PICSC FINAL REPORT

1. Administrative

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2. Public Summary

Epiphytes are specialized plants with a variety of adaptations that allow them to grown in the branches of trees. Epiphytes play important roles in the cloud forest ecosystem and make a large contribution to biodiversity. Water supply is undoubtedly the most important determinant of epiphyte growth, and therefore shifts in rainfall patterns make epiphytes exceptionally vulnerable to global climate change. Plant distributions generally track climate, and epiphytic plants exhibit especially close-knit climate based constraints. Due to strict dependence on the atmosphere for required moisture and nutrients, epiphytes are thus exceptionally sensitive to air quality and climate, and by extension unusually useful for monitoring shifts in climate patterns. Hawaii has a range of climates suitable for epiphytes. In Hawaii, this includes areas with ample rain and/or fog. Over the next 100 years, Hawaii will likely experience overall increasing temperatures with stronger warming at higher elevations (Giambelluca et al. 2008). Overall conclusions suggest that occurrence and duration of droughts during the dry season as well as the length of the dry season may increase (Timm et al. 2015). Studies of epiphyte abundance and composition in Hawaii are few. Only one study (Crausbay and Hotchkiss 2010) investigated vegetation patterns of epiphytes, including vascular species, as part of a larger investigation examining the potential sensitivity to climate change along gradients on Maui’s tropical mountain, Haleakala. Because epiphytes are among the most sensitive plants to atmospheric climate change, our main objective is to establish a baseline from which changes in epiphyte communities can be monitored as a leading near term indicator of likely Hawaiian forest change. We accomplish this by investigating patterns of epiphyte abundance and species composition across elevation and precipitation gradients on windward Hawaii Island. We established study sites across the Eastern portion of the Island of Hawaii, representing a range of climate conditions. We also monitored weather, specifically measuring rain and fog separately, at two sites. In addition, we measured differences in stable isotopes, a way of tracking the source water that plants use, as a pilot study to evaluate the potential importance of fog water.

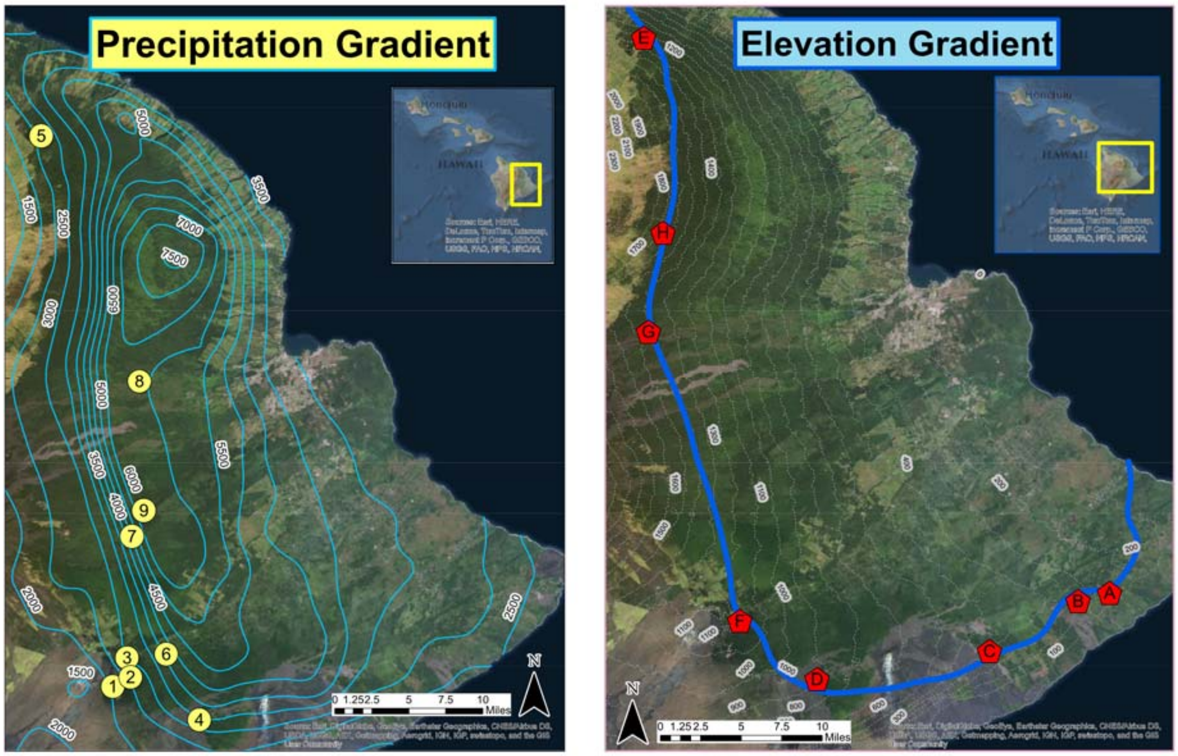
3. Technical Summary

Epiphytes are specialized plants that display a diverse variety of adaptations favoring canopy suspension without soil access (Foster 2001). Due to their habitat above the forest floor epiphytes intercept important fluxes of light, water and nutrients and play important roles in the cloud forest ecosystem (Benzing 1998, Foster 2001). Despite these differences, water supply is undoubtedly the most important determinant of vascular and nonvascular epiphyte distribution (Benzing 1998, Foster 2001). Shifts in patterns of annual and seasonal rainfall make arboreal flora exceptionally vulnerable to displacement and extirpation due to global climate change. Plant distributions generally track climate because temperature and moisture influence metabolic rates (Benzing 1998). Due to strict dependence on the atmosphere for required moisture and nutrients, arboreal flora is thus exceptionally sensitive to air quality and climate, and by extension unusually useful for monitoring phenomena related to global change (Lugo and Scatena 1992). Hawaii has a range of climates suitable for epiphytes. Over the next 100 years, Hawaii will likely experience overall increasing temperatures with stronger warming at higher elevations (Giambelluca et al. 2008). Overall conclusions suggest that occurrence and duration of droughts during the dry season as well as the length of the dry season may increase (Timm et al. 2015). Studies of epiphyte abundance and composition in Hawaii are few. Only one study (Crausbay and Hotchkiss 2010) investigated vegetation patterns of epiphytes, including vascular species, as part of a larger investigation examining the potential sensitivity to climate change along gradients on Maui's tropical mountain, Haleakala. Because epiphytes are among the most sensitive plants to atmospheric climate change, our main objective here is to establish a baseline from which changes in epiphyte communities can be monitored as a leading near term indicator of likely Hawaiian forest change. We accomplish this by investigating patterns of epiphyte abundance and species composition across elevation and precipitation gradients on windward Hawaii Island. We established a precipitation gradient across forest sites on windward Hawaii Island by holding elevation constant at 1000-1200m while varying precipitation between 2400 – and 6400 mm/yr. We also established an elevation gradient by holding rainfall constant at 3000mm. Epiphytes occupy tight, climate-defined niches compared with co-occurring life forms such as trees. Because of Hawaii Island's natural climatic diversity, it is an ideal location to understand how these intrinsically climate sensitive plants interact with the atmosphere and evaluate how they may serve as a near-term indicator of climate change. Here we establish a baseline of corticolous (trunk-based) epiphyte communities by 1) investigating patterns of epiphyte abundance and species composition across elevation and precipitation gradients on windward Hawaii Island, and 2) using physiological measurements to investigate the relative importance of rain vs. fog in epiphyte-atmosphere interactions. Overall, epiphyte communities showed much finer scale responses to climate variation when compared with structurally dominant vegetation. The precipitation gradient exhibits a clear increase in abundance of all epiphyte groups and an increase in diversity with increasing rainfall. Results across the elevation gradient show a higher abundance of filmy ferns and bryophytes above the lifting condensation level where fog incidence is highest and PET is lowest, as well as a marked difference in species composition. A second focus of this investigation involves using stable isotope ecology to trace differences in rain and fog water sources at two sites of equal precipitation: Volcano and Kohala. Results indicate that the $\delta^{18}O$ signature of fog at Volcano is significantly enriched compared to rain, but that sources do not separate at Kohala. Volcano's precipitation patterns include orographic moisture with occasional synoptic scale low-pressure systems that deliver heavy rainfall. Results suggest that the major contributor to precipitation in Volcano is rain whereas horizontally driven moisture is the major contributor at Kohala. Because isotope composition is a marker for vapor source and condensation history, these results indicate very different precipitation patterns at Kohala and Volcano.

5. Organization and Approach

5.1. Study Sites

We investigated patterns of epiphyte abundance and species composition across precipitation and elevation and gradients on windward Hawaii Island. We established fifteen field sites in various climate types across windward Hawaii Island on land owned and managed by Hawaii Volcanoes National Park, Department of Land and Natural Resources, State Division of Forestry and Wildlife, Kohala Watershed Partnership as well as private landowners. We established a precipitation gradient across forest sites by holding elevation constant at 1000-1200m while varying precipitation between 2400 – and 6400 mm/yr (Figure 1A); we established an elevation gradient by holding rainfall constant at 3000mm and varying elevation between 150 and 1700 m (Figure 1B). Several sites were part of both gradients, including one (Ponoholo) in the Kohala Mountains, which climate data suggest may have conditions favorable for fog capture (e.g. high cloud incidence and wind speed). We located closed canopy forest sites dominated by Ohia Lehua (*Metrosideros polymorpha*). This is the most abundant and dominant tree species, distributed from sea level to tree line across extremely wet to extremely dry conditions.



A. B.

Figure 1. Study Sites. A. Nine sites of the precipitation gradient. B. Eight sites of the elevation gradient. Note that three sites belong to both gradients. Another site (Ponoholo) is in the Kohala Mountains and is not shown on these maps, but meets criteria of both gradients.

5.2. Epiphyte Surveys

Variation in host tree bark and canopy structure can have a strong influence on species composition of epiphytes. To control for these host tree differences, and because we were interested primarily in epiphytes that indicate climate across gradients, rather than strictly species composition, we focused on *Metrosideros polymorpha* as a host. We chose trees with a standardized conditions to allow comparison across gradient sties. We only analyzed trees that were 30-50cm Diameter at Breast Height (DBH); this represented the approximate size of canopy trees that were available at all sites. We chose only trees at least 50% alive in the canopy and avoided trees at forest margins because of potential microclimatic effects due to enhanced light. Because branching patterns can dictate different microclimatic patterns, we only choose trees that have no branches (greater than 5cm DBH) below 5m along the trunk. To control for microclimatic patterns associated with funneling water along the trunk of a leaning tree, we did not consider trees deviating from vertical by less than 10°. We did not consider trees with buttress roots taller than 1m or greater than 1m in diameter (measured from the central axis of the tree trunk) due to potential microclimatic effects associated with these complex features. We only considered trees meeting the above criteria for analysis. At each site, we measured all suitable host trees within 10m on each side of a transect line. This process was repeated until we surveyed 21 host trees per site.

To control for intra-annual variation, we collected data during the summers of 2012, 2013 and 2014 from May – September. Using a measured pole, we divided the trunk of each surveyed tree into half-meter intervals from ground level up to 5m (Figure 2). We determined the frequency of bryophytes, and all species of trunk epiphytes by recording the presence of every species in each half-meter section (we did not determine bryophytes down to the species level) from the ground to 5m. We combined increments to get a mean frequency per tree. We avoided counting seedling stage woody epiphytic species by only counting those that were 20 cm or greater in length. Because multiple species of filmy ferns appear similar in the early growth stage, we only counted those large enough to reach maturity and identified those down to the species level. We used binoculars to assess the presence of epiphytes in the upper canopy, above 5m. We only considered species that were identifiable at a distance, and so smaller species (e.g. filmy ferns) in the upper canopy may have been missed. We analyzed all epiphytes in this category as "canopy macro epiphytes." Considering that most trees had epiphytes concentrated lower down, it is likely that few species existed above 5m that had not been detected lower down. The first meter (from the ground to under 1m) showed considerable variation in trunk bases including those with small buttress roots to straight trunks. The increased surface area of the buttress roots greatly altered the microclimate of the trunk below 1m, and thus influenced the epiphyte composition. For this reason and because we were primarily interested in patterns of abundance and species composition on trunks and in the forest canopy, and not on the forest floor, we did not consider the first meter of the tree trunk for analysis.

A. B.

Figure 2. Epiphyte surveys. A. View up a tree trunk with measuring pole alongside. B. Closeup of filmy ferns (*Hymenophyllum* spp.). These tiny ferns have very thin leaves that are highly susceptible to desiccation. Their abundance was high at sites with high rainfall, but also areas at higher elevation within the fog zone, even where rainfall was modest.

5.3. Data Analysis

The frequencies of bryophytes, filmy ferns, epiphytes, and hemi epiphytes were analyzed separately from 1-5m. Patterns of epiphyte species composition and abundance were analyzed across gradients using a Poisson Regression or a Negative Binomial Regression where appropriate. Sørensen's similarity index was used to assess similarity between sites along each gradient using presence and absence of species at each site. One site (Ponoholo) was not considered part the gradient analyses for three reasons. 1) It is the only site at the top of a valley, where wind driven fog is likely an important characteristic of its local climate; 2) it is the only site in Kohala, the oldest geologically and climatically distinct northern region of the island. 3) Initial analyses indicated that it was an outlier on both gradients. It was instead compared directly to each of the other sites with comparable elevation and precipitation including: Niaulani, Thurston, Kane Nui o Hamo, and Humuula. Data from the Ponoholo – 3000mm comparison were analyzed using a Kruskal-Wallis rank sum test and Kruskal-Wallis multiple comparisons test where appropriate.

5.4 Stable Isotope Pilot Study

We chose two sites in different parts of the island to examine the prevalence and isotopic composition of rainfall vs. fog drip. The Volcano Village site is southwest of Hilo in Hawaii Volcanoes National Park. This site receives approximately 2660mm rain/year (Giambelluca 2013). The Kohala site is at the base of Puu Pili, near the Puu O Umi Natural Area Reserve, northeast of Waimea. The Kohala site receives approximately 2350mm rain/ year (Giambelluca 2013). Both sites have an elevation of 1200m – within the orographic cloud belt (approximately 600 – 2000m). According to the Hawaii Rainfall Atlas (Giambelluca 2013) both sites have comparable amounts of relative humidity, but Kohala has a slightly lower yearly Cloud Frequency, higher yearly wind speed, and slightly lower 2pm and yearly average temperatures than Volcano. For this investigation, we used standard tipping bucket gage instrumentation. A separate standard recording 6" diameter tipping bucket for each fog and rain were rigged to measure and then collect its respective water source by draining into a collection device, from which isotope samples were taken for analysis. The tipping bucket instrumentation was rigged to collect fog with a Louvered Screen Fog Gauge (LSFG) described in detail by Juvik and Nullett (1995a & 1995b). The objective of the passive fog collector is to compliment open-site rainfall data by providing standardized cloud-water measurements for inter-site comparison and draining the measured amount into a collection device for isotope sampling. At each monitoring site, a rain gauge and a and LSFG (mounted at 3 m above the ground) were paired at an open site exposed to the prevailing NE trade winds (Figure 5A). The louvered aluminum screen collector gathers horizontally moving cloud droplets that drip down by funnel and plastic tubing into a covered rain gage. A conical, stainless-steel, rain exclusion "hat" (dia. 58 cm) shields the fog screen below from vertical rainfall and most wind blown rain drops. Fog is therefore defined in this study as horizontally moving moisture <0.1mm in diameter at wind speeds <5m/s and larger sized drops at higher wind speeds. Under high wind conditions, some non-vertical rainfall will enter the fog gage. Wind speed and event drop-size estimates were not measured for this experiment. Cumulative water was collected from each source by gluing a funnel to the bottom of the tipping bucket, attaching plastic tubing, and draining it into a custom made 5 gallon screw top bucket. The bucket was placed inside a cooler to help minimize thermal insolation from the sun. The entire site was fenced to prevent disturbance, especially by feral pigs.

The Volcano site precipitation data collection began in November 2013 and ended in January 2015. The Kohala site data collection began in January 2014 and ended in January 2015. Precipitation was logged at 30 second intervals and the gauges recorded the time of each tip. No other climate atmospheric variables were measured. Instead, yearly site averages for relative humidity, cloud frequency, wind speed and temperature were made using the online Hawaii Climate Atlas (Giambelluca et al. 2014).

Sampling for isotope composition performed approximately monthly at Volcano, and every 15-30 days in Kohala. Sampling was more frequent in Kohala to allow adequate draining of the 5 gallon collection devices and thus prevent overflow. The weather station and tipping bucket gauges were connected to data loggers that were downloaded every visit. Stable isotope samples were analyzed for δ 18O via mass spectrometry at the Stable Isotope Ratio Facility for Environmental Research at the University of Utah. Oxygen and isotope results are reported in per mil (‰) relative to Standard Mean Ocean Water (SMOW). Oxygen 18 (δ 18O) analyses were done by equilibration with carbon dioxide and automated analysis; precision is around ±0.2%. Because we are interested in the source water values over time, rain and fog isotope results are presented as simple averages from all the data. To understand how the isotope values changed throughout the year, isotope samples were pooled according to season: Winter: December 21st - March 20th; Spring: March 20th - June 21st; Summer: June 21st - September 23rd and Autumn: September 23rd - Dec 21st. Individual Mann Whitney U tests were used to determine if the values of rain and fog water were significantly different between seasons. A Kruskal-Wallis rank sum test, followed by a Kruskal-Wallis multiple comparisons test where appropriate was used to determine if the isotope value of rain was significantly different between seasons and if the isotope value of Fog was significantly different between seasons at each site.

6. Project Results

6.1. Epiphyte Survey

There were 61 total epiphyte species found across both gradients. These epiphyte species represented 36 Ferns, 9 Monocotyledons and 16 Dicotyledons. Thirty-one species were endemic, sixteen indigenous, nine naturalized, and one Polynesian introduced. Of the distinct species compositions at each individual site, most epiphyte species were endemic ferns. Results across the precipitation gradient indicate that epiphyte species abundance and composition are closely tied to moisture. The “Low” site (2400 mm rain/year at 1100 m elevation) had the fewest epiphyte species and Wailuku (6100 mm rain/year at 1080 m elevation) had the greatest number of species (20). There was a significant relationship between every analysis group measured and increasing precipitation (for example, see Figure 3). The elevation gradient exhibited a mixed pattern. Results of a negative binomial regression indicate a significant increase in moss frequency with increasing elevation ($z= 2.001$, $p=0.0454$). There is no significant relationship in filmy fern frequency or epiphyte frequency with increasing elevation. Multiple relationships indicate decreases in frequency with increasing elevation: a negative binomial regression indicates a significant decrease in hemi epiphyte frequency with increasing elevation ($z= -10.23$; $p < 0.001$) and significant decrease in the frequency of canopy macros epiphytes with increasing elevation ($z= -4.863$, $p < 0.001$). A Poisson regression also indicates a significant decrease in epiphyte richness with increasing Elevation ($z= -6.164$; $p < 0.001$). There is no significant relationship in epiphyte incidences with increasing elevation. With few exceptions, results indicate that the Ponoholo (Kohala Mountain) site had significantly higher frequencies of all variables in comparison to other sites that receive 3000 mm precipitation and have similar elevations (for example, see Figure 4). Ponoholo had significantly higher epiphyte richness (8.43 epiphyte species/tree) than all other sites.

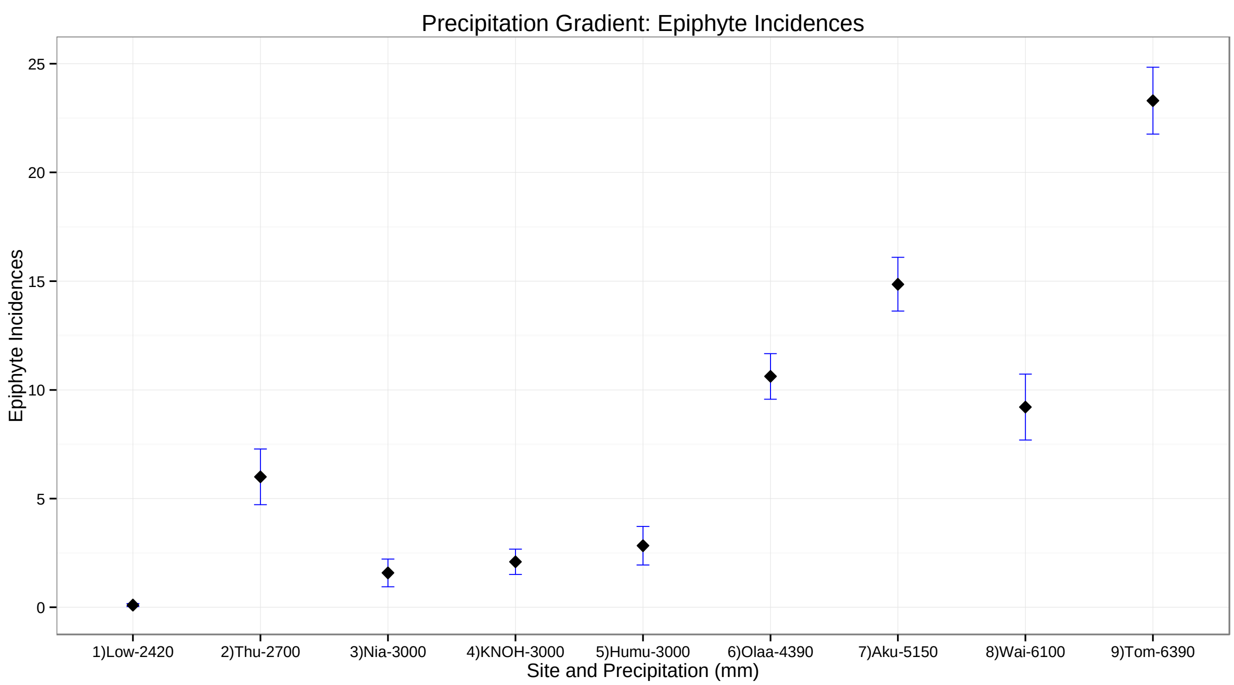


Figure 3. Increase in overall epiphyte frequency with increasing mean annual precipitation.

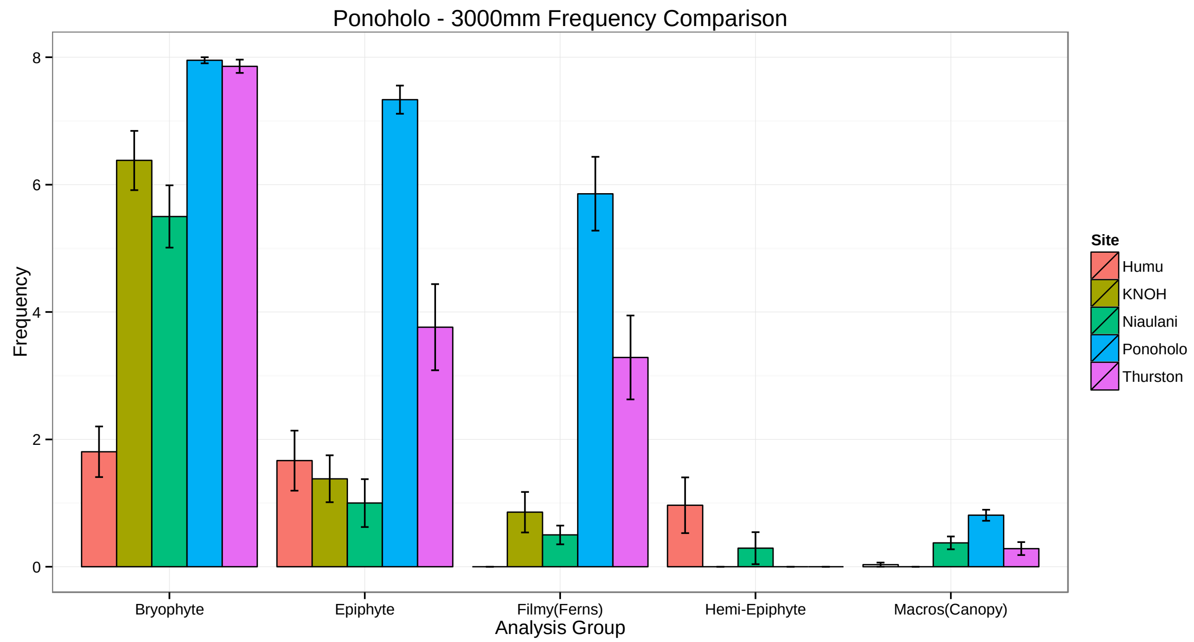
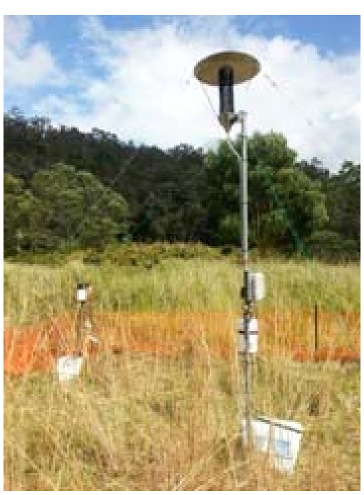
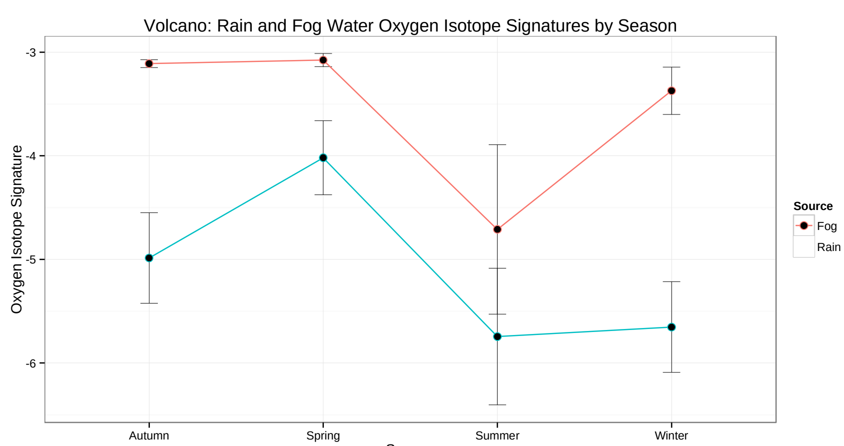


Figure 4. Comparison of Ponoholo (Kohala Mountain) site to other sites with similar rainfall and elevation. Potentially higher fog interception may enhance epiphyte growth at the Ponoholo site.

6.2. Stable Isotope Pilot Study

From January 15th, 2014 – July 22nd 2014, Volcano received 517mm rain and 42.21mm fog. Over the same period, Kohala received 1109.8mm rain and 2601.14mm fog. Fog made up 70.09% of the total precipitation at Kohala and 7.540% at Volcano. From January 15, 2014 – January 14, 2015, Kohala received 1811 mm rain and 4525.71 mm fog. Over this period the mean precipitation was 3168.36 mm and fog accounted for 71.42% of the total. At the Volcano Village site, seasonal analysis indicated that there was not a significant difference between the source values during Spring and Summer, but there were significant differences in Winter and Autumn (Figure 5B); at the Kohala site, there was no significant difference between these values during any season.





A. B.

Figure 5. Stable Isotope Study. A. Fog gauge in the foreground, rain gauge in the background at the Kohala site. B. Isotopic composition of rainwater vs. fog water during different seasons at the Volcano Village site.

7. Analysis and Findings

As we predicted across the precipitation gradient, sites with the highest frequencies of bryophytes, filmy ferns, epiphytes, hemi-epiphytes and canopy macro epiphytes were those on the wetter end of the gradient. In addition, epiphyte richness and incidence of epiphytes were also highest on the wet end of the gradient. The site receiving 6390 mm rainfall/year had the highest frequencies of bryophytes, filmy ferns, epiphytes, hemi-epiphytes, canopy macro epiphytes, in addition to higher epiphyte richness and epiphyte incidences. This underscores the fact that moisture is the most powerful environmental determinant of epiphyte distribution. Comparatively low values at Niaulani (located within a residential area) and Kane Nui o Hamo (located within a matrix of barren lava flows) suggest that forest edge effects increase light and decrease moisture for epiphytes in smaller tracts of forest. As we expected, similarity between sites was generally low across the elevation gradient, reflecting a shift in species composition with increasing elevation. Sites at the higher end of the elevation gradient had lower frequencies of hemi-epiphytes and canopy macro epiphytes, as well as lower epiphyte richness. There was a general leveling off of these patterns near the top of the elevation gradient. Although the high elevation site is within the range of orographic trade wind driven moisture, it is possible that the trade wind inversion is occasionally depressed to the 1700m elevation at Hakalau as noted by its low cloud frequency compared to other sites. Overall, it is evident from results of this investigation that frequencies of bryophytes, filmy ferns, epiphytes, hemi-epiphytes, canopy macro epiphytes in addition to epiphyte richness and epiphyte incidences in Hawaii are closely tied to overall moisture availability. However, epiphyte richness and epiphyte incidences were also high at Ponoholo as compared to all other sites. These results clearly indicate that rainfall alone may not be as important for epiphyte abundance and composition as are other factors, including fog.

As expected, results from the stable isotope pilot study indicate very different precipitation patterns in Volcano and Kohala. Results suggest that the major contributor of precipitation in Kohala is fog, or horizontally moving moisture, whereas the opposite is true for Volcano. Whereas Volcano showed clear differences in isotopic composition during autumn and winter seasons, there was little difference between rain water and fog water at Kohala.

8. Conclusions and Recommendations

This study underscores the close relationship between climate and epiphytic growth patterns. Even where vegetation is broadly similar across a range of climates (in this case, closed-canopy Ohia forest), epiphyte communities vary dramatically, representing a fine-tuned indicator of climatic conditions. Nonetheless, since this study standardized sites to include closed canopy forest, additional questions could be addressed by examining epiphytic communities with varying forest structure. Moreover, anecdotal observations suggest that at the community level, most epiphytic growth occurs on large trees and those with complex branching and ample horizontal surfaces ideal for growth. A within-community comparison of microsites would better characterize the ideal conditions for epiphytic growth. The prevalence of epiphytes at the Kohala site, points to the potential importance of fog deposition, not only to epiphyte communities, but to vegetation and watersheds as well. Because the major input of moisture at Kohala was horizontal moisture (much of it presumably fog), this suggests that the Hawaii Rainfall Atlas could obtain more precise measurements of precipitation by adding a series of fog stations, to collect data on other types of precipitation that are important in Hawaii. Fog incidence appears to be somewhat independent of rainfall, and yet may change in the future with potentially dramatic impacts to epiphyte communities. However, at present, predicted future climate scenarios focus on changes to rainfall and temperature. However our findings underscore the need for future climate scenarios to consider changes to cloud and fog patterns independently from precipitation. Isotope composition is a marker for vapor source and condensation history, so precipitation isotope ratios do not identify a droplet size, but rather a process (orographic versus synoptic-scale). Understanding how these patterns might change is a critical question for future research. Results also suggest that Volcano is a better site for tracing fog input to vegetation. In order to determine what areas receive the most fog, and where it is the most important requires measuring and quantifying fog, differentiating fog from rain, and then tracing physiological differences in uptake of water sources through vegetation uptake across the gradient. Our study supports the idea that stable isotopes can help identify different water sources (rain vs. fog) in uptake by epiphyte species.

9. Management Applications and Products

Our results demonstrate the considerable variation in epiphyte communities across the island of Hawaii. The fine scale relationship with climate and suggests that careful, long-term monitoring of epiphyte communities may help to identify climate impacts ahead of those to broad-scale woody vegetation. While much of the variation in epiphyte communities is due to climate, other factors may influence the frequency and diversity of epiphytes. For example, two sites exhibited comparatively low frequency and diversity of epiphytes due to more fragmented forest structure. One of these (Kane Nui o Hamo) was due to natural fragmentation by recent lava flows, and may also have been influenced by volcanic gas emissions from the nearby Puu Oo vent. The other (Niaulani) however is an old-growth forest stand surrounded by residential areas, pasture, and other types of disturbance. The possibility that the epiphyte community in this small patch of forest appears to have been influenced by surrounding land use suggests that forest management for epiphytes may require a larger scale than previously thought. Restored or replanted forests may not support diverse epiphyte communities until contiguous areas of canopy develop. This also underscores the need for protecting larger areas with intact, old growth forest canopy.

10. Outreach

We have engaged in outreach in several venues as the project has advanced. Two conference presentations (see below) represented the results of the project to both Hawaii-based and international audiences. As our results became clear, we met with vegetation management staff at Hawaii Volcanoes National Park to discuss key management applications to the research. We also received a grant for $2,000, funded by University of Hawaii Diversity and Equity Initiative. Partners included: PIPES (Pacific Internships Program for Exploring Science) at UH Hilo and Pahoa High School. The program connected underrepresented students from Puna, HI – the poorest, least educated and fastest growing district in the state - to the University and higher education through science. The curriculum included a fieldtrip to one of our forested epiphyte study sites (near the school) and a tour of the UH Hilo campus, facilitating a novel learning environment. We also created a Hawaii Climate Change Challenge board game. Hard copies of this game were used in class visits and distributed to teachers and other programs for further use. This learning tool was developed to reach a variety of age levels (12 and up) to teach about the impacts of climate change in Hawaii, as well as personal actions that help mitigate climate change.

We also provided work experience for six student workers/interns during the course of each study, partially thanks to additional funding through the George Melendez Wright Foundation and the NSF-sponsored REU and PIPES programs at UH Hilo. These provided key experiences for university students, some of whom have been employed in science and conservation upon graduation.

10.1. Presentations

Kettwich, S.K.A., and J.P. Price. (in prep) Epiphytes as a bioindicator of climate in the Hawaiian Islands. (intended publication venue: *Biotropica*).

10.2. Presentations

Kettwich, S.K.A., and J.P. Price. Epiphytes as a bioindicator of climate in the Hawaiian Islands. PICSC / PICCC Science Symposium. Honolulu, HI, USA. February 26-27, 2015.

Kettwich, S.K.A., and J.P. Price. Epiphytes as an indicator of climate change in the Hawaiian Islands. American Geophysical Union Annual Conference, San Francisco, CA, USA. December, 2013.

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