Oct. 2015. <http://en.wikipedia.org/wiki/Sooty_tern>.

"Species." Sooty Tern (Onychoprion fuscatus). Web. 8 Oct. 2015. <http://www.birdlife.org/datazone/speciesfactsheet.php?id=3288>.

Education Standards

Next Generation Science Standards	• **MS-ESS3-1**. Construct a scientific explanation based on evidence for how the uneven distributions of Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes. • **MS-LS2-3.** Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem. • **MS-LS2-4.**Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations. • **HS-ESS3-1**. Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity • **HS-ESS3-2**. Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios. • **HS-LS4-5**. Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species.
Ocean Literacy Principles	• **4C** - The ocean provided and continues to provide water, oxygen, and nutrients, and moderates the climate needed for life to exist on Earth (Essential Principles 1, 3, and 5). • **5D** - Ocean biology provides many unique examples of life cycles, adaptations, and important relationships among organisms (symbiosis, predator-prey dynamics, and energy transfer) that do not occur on land. • **6B** - From the ocean we get foods, medicines, and mineral and energy resources. In addition, it provides jobs, supports our nation's economy, serves as a highway for transportation of goods and people, and plays a role in national security. • **6D** - Humans affect the ocean in a variety of ways. Laws, regulations, and resource management affect what is taken out and put into the ocean. Human development and activity leads to pollution (point source, nonpoint source, and noise pollution), changes to ocean chemistry (ocean acidification), and physical modifications (changes to beaches, shores, and rivers). In addition, humans have removed most of the large vertebrates from the ocean. • **6G** - Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

2 Student Worksheet

Pacific Remote Islands Marine National Monument: Guano and Nutrient Cycling Worksheet

Name______________________________________ Date____

Part 1: Where are we?

1. With a partner, brainstorm what these latitude and longitude coordinates might represent. In general, where are these positions on the planet? What do these locations have in common?

2. Using the plotting sheet, actually plot these latitude and longitude coordinates. Pay careful attention to °N vs. ° S and ° W vs. ° E.
3. Based on your plotting, revise your answers from Question 1.

4. Why might these locations be important to protect?

Part 2: Food Webs and Nutrient Flows

Directions: Answer the following questions.

1. What are primary producers in the marine environment? Where do they get their nutrients from?

2. **Nutrient reservoirs** are places where nutrients are stored for a long period of time. In the simulation we just did, what would be the nutrient reservoir? What might control how long the nutrients remain in that reservoir? Explain your reasoning.

3. What is the role of bacteria in food webs and nutrient cycles?

4. How are food webs and nutrient cycles related?

Part 3: Focus on Jarvis Island

Jarvis Island, located just south of the Equator in the central pacific (0° 22'S x 160° 01'W), is a US National Wildlife Refuge and part of the Pacific Remote Islands Marine National Monument. This island is excellent seabird nesting habitat and currently there are 20 different seabird species that spend time on the island. The largest group is a colony of sooty terns (*Onychoprion fuscatus*) that numbers more than a million and is one of the largest sooty tern colonies anywhere in the world. It is thought that in the past their numbers might have been much greater.

Source: US Fish and Wildlife

Thanks to many generations of seabirds, parts of the island of Jarvis have been buried in thick layers of bird poop known as ***guano*** deposits. Since these deposits are very rich in ***bioavailable*** nitrogen and phosphate, this island (and others like it) became very valuable as a source of fertilizer during the late 1880's when ***synthetic fertilizers*** were not available. The guano resources of Jarvis were so valuable that the island was claimed for the United States under the US Guano Islands Act of 1856. In fact, all the islands in the Pacific Remote Island Marine National Monument (PRIMNM), with the exception of Wake Island, were claimed by the US for their guano resources, which gives indication of how important fertilizers were to the US agricultural industry. Heavily mined for guano from 1858 till 1879, guano transport ships such as the *White Swallow* removed a total of 300,000 tonnes (600,000,000 lbs) of guano from Jarvis. This is equivalent to filling 1200 Olympic sized swimming pools full of bird poop!!

Historical ownership is not the only legacy of guano mining on these islands. Rats and mice came to the islands aboard the guano ships and quickly adapted to a diet of seabird eggs and chicks. In addition, domesticated cats were introduced in the 1930s to control the rodent populations, but easily adapted to a bird-based diet once the rodents were exterminated. Ground nesting birds such as sooty terns were especially susceptible to predation by rats and cats and many seabird species were extirpated (localized extinction) altogether. Indeed by 1966 only three species of seabirds remained on Jarvis Island when the Pacific Ocean Biological Survey Program visited. The ecological devastation resulting from these invasive species remains a lasting legacy of the guano mining era and is one of the major challenges faced by the managers of the Monument today.

Part 4: Climate Mapping

Climate is one significat factor that will control where guano resources will develop. Use the data from your plotting exercise in Part 1 to determine the average montly and annual rainfall for each island and answer the following questions.

NAME	LATITUDE	LONGITUDE	MONTHLY RAINFALL (cm)	ANNUAL RAINFALL (cm)
Baker Island	0° 12'N	176° 29'W		
Howland Island	0° 48'N	176° 37'W		
Jarvis Island	0° 22'S	160° 01'W		
Johnston Atoll	16° 45'N	169° 31'W		
Kingman Reef	6° 23'N	162° 25'W		
Palmyra Atoll	5° 53'N	162° 05'W		
Wake Island	19° 18'N	166° 38'W		

1. Which islands in the PRIMNM receive the most rainfall? Which island receives the least?

2. Which islands do you think historically had the least and best developed guano reserves and how do you think climate impacts the development of these reserves?

Part 5: Poop calculations

In addition to climate, guano development depends on the number of birds pooping and how much each bird is pooping. Below are the bird counts for two different years from Howland, Baker and Jarvis Islands. If one bird poops on average ***0.6 lbs of poop a year***, how much guano would develop on those islands in each different year from all the birds? Show your work!

Table 2 Seabird counts at the time of cat eradication for Jarvis, Baker, and Howland Islands and subsequent seabird counts on each island several years after cat eradication. The numbers represent the largest count of birds documented on a single trip but not the total population, as birds nest throughout the year.

Scientific Name	Common Name	Jarvis 1982	Jarvis 2004	Baker 1965	Baker 2002	Howland 1986	Howland 2007
Phaethon rubricauda	Red-tailed tropicbird	2500	2500	15	72	122	496
Sula dactylatra	Masked booby	3000	7000	400	3134	2387	3763
Sula leucogaster	Brown booby	500	2000	10	375	15	275
Sula sula	Red-footed booby	550	1000	1	714	41	825
Fregata minor	Great frigatebird	50	2400	3	900	0	550
Fregata ariel	Lesser frigatebird	1500	4000	0	16,200	0	3850
Onychoprion fuscatus	Sooty tern	1,000,000	+1,000,000	6000	1,600,000	0	150,000
Onychoprion lunatus	Grey-backed tern	6	1100	25	2000	0	2000
Anous stolidus	Brown noddy	1	10,000	1000	3600	50	1000
Procelsterna cerulea	Blue noddy	1	650	0	26	0	11
Gygis alba	White tern	12	11	0	38	2	50
Nesofregetta fuliginosa	Polynesian storm-petrel	1*	3	0	0	1	0
Puffinus nativitatis	Christmas shearwater	0	20	0	0	0	0
Puffinus bailloni	Tropical shearwater	0	20	0	0	0	0
Puffinus pacificus	Wedge-tailed shearwater	100	41	0	10	0	1*

*Birds found dead

Sources: Clapp and Sibley 1965; Forsell and Berendzen 1986; Sibley and Clapp 1965; Skaggs 1994; US Fish and Wildlife Service 2007

Jarvis 1982	Jarvis 2004
Baker 1965	Baker 2002
Howland 1986	Howland 2007

1. Which *year* and *island* had the greatest guano production?

2. Using the greatest guano production rate, how many *years* would it take to get 600,000,000 lbs of guano (the amount mined from Jarvis between 1858 and 1879)?

3. How many years would it take to develop 600,000,000 lbs if you used the lowest guano production rate?

4. Based on the numbers you just calculated, would you describe guano on these islands as a renewable resource? Why or why not?

Part 6: Summary

Directions: Based on what you have learned, answer the following questions:

1. Describe the process of seabird guano development on islands from source to reservoir. Be sure to include a discussion of climate.

2. What would be a sustainable amount of guano that could be harvested from these islands?

3. What are some of the environmental consequences of guano mining in the PRIMNM?

4. Guano is not being mined from these islands today. What are some reasons, both economic and ecological that guano mining operations may have stopped?

3. Student Worksheet ANSWER KEY

NOAA FISHERIES

Pacific Remote Islands Marine National Monument: Guano and Nutrient Cycling Worksheet ANSWER KEY

Name_____________________________________ Date____

Part 1: Where are we?

1. With a partner, brainstorm what these latitude and longitude coordinates might represent. In general, where are these positions on the planet? What do these locations have in common?

   Answers will depend on students' familiarity with the concepts of latitude and longitude and world geography. They should be able to determine that all the lat/long coordinates are generally in the Pacific Ocean and that the sites are likely islands. As a helpful point of reference, you may want to let students know that Hawaii is located at approximately 21° 18'N x 157° 47'W.

2. Using the plotting sheet, actually plot these latitude and longitude coordinates. Pay careful attention to °N vs. ° S and ° W vs. ° E.

   A helpful way to remember latitude and longitude is to have the students think about a ladder. "Ladditude" would be the horizontal rungs of a ladder, that allow you to climb up and down, and the "Long"itude would be the long sides of the ladder that run vertically. It will also be helpful to give the students an overview of the plotting sheet before they begin plotting. Hawaii is drawn on the map as a point of reference, longitude is on the x-axis, latitude is on the y-axis, and the grid frame has two colors to help with plotting.

3. Based on your plotting, revise your answers from Question 1.

   All the islands are located in the central Pacific Ocean, west of Hawaii and east of the date line. All of the islands fall in the tropics and subtropics which generally indicates hot climates and limited seasons. Some students may also comment based on their plotting that a number of the islands are pretty dry and remote.

4. Why might these locations be important to protect?

   Answers will vary, but ideally students will come up with that these islands are home to many unique species. In particular, these islands are very important as seabird nesting habitat.

Part 2: Food Webs and Nutrient Flows

Directions: Answer the following questions.

1. What are primary producers in the marine environment? Where do they get their nutrients from?

   Primary producer in the marine environment are typically phytoplankton who can use photosynthesis for an energy source. Their productivity is limited by their access to nutrients in the water and the amount of sunlight they receive. The amount of nutrients in the water is controlled by the rate of N_2 fixation from the atmosphere (thanks to both heterotrophic and autotrophic bacteria species), upwelling from the deep ocean, inputs from land via rivers or wind, and nutrients released by the decomposition of organic matter by bacteria. The availability of nutrients in the upper ocean frequently limits the abundance of organisms in the upper oceans.

2. **Nutrient reservoirs** are places where nutrients are stored for a long period of time. In the simulation we just did, what would be the nutrient reservoir? What might control how long the nutrients remain in that reservoir? Explain your reasoning.

   The island is a nutrient sink, or a ***nutrient reservoir****, which traps and immobilizes the nutrients away from access by living organisms. The amount of precipitation will control how long nutrients remain in the island reservoir. If there is a lot of rain, nutrients will be washed back into the ocean, but if not, they tend to stay put. Large deposits of bird poop are known as guano.*

3. What is the role of bacteria in food webs and nutrient cycles?

   Bacteria are the decomposers in food webs. As they break down dead organisms and release many of the nutrients locked up in those cells back to the ocean through their waste. In addition, many bacteria are able to fix nitrogen from the atmosphere making it available to organisms that are not able to fix nitrogen on own.

4. How are food webs and nutrient cycles related?

   A food web describes how energy moves through the living (organic) part of any ecosystem. Nutrients are also moved in this way, however, nutrients can also be moved around by non-living (inorganic) processes such as the weathering of rocks, deposition of sediments by wind, and inorganic chemical reactions. The organic and inorganic movement of nutrients together makes up the nutrient cycle.

Part 3: Focus on Jarvis Island

Jarvis Island, located just south of the Equator in the central pacific (0° 22'S x 160° 01'W), is a US National Wildlife Refuge and part of the Pacific Remote Island Marine National Monument. This island is excellent seabird nesting habitat and currently there are 20 different seabird species that spend time on the island. The largest group is a colony of sooty terns (*Onychoprion fuscatus*) that numbers more than a million and is one of the largest sooty tern colonies anywhere in the world. It is thought that in the past their numbers might have been much greater.

Source: US Fish and Wildlife

Thanks to many generations of seabirds, parts of the island of Jarvis have been buried in thick layers of bird poop known as ***guano*** deposits. Since these deposits are very rich in ***bioavailable*** nitrogen and phosphate, this island (and others like it) became very valuable as a source of fertilizer during the late 1880's when ***synthetic fertilizers*** were not available. The guano resources of Jarvis were so valuable that the island was claimed for the United States under the US Guano Islands Act of 1856. In fact, all the islands in the Pacific Remote Island Marine National Monument (PRIMNM), with the exception of Wake Island, were claimed by the US for their guano resources, which gives indication of how important fertilizers were to the US agricultural industry. Heavily mined for guano from 1858 till 1879, guano transport ships such as the *White Swallow* removed a total of 300,000 tonnes (600,000,000 lbs) of guano from Jarvis. This is equivalent to filling 1200 Olympic sized swimming pools full of bird poop!!

Historical ownership is not the only legacy of guano mining on these islands. Rats and mice came to the islands aboard the guano ships and quickly adapted to a diet of seabird eggs and chicks. In addition, domesticated cats were introduced in the 1930s to control the rodent populations, but easily adapted to a bird-based diet once the rodents were exterminated. Ground nesting birds such as sooty terns were especially susceptible to predation by rats and cats and many seabird species were extirpated (localized extinction) altogether. Indeed by 1966 only three species of seabirds remained on Jarvis Island when the Pacific Ocean Biological Survey Program visited. The ecological devastation resulting from these invasive species remains a lasting legacy of the guano mining era and is one of the major challenges faced by the managers of the Monument today.

Part 4: Climate Mapping

Climate is one significat factor that will control where guano resources will develop. Use the data from your plotting exercise in Part 1 to determine the average montly and annual rainfall for each island and answer the following questions.

NAME	LATITUDE	LONGITUDE	MONTHLY RAINFALL (cm)	ANNUAL RAINFALL (cm)
Baker Island	0° 12'N	176° 29'W	*10*	*120*
Howland Island	0° 48'N	176° 37'W	*10*	*120*
Jarvis Island	0° 22'S	160° 01'W	*10*	*120*
Johnston Atoll	16° 45'N	169° 31'W	*2*	*24*
Kingman Reef	6° 23'N	162° 25'W	*25*	*300*
Palmyra Atoll	5° 53'N	162° 05'W	*25*	*300*
Wake Island	19° 18'N	166° 38'W	*8*	*96*

1. Which islands in the PRIMNM receive the most rainfall? Which island receives the least?

   Palmyra Atoll and Kingman reef receive the most rainfall of any of the islands. Johnston Atoll receives the least.

2. Which islands do you think historically had the least and best developed guano reserves and how do you think climate impacts the development of these reserves?

   While all the islands are great habitat for seabirds (good nesting habitat, few predators, and productive waters in which to feed due to upwelling around islands) guano only develops in regions that have limited precipitation. Significant rainfall prevents guano development at Palmyra Atoll and Kingman Reef because the bird poop is physically washed away or the nutrients are leached out of the soil before guano reserves can develop. Jarvis, Howland, Baker, Johnston Atoll and Wake Island all historically had well developed guano resources. Jarvis, Howland, and Baker islands were mined extensively during the 1800s, but Johnston Island was mined only sporadically and Wake Island was not mined for guano at all.

Part 5: Poop Calculations

In addition to climate, guano development depends on the number of birds pooping and how much each bird is pooping. Below are the bird counts for two different years from Howland, Baker and Jarvis Islands. If one bird poops on average ***0.6 lbs of poop a year***, how much guano would develop on those islands in each different year from all the birds? Show your work!

Table 2 Seabird counts at the time of cat eradication for Jarvis, Baker, and Howland Islands and subsequent seabird counts on each island several years after cat eradication. The numbers represent the largest count of birds documented on a single trip but not the total population, as birds nest throughout the year.

Scientific Name	Common Name	Jarvis 1982	Jarvis 2004	Baker 1965	Baker 2002	Howland 1986	Howland 2007
Phaethon rubricauda	Red-tailed tropicbird	2500	2500	15	72	122	496
Sula dactylatra	Masked booby	3000	7000	400	3134	2387	3763
Sula leucogaster	Brown booby	500	2000	10	375	15	275
Sula sula	Red-footed booby	550	1000	1	714	41	825
Fregata minor	Great frigatebird	50	2400	3	900	0	550
Fregata ariel	Lesser frigatebird	1500	4000	0	16,200	0	3850
Onychoprion fuscatus	Sooty tern	1,000,000	+1,000,000	6000	1,600,000	0	150,000
Onychoprion lunatus	Grey-backed tern	6	1100	25	2000	0	2000
Anous stolidus	Brown noddy	1	10,000	1000	3600	50	1000
Procelsterna cerulea	Blue noddy	1	650	0	26	0	11
Gygis alba	White tern	12	11	0	38	2	50
Nesofregetta fuliginosa	Polynesian storm-petrel	1*	3	0	0	1	0
Puffinus nativitatis	Christmas shearwater	0	20	0	0	0	0
Puffinus bailloni	Tropical shearwater	0	20	0	0	0	0
Puffinus pacificus	Wedge-tailed shearwater	100	41	0	10	0	1*

*Birds found dead

Sources: Clapp and Sibley 1965; Forsell and Berendzen 1986; Sibley and Clapp 1965; Skaggs 1994; US Fish and Wildlife Service 2007

Jarvis 1982 *1,008,220 birds x 0.6 lbs/bird/year = 604,932 lbs/year*	**Jarvis 2004** *1,030,745 birds x 0.6 lbs/bird/year = 618,447 lbs/year*
Baker 1965 *7,454 birds x 0.6 lbs/bird/year = 4,472 lbs/year*	**Baker 2002** *1,627,069 birds x 0.6 lbs/bird/year = 976,241 lbs/year*
Howland 1986 *2,618 birds x 0.6 lbs/bird/year = 1,571 lbs/year*	**Howland 2007** *162,820 birds x 0.6 lbs/bird/year= 97,692 lbs/year*

1. Which *year* and *island* had the greatest guano production?

   Baker Island in 2002 had the highest number of birds (1,627,069 birds) which means it also had the highest guano production rate.

2. Using the greatest guano production rate, how many *years* would it take to get 600,000,000 lbs of guano (the amount mined from Jarvis between 1858 and 1879)?

   600,000,000 lbs / 976,241 lbs/year = 615 years

3. How many years would it take to develop 600,000,000 lbs if you used the lowest guano production rate?

   600,000,000 lbs / 1,571 lbs/year = 381,971 years

4. Based on the numbers you just calculated, would you describe guano on these islands as a renewable resource? Why or why not?

   Generally speaking, no, this is not a very renewable resource. If the bird populations were much larger, or we mined much less guano, this might be a renewable resource, but at the rates of guano mining in the past, this is not a renewable resource.

Part 6: Summary

Directions: Based on what you have learned, answer the following questions:

1. Describe the process of seabird guano development on islands from source to reservoir. Be sure to include a discussion of climate.

   Bioavailable nutrients present in ocean water (the source) are used by phytoplankton in their growth and development. As primary producers, the phytoplankton are the base of a large marine food web. Nutrients, as well as energy, flow through the trophic level of the food web until they reach seabirds who transfer food and nutrients to their chicks. Since the chicks are flightless and the parents spend a lot of time nesting, their wastes accumulate on the islands instead of returning directly to the ocean to be recycled by bacteria and other decomposers. If the climate is dry enough, wastes will not be washed off the islands due to precipitation events and over long time scales a nutrient sink, or large guano reservoir, will develop.

2. What would be a sustainable amount of guano that could be harvested from these islands?

   A sustainable guano mining operation would not take more guano each year than is being produced. Based on our rough calculations about ~900,000 lbs of guano are produced on Baker Island each year. This is enough fertilizer for about 4500 acres of farmland, far less than 1% of all the farmland in the US. In short, the limited supply of guano and the ecological disturbances of guano mining mean that sustainable guano mining operations are not really possible today.

3. What are some of the environmental consequences of guano mining in the PRIMNM?

   The introduction of invasive species, disturbance of seabirds and destruction of seabird habitat are all consequences of guano mining.

4. Guano is not being mined from these islands today. What are some reasons, both economic and ecological that guano mining operations may have stopped?

   Guano is not being mined from the islands for many reason. First, development of synthetic fertilizers made guano mining mostly obsolete, though organic farming has renewed some interest. In addition, given that these islands are very remote, it would be hard to bring the guano to markets in a cost-effective way. Additionally many guano reserves were depleted during the late 1800s and have not been renewed. Finally, and most importantly, mining operations dramatically disturb the bird populations and expose them to threats from invasive species. Many of these bird species are currently threatened or endangered, and these remote islands are their only breeding grounds. Given that these islands are critical to the long term sustainability of these bird populations, protecting and restoring these island habitats is a huge part of the mission of the Marine National Monument Program.

4. Student Plotting Worksheet

NOAA FISHERIES

Pacific Remote Islands Marine National Monument: Plotting Worksheet

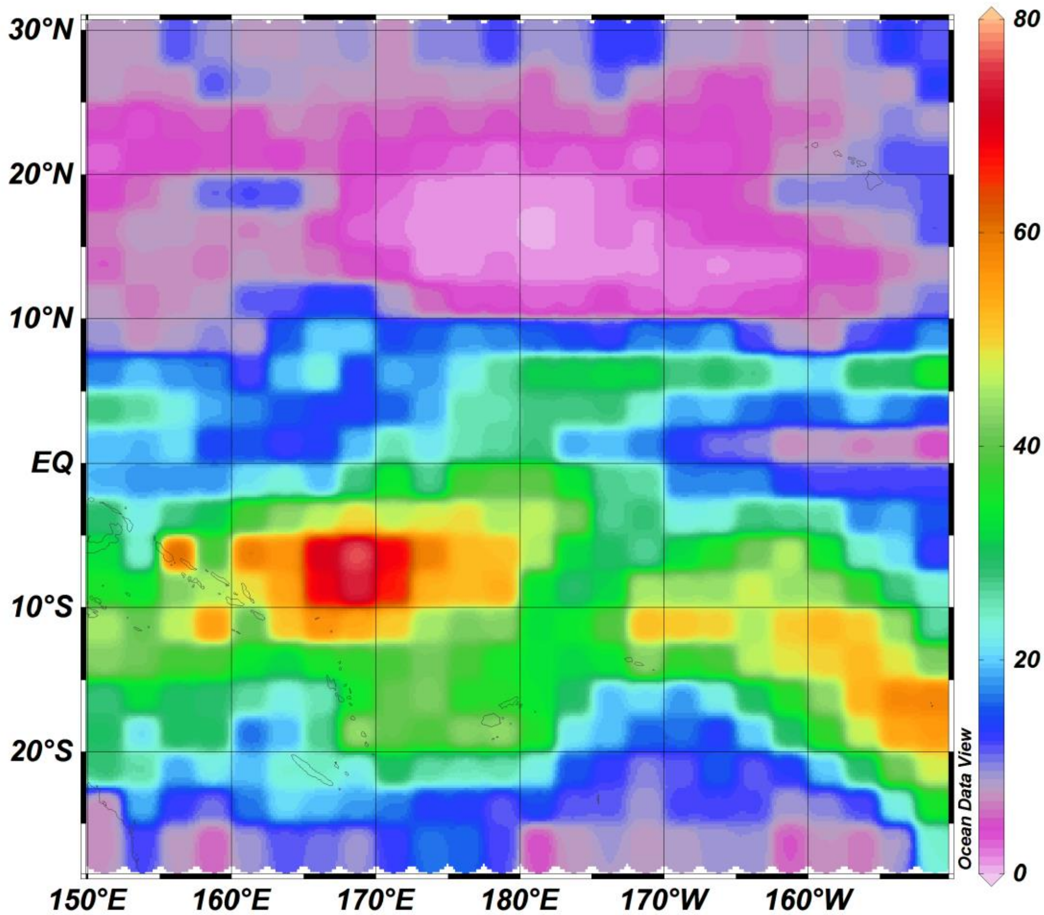


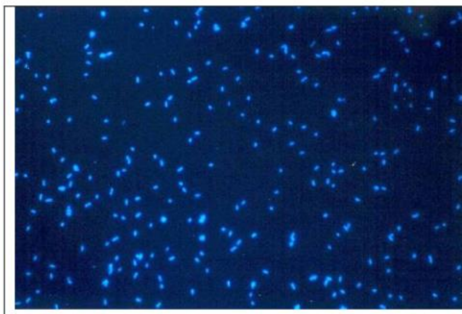
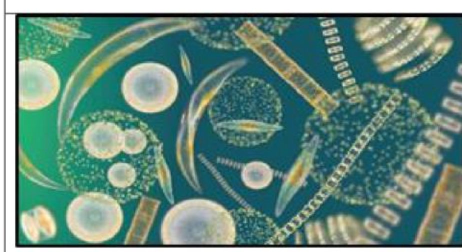
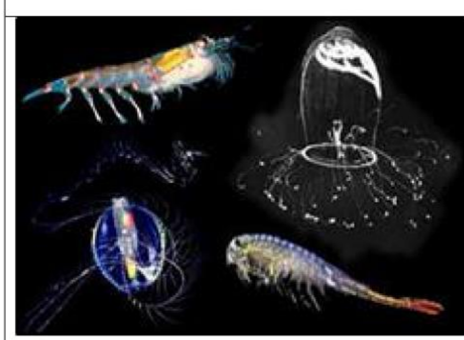
Figure 1: Monthly Average Precipitation [cm]

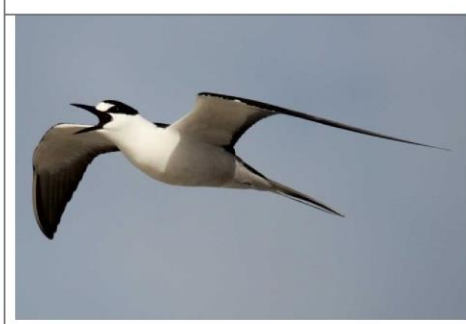
LOCATION	LATITUDE	LONGITUDE
1	0° 12’N	176° 29’W
2	0° 48’N	176° 37’W
3	0° 22’S	160° 01’W
4	16° 45’N	169° 31’W
5	6° 23’N	162° 25’W
6	5° 53’N	162° 05’W
7	19° 18’N	166° 38’W

5. Nutrient Web Cards

NOAA FISHERIES

Pacific Remote Islands Marine National Monument: Nutrient Web Cards

	**Marine Bacteria** **Nutrient Sources:** water and atmosphere **Efficiency:** Every time you collect 4 nutrients, recycle 3 back into the water.
	**Marine Phytoplankton** **Nutrient Sources:** water **Efficiency:** Every time you collect 4 nutrients, recycle 2 back into the water.
	**Marine Zooplankton** **Nutrient Sources:** phytoplankton **Efficiency:** Every time you collect 4 nutrients, recycle 2 back into the water.

	**Squid** **Nutrient Sources:** zooplankton **Efficiency:** Every time you collect 4 nutrients, recycle 2 back into the water.
	**Anchovy** **Nutrient Sources:** zooplankton **Efficiency:** Every time you collect 4 nutrients, recycle 2 back into the water.
	**Sooty Tern** **Nutrient Sources:** squid and anchovies **Efficiency:** Every time you collect 4 nutrients, recycle 2 back into the water. **Reproduction:** When you have 6 nutrients, give 3 to a chick on the island.

	**Sooty Tern Chick** **Nutrient Sources:** sooty tern parent **Efficiency:** Every time you collect 4 nutrients, recycle 2 onto the island.