Final Report:

Lana`i Fog Drip Study

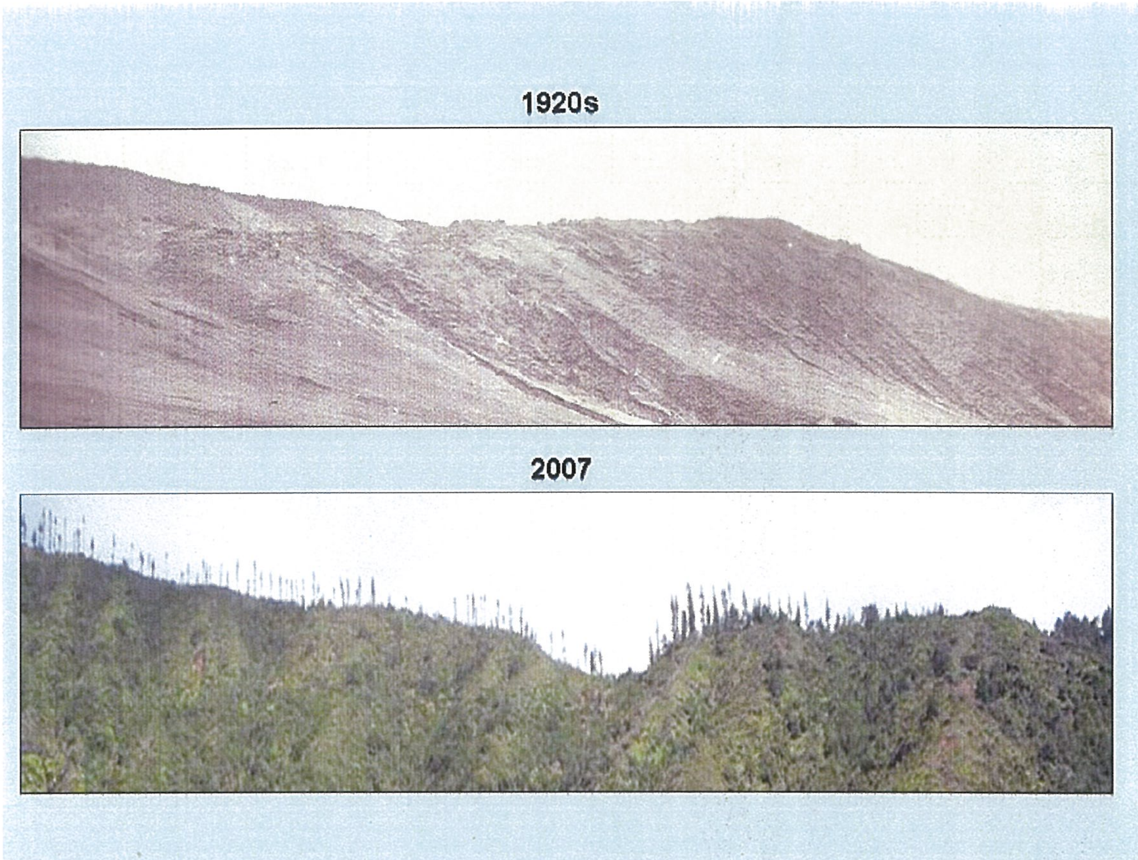

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Exhibit 41B

Executive summary

The present Lana`i fog drip study was initiated in September 2006 to instrument the Lāna'i mauka-watershed (the summit ridge associated with the "Munro-trail") and monitor the contribution of direct cloud-water interception ("fog drip") by planted, mature Cook pine trees (***Araucaria columnaris***). This study focused specifically on the windward exposed, watershed area at elevations above 2,100 ft (650 m), within the generally perceived "fog zone" on Lāna'i. This represents a total area of approximately 2,922 acres or 4.56 mi^2 (11.81 km^2). The present study was undertaken in an attempt to replicate, verify, and spatially expand results of the seminal fog drip study undertaken at Lāna'ihale in the 1950s, by scientists associated with the Hawaii Pineapple Research Institute.

Multiple open-site meteorological stations (with adjacent Cook pine throughfall monitoring) were sited at locations along an altitudinal gradient in the Lāna`ihale watershed (Munro Trail) and monitored for a 20 month period (January 2007- August 2008).

The current study has documented a substantial cloud-water (fog drip) resource in the upper Lāna`ihale watershed above 2,500 ft. In the summit region the measured fog drip from mature Cook pine can reach several hundred inches per year at well exposed sites. These values far exceed earlier measurements associated with the PRI study during the 1950s. Differences can be attributed to the fact that Cook pines are now much larger, and the cloud-water resource has been found to increase exponentially at higher elevations above the original PRI study site at 2,750 ft. We are able to successfully model Cook pine throughfall using open-site fog gauge measurements. This offers the potential for comparatively inexpensive and simple long term monitoring of the cloud-water resource and fog drip recharge in the Lāna`ihale watershed without future, direct and cumbersome measurement of actual throughfall.

A simple water-balance model for individual mature Cook pines in the upper watershed indicated as much as 300+ in. of canopy cloud-water interception and resultant fog drip contribution to throughfall, compared to only about 16 in. of throughfall contribution from direct rainfall. Further studies would be required to evaluate the "cumulative" fog drip impact of the substantial Cook pine plantings in areas of the watershed where fog exposure may be somewhat less than the "ideal" summit ridge sites monitored as part of this project. However, the potential appears greater than estimates based on the earlier 1950s data.

For the watershed area above 2,500 ft, based on the exposure, aspect and elevation of our monitored Cook Pine, we developed a spatial suitability model depicting priority areas for future Cook Pine reforestation, where the potential for additional fog drip augmentation (to ground water recharge) would be maximized..

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1. Introduction

Pursuant to a contract entered into between Castle & Cooke and Pacific Environmental Planning in April 2006, work was initiated to instrument the Lānaʻi mauka-watershed (the summit ridge associated with the "Munro-trail") and monitor the contribution of direct cloud-water interception ("fog drip") by planted, mature Cook pine trees (***Araucaria columnaris***). This study focused specifically on the windward exposed, watershed area at elevations above 2,100 ft (650 m)[1], within the generally perceived "fog zone" on Lānaʻi. This represents a total area of approximately 2,922 acres or 4.56 mi^2 (11.81 km^2). The present study was undertaken in an attempt to replicate, verify, and spatially expand results of the seminal fog drip study undertaken at Lānaʻihale in the 1950s, by scientists associated with the Hawaii Pineapple Research Institute (Ekern 1964.)

2. Background

Lānaʻi Island, lying in the leeward "rain shadow" of West Maui (and thus blocked from direct exposure to moisture laden NE trade winds), receives relatively modest rainfall; averaging about 20 in/year (500 mm) over the entire island (**Figure 1**). Even the highest elevations of the island (Lānaʻihale at 3,366 ft /1,025 m) receive only about 40 inches (1000 mm) of rainfall per year. In contrast, on the windward slopes of nearby West Maui, at similar and higher elevations directly exposed to the prevailing trade winds, annual rainfall averages 150-350 inches/year (3,800 - 9,000 mm).

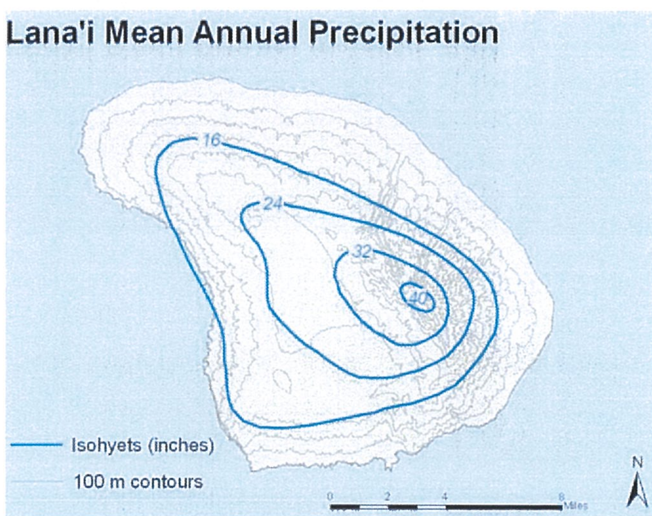


Figure 1. Lānaʻi rainfall.

[1] Many of the meteorological sensors, analytical tools, and scientific references employed in this study utilize metric system measurements. In most of the tables, diagrams, and text references for this report we have typically included both English and metric units.

Over the period of 1955-58, the Pineapple Research Institute (PRI) in Hawai`i undertook one of the first, and still widely cited quantitative studies of direct cloud-water interception ("fog drip") by trees on the trade wind exposed mountain ridge of Lāna'i. This research was in response to the early 20th Century qualitative observations by the island's land manager, George Munro, who noted the incessant "dripping" of water from a tall, frequently cloud-shrouded Norfolk Island pine tree (***Araucaria heterophylla***) growing near his home. Munro went on to have thousands of closely related Cook Pines (***Araucaria columnaris***) planted on the largely deforested, summit ridge (elevation 2,100-3,366 ft /650-1025 m) of this semi-arid island. This effort was sustained by the hope that cloud-water interception could supplement the groundwater recharge of high-level aquifers that supported irrigation of a vast pineapple plantation on the island.

The multi-year, PRI study of Cook pine cloud-water interception focused on a single, windward exposed tree at an elevation of 2,750 ft (838 m) on the summit ridge (**Figure 2**). This study concluded that fog drip under the Cook pine canopy supplemented annual rainfall (averaging 50 in/yr or 1,270 mm) by about 30 in (762 mm), even after the canopy throughfall was "corrected" for a presumed substantial non-vertical windblown rainfall component intercepted by the vertical silhouette of the tree. In the original study Ekern (1964) acknowledged, but failed to provide a quantitative estimate for tree canopy "interception loss" in his water-yield calculations for the Cook pine. Interception loss is defined as falling precipitation that wets leaves and stems (and is thus "stored" in the tree canopy), and later evaporates back to the atmosphere without reaching the ground. Ekern further assumed that a major component of the difference between his annual open-site rainfall measurement (50 in/yr or 1,270 mm) and the Cook pine throughfall (130 in/yr or 3,300mm) could be attributed to windblown rainfall (not cloud or fog water) collected by the vertical silhouette of the tree. This rain would otherwise have fallen to the ground on the leeward, "rain shadow" side of the tree. He estimated this non-vertical rain catch component to be equivalent to the vertical rainfall (i.e. 50 in/yr), and derived his fog drip gain by subtraction as:

130 in throughfall – 50 in vertical rainfall – 50 in non-vertical rainfall
= 30 in. fog drip addition (60% of rainfall)

In order to achieve such a high non-vertical rainfall component Ekern must have assumed that the average (by volume) windblown rainfall drop inclination angle was at least 45°. Ekern's estimate of non-vertical rain catch, absent any companion wind speed, rainfall intensity, or raindrop size measurements, must be considered highly speculative; perhaps adopted to insure a scientifically conservative "first-approximation" of this newly quantified fog drip phenomenon. The PRI study also employed various mechanical wire screen and "harp" fog collectors to evaluate the fog catch efficiency of various artificial materials.

Figure 2. The PRI Cook pine study site, Lāna'ihale summit ridge (2,750 ft)

In the present study supported by detailed, hourly (event-scale) wind speed, and precipitation intensity data, we conclude that non-vertical rainfall represents only about a 30% gain for mature Cook pine on the Lāna`ihale ridge. This was derived by employing new, single-tree models for interception loss (Xiao, 2000) and established rain drop size/ inclination angles in Hawai`i (Giambelluca, et al. 2009). This approach yields an estimate of 34° for average raindrop inclination angle in the Lāna`ihale environment (based on an average wind speed during precipitation events of 5.2 mph, or 2.3 m/s); substantially below Ekern's 45° figure. We further applied a conservative canopy interception loss factor (15%), so that the "net" non-vertical rainfall gain was estimated at 15% of rainfall (Rainfall +30% -15%= 15%). This represents a more realistic approximation for a Cook pine rather than Ekern's 100% estimate (as evaluated above, Ekern would have had to invoke a very high estimated raindrop inclination angle to achieve his 100% non-vertical rainfall gain for the tree. If our new correction (15%) is applied to the original 1950s results, we derive a significantly greater fog drip component (130 – 50 – 7.5[15% of 50]) = to 72.5 in/yr (1,840 mm/yr). This translates to fog drip equal to 145% of open-site rainfall (50 in), compare with Ekern's original estimate (30/50) of fog drip equal to 60% of rainfall for a single Cook pine.

The present, spatially expanded resurvey of cloud-water interception across the entire Lāna'i summit ridge was undertaken utilizing automated weather stations, paired with under-canopy throughfall, stemflow, and soil moisture monitoring at nearby mature Cook pines (70-80 ft tall or 21-24 m). We also collected some limited comparative data on the fog drip contribution for other spatially extensive forest vegetation types in the upper watershed (i.e. *Guava* and *Eucalyptus*). Data were collected continuously and averaged at hourly intervals; a time-scale allowing for detailed analysis of individual precipitation events and associated meteorological and water-balance conditions. Such instrumentation was unavailable during the earlier PRI fog drip study. Our results, for selected ridge sites, indicate Cook pine throughfall rates more than an order-of-magnitude greater than found earlier. These differences may be largely attributed to the fact that the

30 ft (9 m) tall Cook pines of the 1950s are now towering to 70-80 ft (21-24 m), and additional new data indicating atmospheric conditions favoring cloud-water interception increase dramatically at higher ridge elevation (2900-3366 ft / 883-1,026 m); well above the location of the original PRI study site at 2,750 ft (838 m).

3. Methodology

A network of meteorological/hydrological monitoring stations was installed within the Lāna`ihale watershed (September - December, 2006), along altitudinal and windward-slope aspect gradients to provide comprehensive sampling of the magnitude and spatial variation in potential cloud-water input. **Figure 3** illustrates the locations of the seven primary meteorological-hydrological monitoring stations employed in this study. Six of these stations were located at elevations above 2,100 ft (650 m), within the generally perceived "fog zone" on Lāna'i (red line in **Figure 3**). This 2,100ft (650 m) contour encloses approximately 4,388 acres (1,774 ha) of mauka watershed. It should be noted that for the purposes of this study, we focused only on that portion (2,922 acres or 1,182 ha) of the summit and windward watershed directly exposed to condensing orographic cloud. A seventh station was positioned on the windward slope below the fog zone (at 1,660 ft or 507 m), to serve as a control site for evaluating mountain water-balance relations in areas where fog is either absent or of minor significance. The altitudinal position of each of the seven stations in relation to the PRI site of the 1950s is illustrated in **Figure 4**. No station was installed at the exact location of the earlier PRI study site because during the intervening five decades, this initially "exposed" site had become heavily overgrown by *Guava*, *Eucalyptus*, and other alien tree species. Today, only the emergent tops of some of the remaining mature Cook pines in the area reach above this dense, surrounding vegetation. For this site the remaining Cook pines have only reduced exposure to low clouds passing over the ridge. We did "bracket" (with respect to elevation) the original PRI site with slightly lower and higher elevation sampling stations (station #4 at 3022 ft. and station #5 at 2510 ft; see **Figures 3 & 4**) that better reproduced the exposed ridge conditions of the 1950s. Initially we intended to install one or more stations on windward lateral ridges descending from the summit ridge in order to provide some redundancy in the altitudinal gradient sampling along the summit ridge. However, this would have involved cutting/maintaining ridgeline trails through the dense *Uluhe* (*Dicranopteris linearis*) scrubland; an activity considered incompatible with ongoing habitat conservation efforts for the federally endangered Hawaiian Petrel (*`Ua`u =Petrodromus sandwichensis*) that nests in this mountain area. Such trails potentially open foraging avenues, allowing feral cats to predate on the young of such ground-nesting (burrow) seabirds. Meteorological station guy-wires were also draped with white tape to increase visibility and reduce the risk of bird collisions (see **Figure 5**). Differences in research design between the current study and the PRI study of the 1950s are shown in **Table 1**.

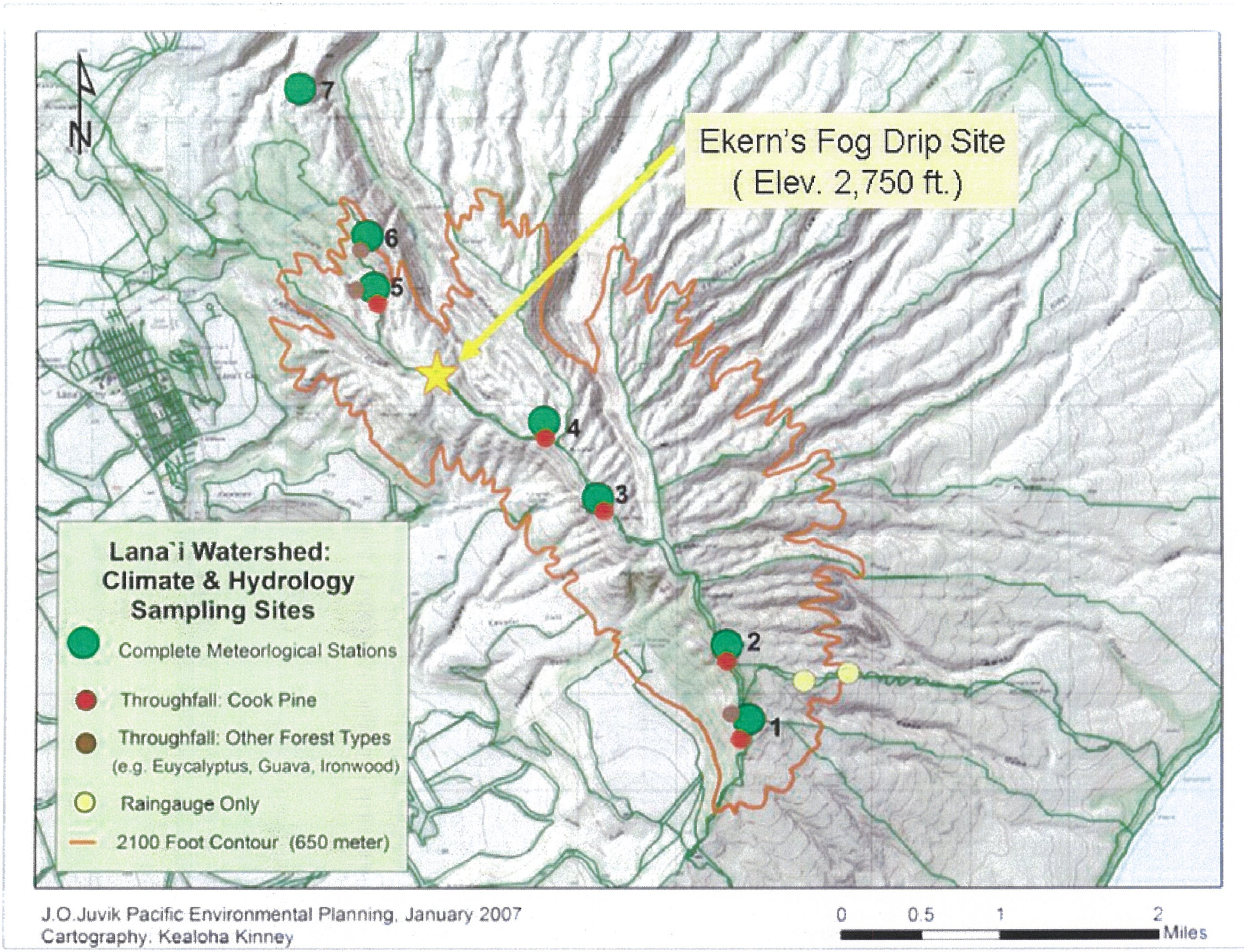


Figure 3. Meteorological and fog drip monitoring network, Lāna'i summit Ridge

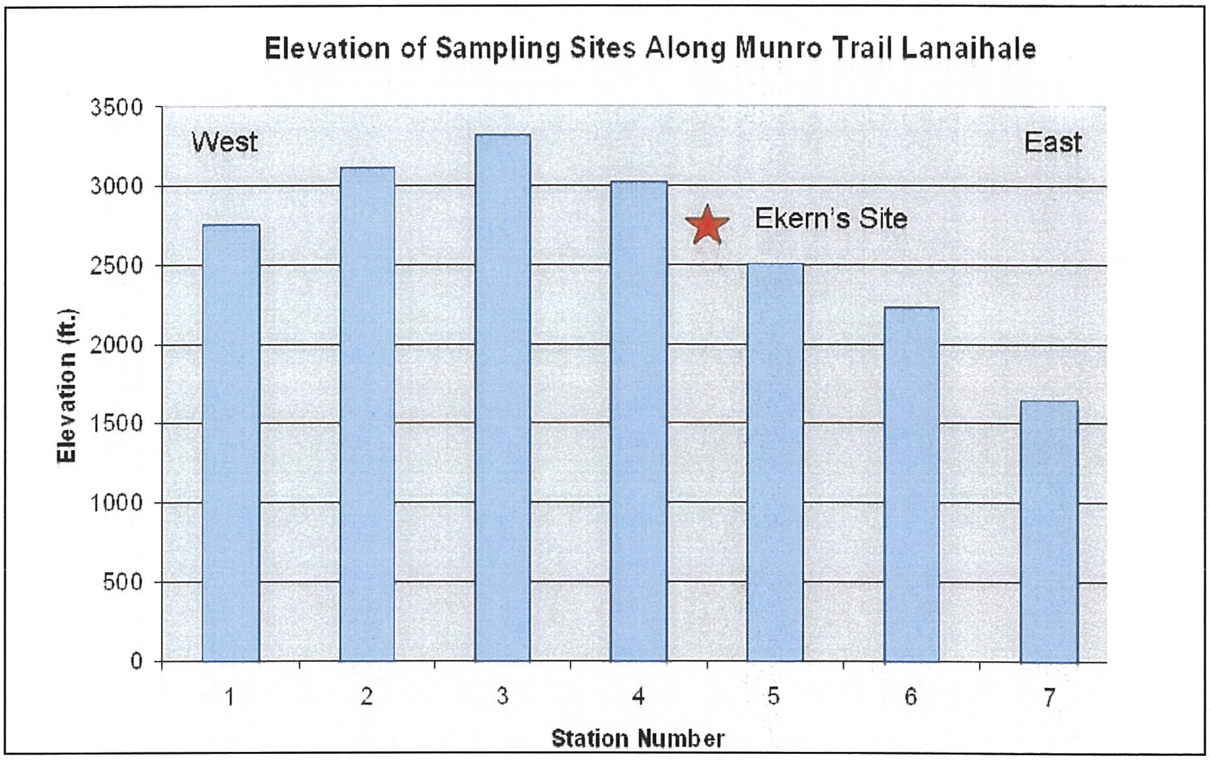


Figure 4. Elevation of sampling sites along Lāna'i summit ridge.

Table 1. Experimental design differences between PRI (1950s) and current study

VARIABLES	EKERN (1956 - 58)	CURRENT (2006 - 2008)
Sample Sites	1	7
Sample Elevations	2,750 ft.	1,650 – 3,350 ft.
Cook Pine Sample Size	1	5 (Including additional short-term measurements for *Eucalyptus, & Guava*)
Rain Gauges	8 (Manual)	100 – 110 (Recording)
Cook Pine Height	30 ft.	70 – 80 ft.
Cook Pine Trunk Diameter	10 – 12in	25 – 31in

A. Open-site meteorological stations

At each sampling site (**Figure 3**) we deployed Hobo Weather Stations (Onset Computer Corp.) configured to log and store meteorological data at hourly intervals. Open-site meteorological stations were positioned along the summit ridge (Munro Trail) in areas with unobstructed windward exposure to the North and North-East trade winds.

Each station included two, 10ft (3 m) masts (**Figure 5**); one supporting the standard meteorological instruments (wind speed and direction, solar radiation, air temperature & humidity). On the other mast, a mechanical fog gauge (**Figure 6**) similar to that utilized in the original 1950s PRI study was deployed at a height of 10 ft (3 m). The mechanical fog gauge is composed of a cylindrical, louvered aluminum screen collector, on which horizontally moving cloud droplets impact and drip down via plastic tubing into a covered rain gauge (Juvik and Ekern 1978, Juvik and Nullet 1995a). The utility of the fog gauge is that it presents a standard collection surface that can be used at different locations to accurately characterize comparative cloud-water interception. The screen fog gauge collector has a vertical surface area equal to 2.83 times the area of the standard rain gauge. The fog gauge output is divided by 2.83 to convert fog to a "unit vertical catch," equivalent to the collection area of the standard rain gauge. A stainless-steel "hat" on the fog gauge covers the collecting screen to exclude direct rainfall from entering the gauge. Under extreme high wind conditions, some non-vertical rainfall will occasionally enter the fog gauge. However, with simultaneous wind speed and rain gauge measurements available, corrections can be made to the fog gauge output. An open-site rain gauge was also positioned near the station. Soil moisture at -4 in (-10 cm) depth was monitored under adjacent low statue shrub or herbaceous cover in close proximity to the station. Stations were visited for data recovery and sensors servicing approximately every one-two weeks during the study. The temperature, humidity, wind speed, and solar radiation data were used in the calculation of potential evapotranspiration estimates for the watershed.

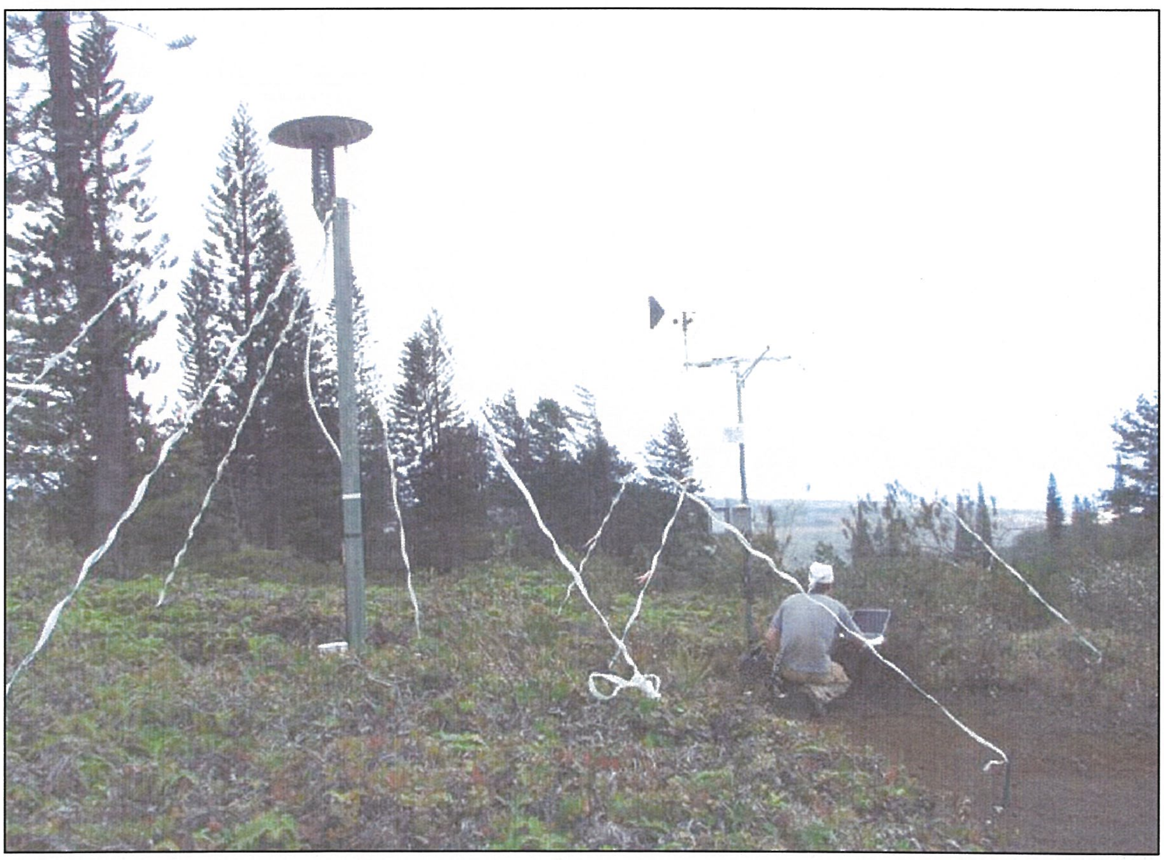


Figure 5. Open-site meteorological station, fog gauge at left.

Figure 6. Standard open-site fog gauge with collection screen (black) and rain shield "hat".

B. Cook pine throughfall and stemflow monitoring

At each sampling site, within 150 ft (45 m) distance from the meteorological station, a mature Cook pine was selected for measurement of canopy throughfall. The methodology was to select similar sized, mature trees at each different ridge site to insure a fair comparison of how nearly identical Cook pine performed at different elevations across the summit ridge watershed. Criteria for tree selection included:

1) mature trees (trunk diameter at breast height 25-31in or 60 cm – 80 cm; tree height 70-80 ft or 21-24 m; vertically projected tree canopy area 260-280 ft^2 or $\pm$ 25 m^2)
2) trees with direct and unobstructed down-slope "view" to windward over the entire vertical silhouette of the tree
3) trees with full, undamaged canopies (no deformed or broken trunks or substantial loss of upper branches)

Under each Cook pine an array of rain gauges was randomly placed beneath the center of the circular canopy (do to prevailing wind conditions, summit ridge trees typically inclined slightly from vertical so that the center was usually displaced 4-6 ft (1.2-1.8m) in the lee (south) of the tree trunk.

The earlier PRI study deployed a total of 8 randomly positioned, manual rain gauges beneath the Cook pine (combined orifice collection area of the 8 in diameter rain gauges was 402 in^2 or 2.8 ft^2 (0.26 m^2) which represented less that 1% (i.e. 0.93%) of the total tree canopy area (300 ft^2 or 27.9 m^2). The question of whether these sampling results were reasonably representative of true throughfall (given the typical spatial heterogeneity associated with throughfall) was resolved during a portion of the PRI study when a full sheet metal catchment was installed under the entire tree canopy, allowing for a 100% throughfall catch (**Figure 7**). These results were comparable (within 4%) with those derived from the smaller rain gauge sampling area. This is not surprising given that the symmetrical and uniform architecture of Cook pine (as compared with other more randomly branching trees) argues for a less heterogeneous spatial pattern of canopy throughfall. This confirms that a relatively small, random sample is adequate to characterize the entire canopy catch. In the present study we structured throughfall sampling to exceed 1% of the total canopy area of each tree in the study. A total of four 6 in (15.2 cm) diameter recording rain gauges were randomly positioned under canopy the (**Figure 8**). For three of the gauges, water collection was expanded by attaching two metal troughs (each 35 in long) that increase the rain gauge effective collection area and improve throughfall sampling by providing a water collecting "transect" under the canopy (Juvik and Nullet 1995b). The troughs increased the collection area of each of the three rain gauges by a factor of 4.91. A fourth, under canopy rain gauge remained unmodified. The total throughfall collection area of the 3 trough gauges (now equal to the effective catch of almost 15 individual, 6 in rain gauges) and the additional unmodified rain gauge totaled 3.09 ft^2 or 1.1% of average Cook pine canopy area 269 ft^2 (25 m^2), for the trees used in this study.

Figure 7. Full canopy sheet-metal catchment installed under Cook pine during 1950s PRI study.

Figure 8. Throughfall collectors under Cook pine, including "trough-gauges" and standard rain gauge (center extreme left). Stem-flow collector visible on tree at right.

In order to further randomize throughfall collection (i.e. reduce sampling error), the trough gauges were rotated in-place to 45°, 90 ° or 135 ° on a monthly basis to change the areas being sampled under the tree. The single, unmodified rain gauge was mounted on a firm platform with four designated (non-overlapping) position through which this rain gauge was also moved on a monthly basis. A statistical comparison of between-gauge variability (variance) under individual trees, supported the conclusion that our sampling density was sufficient to reasonably characterize canopy throughfall.

For some short-term monitoring of throughfall from other vegetation types, the sampling design was modified to reflect the differing canopy scales associated with ***Guava*** (**Figure 9**) and ***Eucalyptus*** forest cover (**Figure 10**).

Figure 9. Throughfall and stem-flow sampling under *Guava*.

Figure 10. Multiple rain gauge (n = 15) throughfall sampling under *Eucalyptus*

In addition to throughfall, another potential pathway for precipitation movement through a tree canopy involves stemflow, the movement of canopy water down the main trunk of a tree. In general, the architecture of Cook pine (drooping limbs that intersect with the main trunk at right angles and thus do not effectively channel intercepted water down the main trunk) does not generally promote significant transport of water from the tree canopy to the ground via stemflow. However, in order to fully document all water movement through the Cook pine canopy we sampled stemflow on all of our monitored Cook pines. At each cardinal azimuth (N, S, E, W) on the main trunk we installed 4 in (10cm) wide stem-flow collectors (notched under the bark) that fed to a common drainage tube linked to a covered automatic rain gauges (see **Figure 8**, at left) The combined sample width of the 4 collectors (4 x 4 in= 16 in or 40.6 cm) typically represent about a 16-20% sample of the entire tree trunk circumference which ranged from 78-97 in. (200-245cm). Throughout the study period, stemflow consistently totaled less than 1% of throughfall and this variable was consequently ignored as a significant component to throughfall in subsequent analysis. We also deployed multiple soil moisture sensors at a depth of 4in (10cm) under the monitored Cook pine canopies, for comparison with simultaneous measurements taken at adjacent open-sites.

4. General precipitation conditions on Lāna'i during the fog drip Study

One of the common difficulties in generalizing and extrapolating from short-term, field meteorological measurements in Hawai`i is consideration of how closely the sampling period measurements represented long term "average" conditions at a specific site. Many (particularly drier) areas in the Hawaiian Islands experience relatively high seasonal and inter-annual variability in precipitation, based on both local and larger scale synoptic conditions in the Pacific (e.g. annual number of winter frontal passages, multi-year oscillations in El Niño or La Niña conditions, etc.) For example during the 1955-58 PRI fog drip study, La Niña conditions prevailed, yielding annual rainfall totals on the summit ridge of Lāna'i of about 50 in/yr (1,270 mm) This rainfall was substantially above the long term average rainfall for the Lāna`ihale summit area (38.3in/yr or 974mm).

Meteorological station installation and initial data collection for the present study took place over the period September –November 2006 and the network became fully operational in December 2006. With the exception of some limited comparative data for December 2006, the effective data collection period for this study covered the 20 month period January 2007- through August 2008.

The Lāna'i City rain gauge (State # 672) has the longest and most complete rainfall record on the island. **Figure 11** presents both the long-term average monthly rainfall for Lāna'i City and the actual rainfall recorded during the twenty-month study period. Over these twenty-months Lāna'i City received only 43.7 inches (1,110mm) or 79.3% of the long term average (55.3 in) for this period. Overall conditions were actually much drier than the forgoing numbers suggest because 24.6 in (625 mm) or 56.2% of all the project period rainfall fell during the two months of November – December 2007. Further, during 15 of the 20 months rainfall was significantly below long-term monthly averages. The field meteorological monitoring for this study had initially been proposed to extend only one year (2007). However, the abnormally dry conditions that prevailed during the first ten months of 2007 (with the exception of March) necessitated extending the data collection period through August 2008 to gain potentially more representative precipitation conditions. The previous PRI study documented significantly greater relative importance of fog drip during low rainfall summer months. The summer (June-August) 2008 rainfall on Lāna'i proved to be much more representative of long term conditions than the exceptionally dry 2007 (see **Figure 11**).

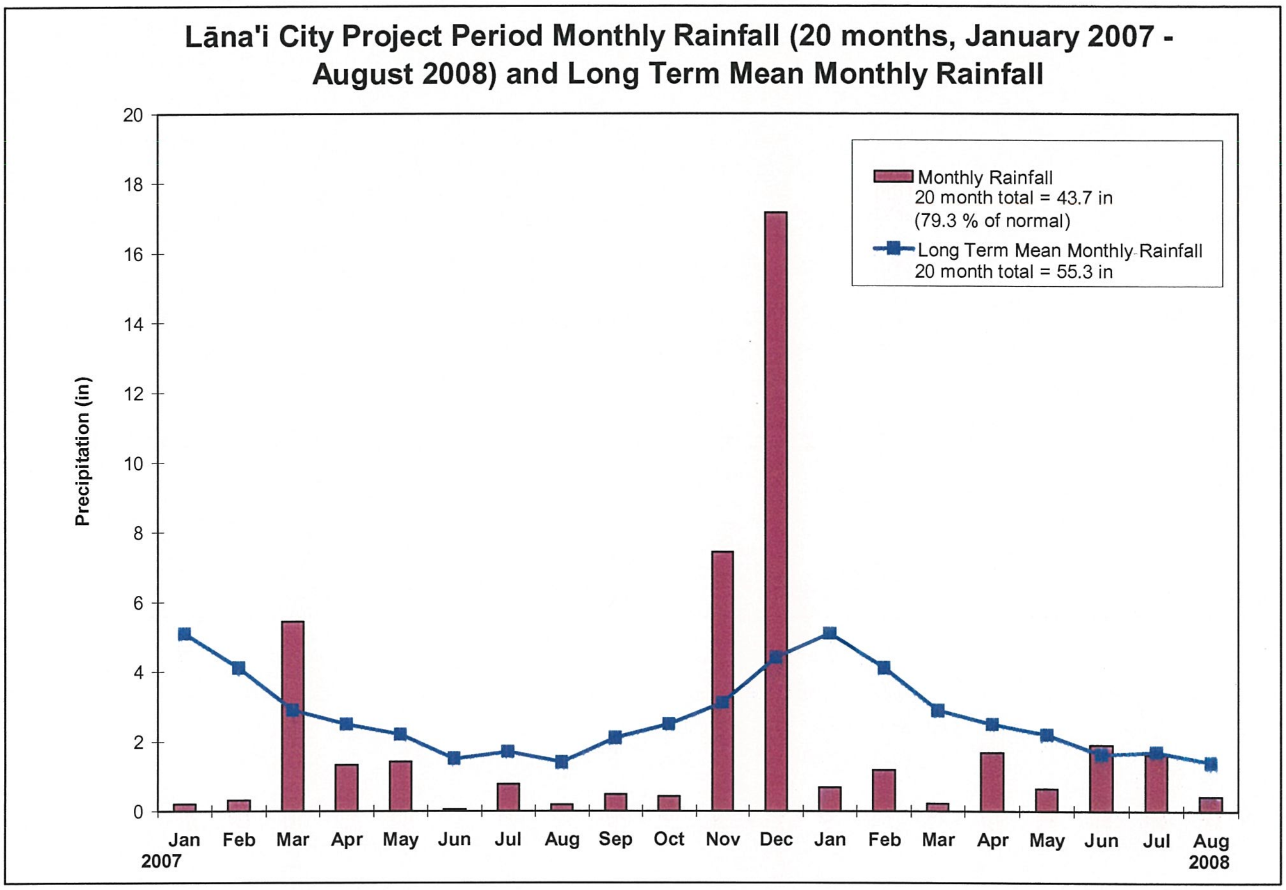


Figure 11. Lāna'i City rainfall during the project period.

The same Lāna'i City seasonal pattern of reduced summer rainfall also prevails in the islands mauka watershed. Long-term rainfall records (1963 – 2004) for the Lāna`ihale summit at 3,366 ft (1,025 m) annually averaged 38.3 in. (975 mm) with a distinct summer minimum (**Figure 12**). These summit rain gauge measurements were discontinued in 2004. Our various summit ridge rainfall measurements during the study period mimicked the Lāna'i City pattern of generally lower than normal monthly and aggregate rainfall totals.

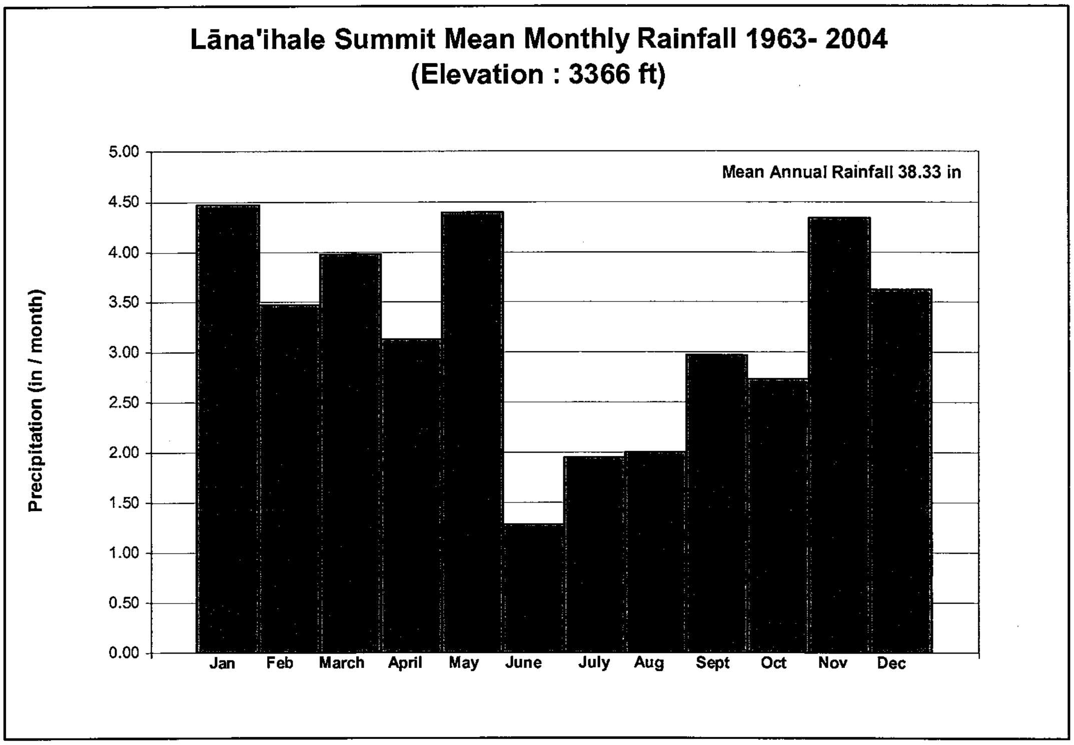


Figure 12. Long term average monthly rainfall at Lana`ihale summit.

5. Results and Discussion

A. Open-site rainfall and fog in the Lana`ihale watershed

The first objective of the study was to characterize the influence of elevation on open-site rainfall and fog (cloud-water) distribution across the mauka watershed, and further determine if fog input could be empirically modeled from simple rainfall measurements alone. For each of the mountain meteorological stations, **Figures 13 & 14** display the distribution of winter and summer totals for rain and fog over a combined 9-month period (months chosen because there was no missing data for any of the recording stations). For the sample periods presented it will be observed that both rainfall and fog values (**Tables 2 & 3**), for all stations, are higher during the normally wetter winter month. In both seasons the fog component increases dramatically at the higher elevation stations, and more so at those stations located on the humid western end of the transect (Stations #3, 4 and 5). Although absolute water catch amounts from the mechanical screen fog gauge are greater in winter, fog as a proportion of rainfall is consistently higher in summer. As an example, winter fog totals (**Figure 13**) for station #3 equaled 57.4 in or 425% of the 13.5 inches of rainfall recorded at this station. For the summer period (**Figure 14**) at the same station, the 39.6 in of recorded fog represented 671% of measured summer rainfall (5.9in). These results are consistent with the earlier PRI study (Ekern, 1964) that documented an increased relative fog contribution during lower rainfall summer periods.

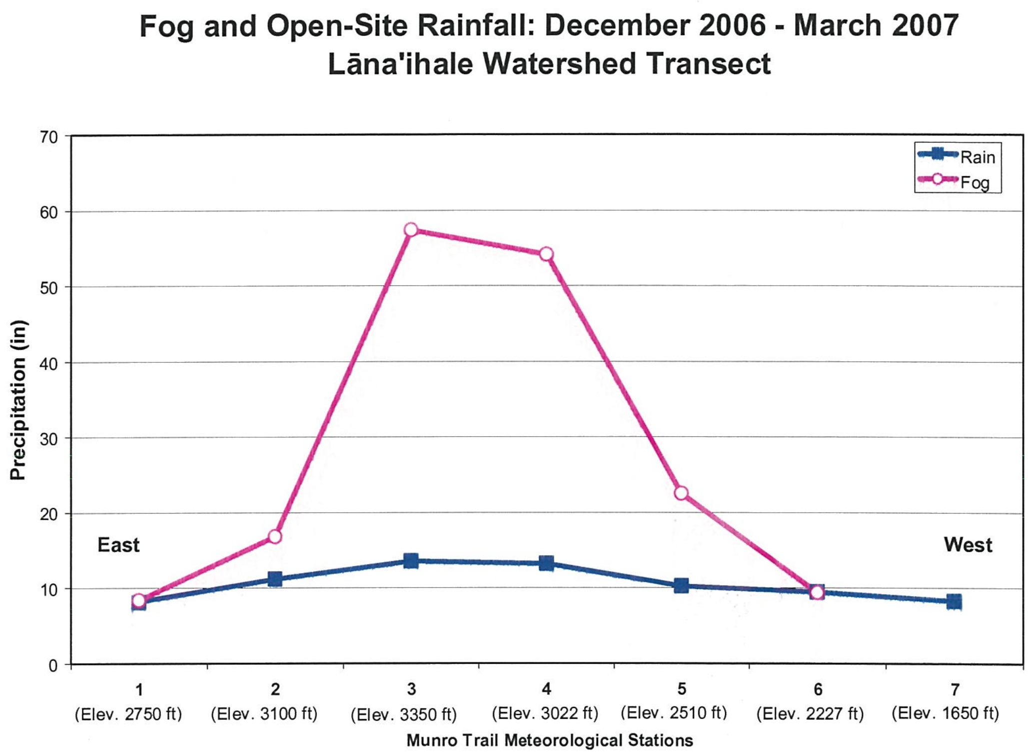


Figure 13. Winter rain and fog totals.

Table 2. Fog and open-site rainfall: December 2006 – March 2007 Lana`ihale watershed transect

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
Rain (in.)	8.1	11.1	13.5	13.2	10.2	9.4	8.2
Fog (in.)	8.3	16.8	57.4	54.1	22.5	9.4	-----
Fog / Rain	102.8	150.8	424.8	410.5	219.9	99.9	-----

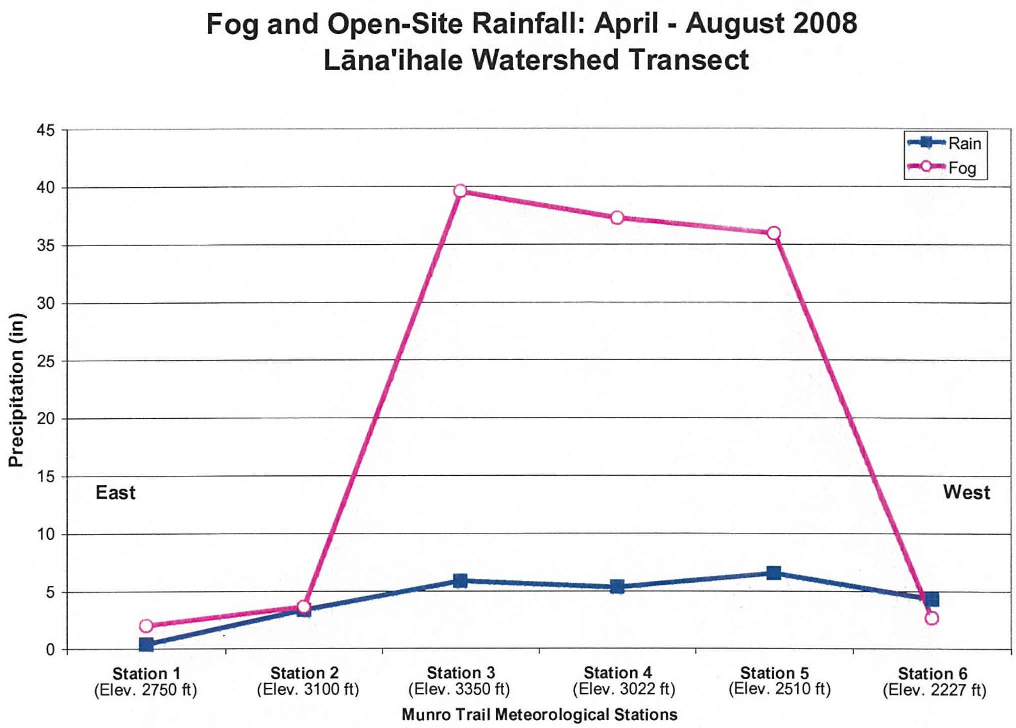


Figure 14. Summer rain and fog totals.

Table 3. Fog and open-site rainfall: April – August 2008
Lana`ihale watershed transect

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Rain (in.)	0.4	3.4	5.9	5.3	6.6	4.3
Fog (in.)	2.0	3.6	39.6	37.3	35.9	2.7
Fog / Rain (%)	516.3	108.6	675.9	697.8	547.4	62.9

Figure 15 illustrates fog and rainfall for the combined 9-month period. The precipitation totals for each station are presented in **Table 4,** along with the fog/rain ratio (%) for each station. Although fog is dramatically higher than rainfall at higher elevation and to the west along the sampling transect, both curves illustrate a common spatial pattern of relative increase and decrease. In **Figure 16**, station rainfall is plotted against the logarithm of fog (data from **Table 1**) to provide a simple, yet robust (high statistical significance; $p < 0.01$) empirical regression model for estimating fog catch from rainfall data. Although substantially different in magnitude, it is not unexpected that fog and rain (which represent different drop sizes along a precipitation continuum) should be reasonably correlated since the atmospheric/orographic conditions favoring precipitation formation are essentially the same. The utility of this model will come to bear in a subsequent section of this report, where an effort is made to extrapolate our limited sampling period results to estimate long term "average" fog and Cook pine throughfall conditions across the watershed.

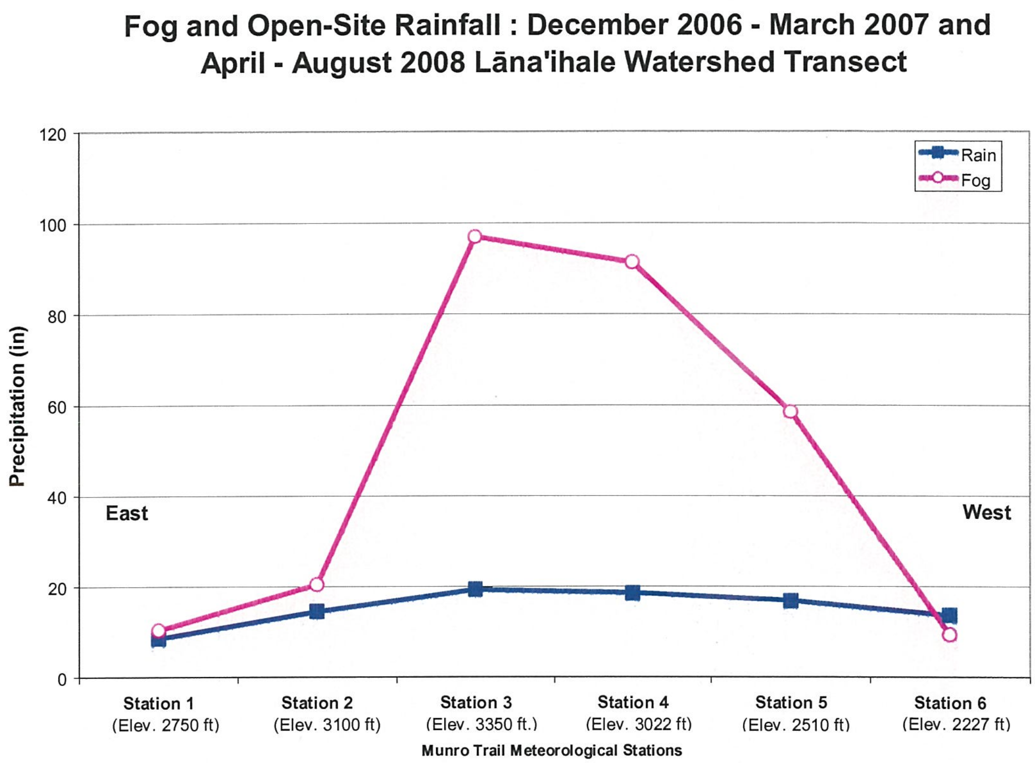


Figure 15. Combined winter-summer rain and fog totals

Table 4. Fog and open-site rainfall: December 2006 - March 2007 and April - August 2008 Lāna'ihale watershed transect

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Rain (in.)	8.5	14.5	19.4	18.5	16.8	13.7
Fog (in.) **[Log Fog]**	10.3 [1.01]	20.4 [1.31]	96.9 [1.98]	91.4 [1.96]	58.4 [1.76]	12.1 [1.08]
Fog / Rain (%)	121.8	141.0	500.8	493.4	347.8	88.3

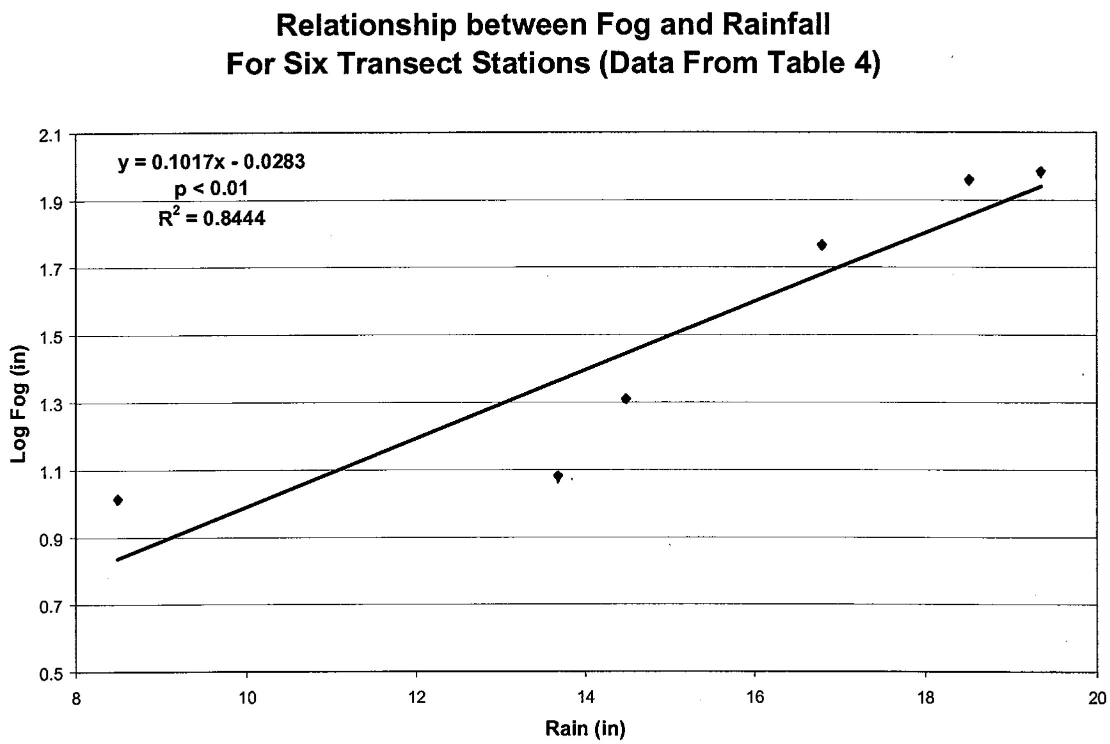


Figure 16. Relationship between 9-month totals from rainfall and fog (log) for transect stations #1-6.

B. Cook Pine throughfall in the Lānaʻihale watershed

With a very large data set of automated hourly measurements of Cook Pine throughfall and both open-site rain and fog we were able to analyze more than a thousand individual precipitation events at multiple stations positioned along the summit ridge transect. One goal of this analysis was to determine if a predictable relationship could be uncovered between comparatively easy to measure open-site parameters (rain and fog) and Cook pine throughfall. **Figure 17** (**Table 5**) illustrates the relationship between cumulative rainfall and Cook pine interception for a 5-month sample period in 2008. This pattern is generally congruent with rainfall/fog relationships established for the transect (see **Figures 13 - 15**). It will be noted (**Table 5**) that under very low rainfall conditions (e.g. Station#1), the throughfall/rain ratios (%) can become astronomical as fog drip dominates the precipitation contribution. Ekern (1964) found Cook pine interception to reach 13-times measured open-site rainfall during extremely dry periods, adding at least some valuable ground water recharge during periods when recharge from rainfall could be expected to be absent or minimal. For the sample period provided (**Figure 17**) it can be seen from **Table 5** that although total period Cook Pine throughfall at Station #1 was only 8.5 in compared to 41.2 in. at Station #4, the 8.5 in equaled more than 21-times rainfall at Station #1. When a large number of precipitation and throughfall event were aggregated, the ratios of throughfall to rainfall and fog converged on relatively stable values for both summer and winter seasons at each station. In **Figures 18-29**, winter, summer and combined rain, fog and throughfall values are shown, respectively for transect stations #1,2,4, and 5[2]. It will be noted that for combined winter-summer data from all stations (**Figures 20, 23, 26**, and **29**) that total Cook pine throughfall ranged from 4.45-times rainfall at Station #1 to 12.3- times rainfall at Station #4. These values all far exceed throughfall/rain ratios recorded during the earlier PRI study (see Page 4), and are doubtless, in part, due to both the larger trees used in the current study and the fact that most of our sites (#1-4) were at higher, more fog-favorable elevations on the summit ridge. As an example of the absolute magnitude of Cook pine throughfall in the summit region (**Figure 26**), over an almost 300 day period, Station #4 recorded 193.8 in of Cook pine throughfall while adjacent open-site rainfall equaled only 15.8 in.

Because of the inherent difficulty and complexity of measuring heterogeneous under-canopy throughfall, we utilized the large precipitation-event data set to evaluate empirical models for estimating throughfall from open-site measurements. We will use one extreme case as an example. **Table 6** illustrates precipitation relationships at Station #2 for the exceptionally dry month of October 2007. Measurable rainfall of 0.13 in (3.3 mm) occurred on only three days during the month. The companion open-site fog gauge recorded precipitation on 23 days totaling 4.13in (31.8 -times rainfall), while Cook pine throughfall was recorded on 21 days yielding 11.7 in or 89.9 times rainfall. It is obvious that for this period daily open-site rainfall would be a very poor predictor of nearby Cook pine throughfall as in illustrated in the regression plot in **Figure 30.** In **Figure 31** the open-site fog gauge values are plotted against throughfall for the same period and a very robust (high statistical significance) relationship is apparent. If we examine similar precipitation relationships for a larger data set during more "average" rainfall periods, similar conclusions can be drawn. **Figure 32** illustrate the relationship between open-site rainfall and fog catch for a sample period at Station #4. The results indicate no significant relationship. Although the condensation processes that produce both fog and rainfall are similar, at the scale of individual events there is little correspondence between those events that are predominantly rain or fog. As a consequence, since fog is typically the more frequent event, we would likewise expect a poor correlation between event rainfall and adjacent Cook pine throughfall as is illustrated in **Figure 33** (duplicating the statistical weakness of the relationship shown in **Figure 30**). In **Figure 34** open-site fog catch is plotted against Cook pine throughfall producing a highly significant predictive relationship. Over the absolute range of fog and throughfall values a somewhat more robust (normalized data distribution on X-Y axis) model is obtained using log transformed data (**Figure 35**). The practical utility of this relationship is that easily measured open-site fog catch data can be used to reasonably predict Cook pine throughfall in the upper Lāna'ihale watershed. In the future management of the watershed, fog gauge measurements could dramatically improve the ability to realistically monitor groundwater recharge rates attributable to Cook pine fog drip without the need for complicated direct throughfall measurements.

[2]For simultaneous measurement periods, Station #3 and #4, both at the highest elevations on the transect showed very similar values for all precipitation parameters (with Station #3 values consistently slightly higher). However, because repeated branch-falls caused damage to throughfall collectors, and other sensor failures at Station #3 rendered a less complete continuous data record, we have utilized the more complete and slightly more conservative values from Station #4 to characterize Lāna'ihale summit area precipitation relationships for this study (**Figures 24-26**)

As an illustration of the procedure for scaling-up the precipitation event data in **Figures 18-29** to annualized Cook pine throughfall estimates under "normal" (average rainfall conditions), we can focus on summit zone, high throughfall Station #4 (**Figure 26**). Rainfall for the 297 days was 15.8in (41.3% of the 38.3 long term average annual rainfall in the summit area, see **Figure 12**). If we use the winter and summer throughfall/rainfall ratios in **Figure 24** (4.3) and **Figure 25** (18.5) applied to average long term winter and summer rainfall for the summit area (see **Figure 12**), rather than the sample period rainfall, estimated annual Cook pine throughfall at station #4 would be 385.8 in. (9,799 mm). This scaling-up is based on the robust relationship between rainfall and fog catch (**Figure 16**). Given full evaluation of all of our data we believe this is a reasonable estimate for mature, well-exposed Cook pine throughfall in the summit area. This gross throughfall value would still need to be corrected to determine the net contribution from fog drip as distinct from the direct rainfall and non-vertical rainfall components also intercepted by the tree. If we add the non-vertical rainfall contribution (15% of rainfall or 5.7 in [0.15 x 38.3]) to average annual rainfall (38.3 in), the total throughfall component attributable to both forms of rainfall is 44in, and the net Cook pine fog drip becomes 341.8 in (385.8 – 44). This value is more than 10-times the Cook pine fog drip estimate derived in the earlier PRI study.

Table 5. Rainfall and Cook pine throughfall: April – August 2008 Lāna'ihale watershed transect

	Station 1	Station 2	Station 4	Station 5	Station 6
Rain (in.)	0.4	3.4	5.3	6.6	4.3
Throughfall (in.)	8.5	24.7	41.2	28.1	-------*
Throughfall / Rain (%)	2125	726.5	777.4	425.7	-------

*No Cook Pine measurement from Station # 6

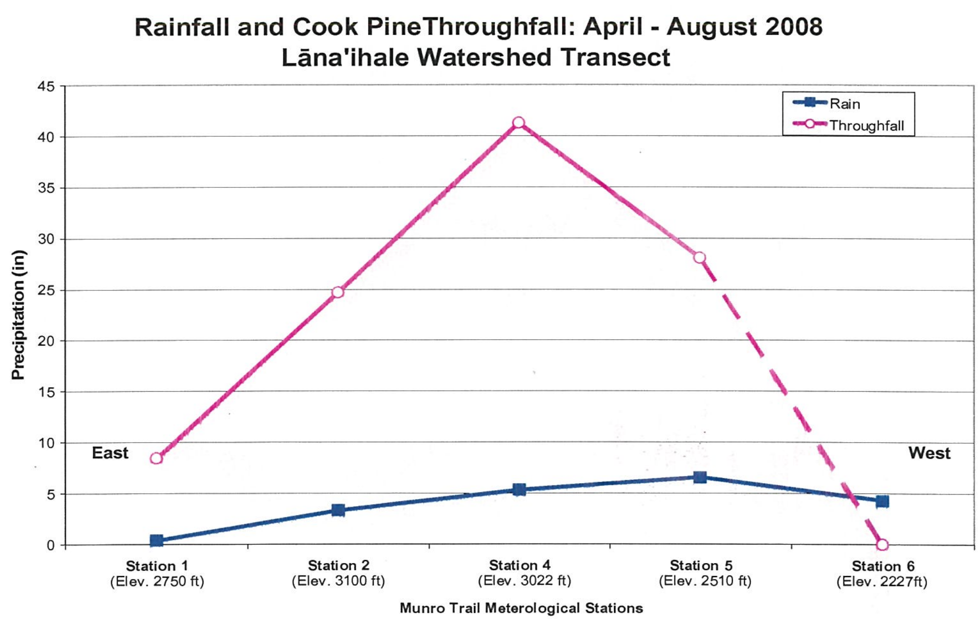


Figure 17. Throughfall/rain relationships.

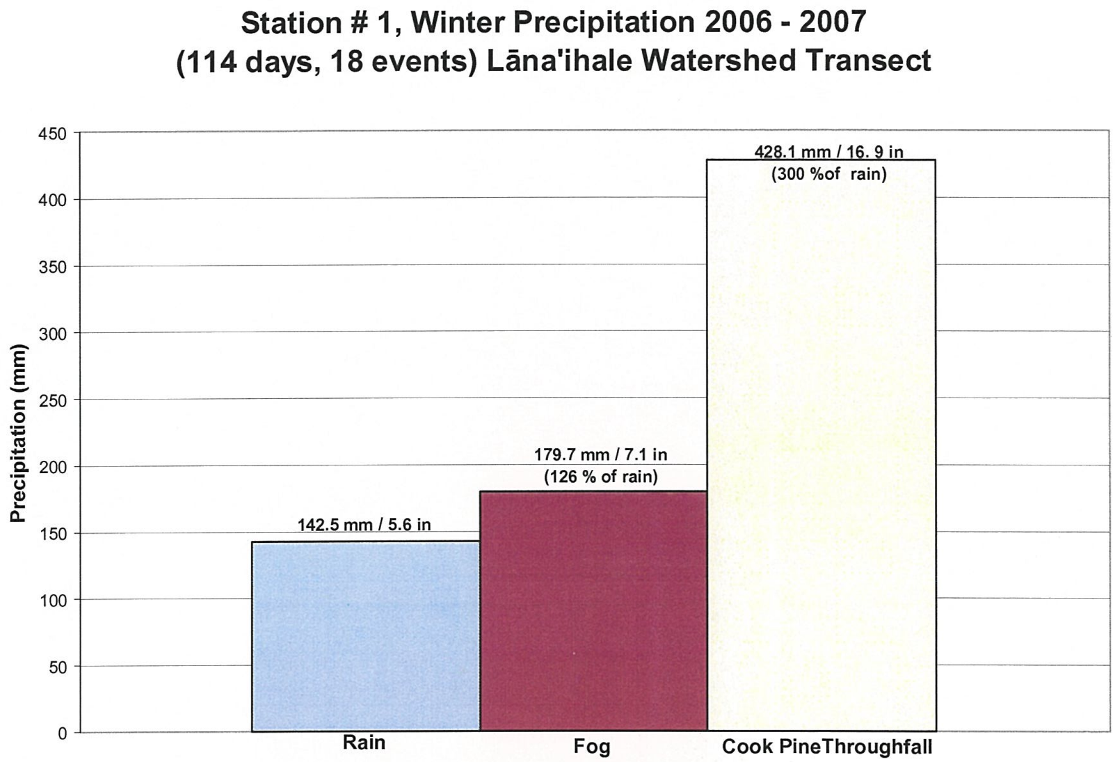


Figure 18. Rain, fog, and throughfall (Station #1)

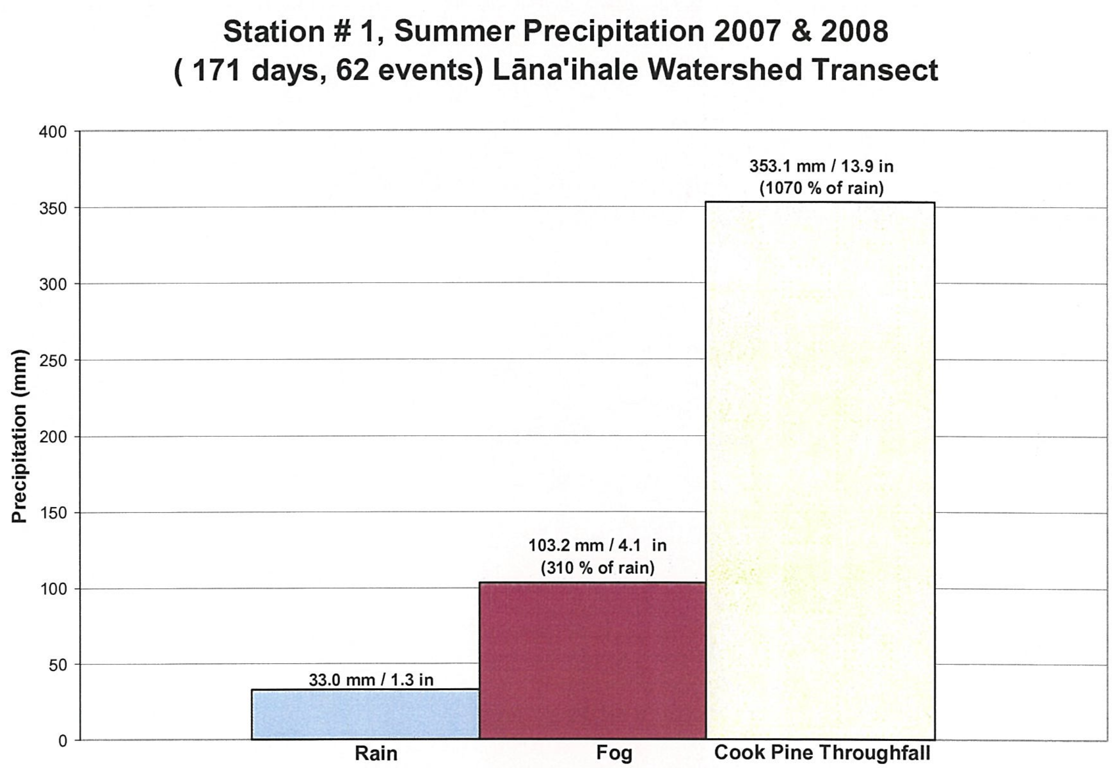


Figure 19. Rain, fog, and throughfall (Station #1)

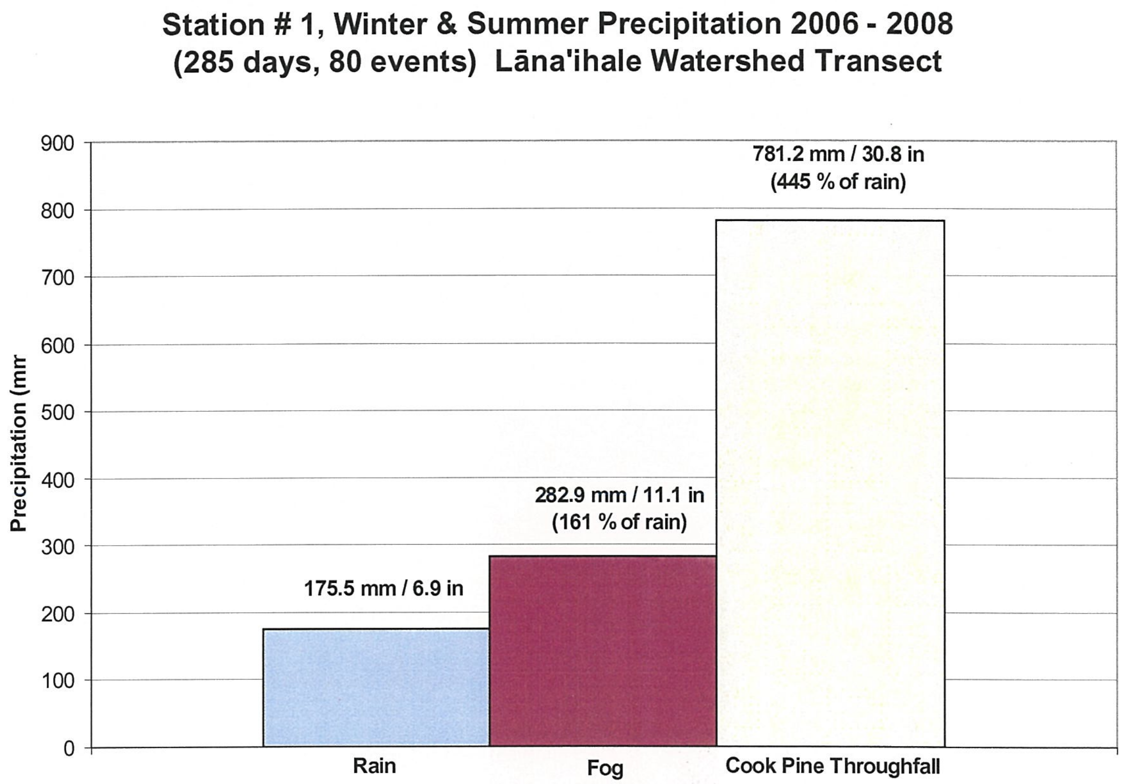


Figure 20. Rain, fog, and throughfall (Station #1)

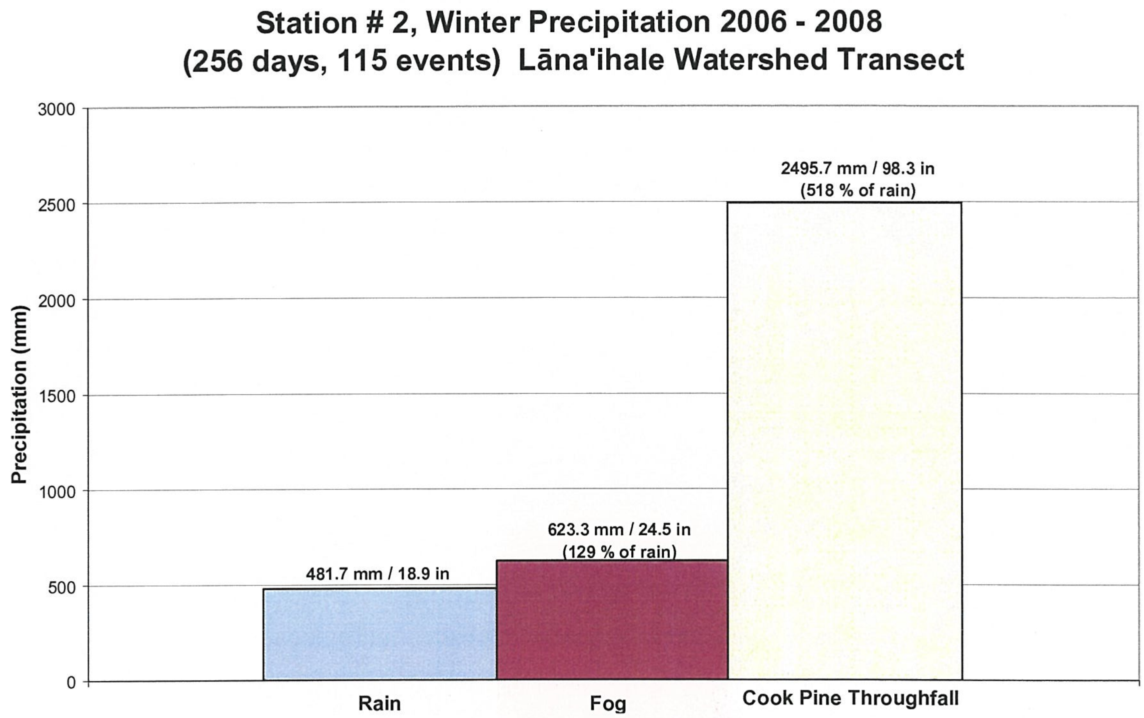


Figure 21. Rain, fog, and throughfall (Station #2)

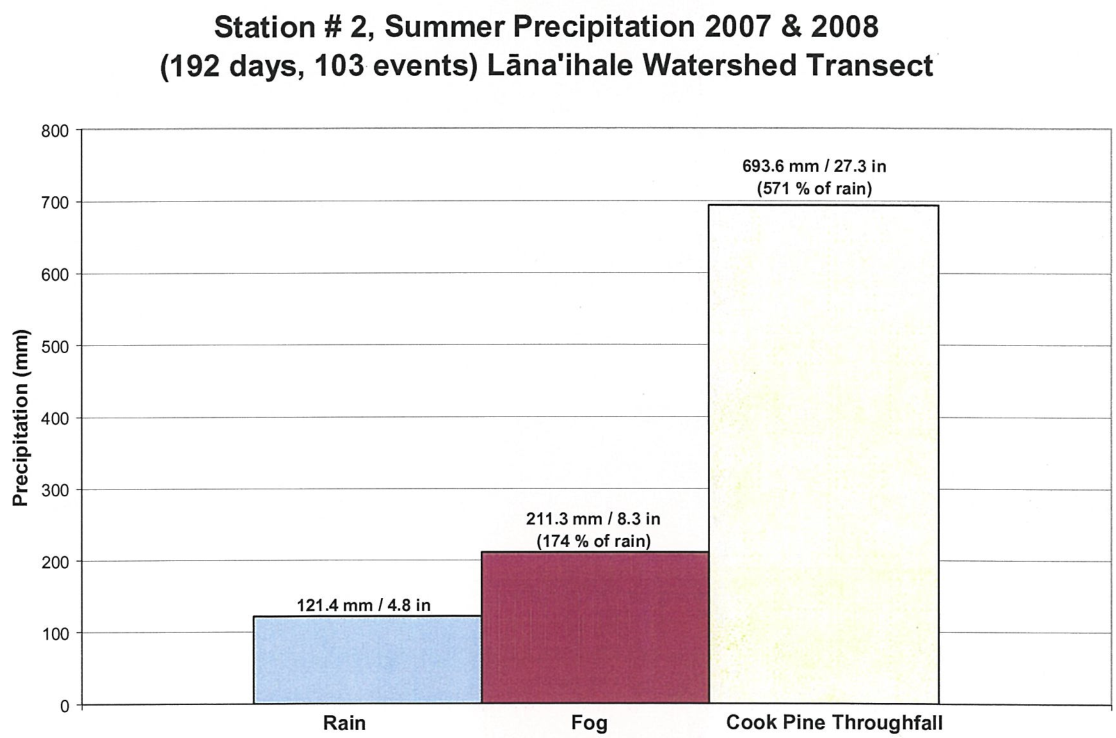


Figure 22. Rain, fog, and throughfall (Station #2)

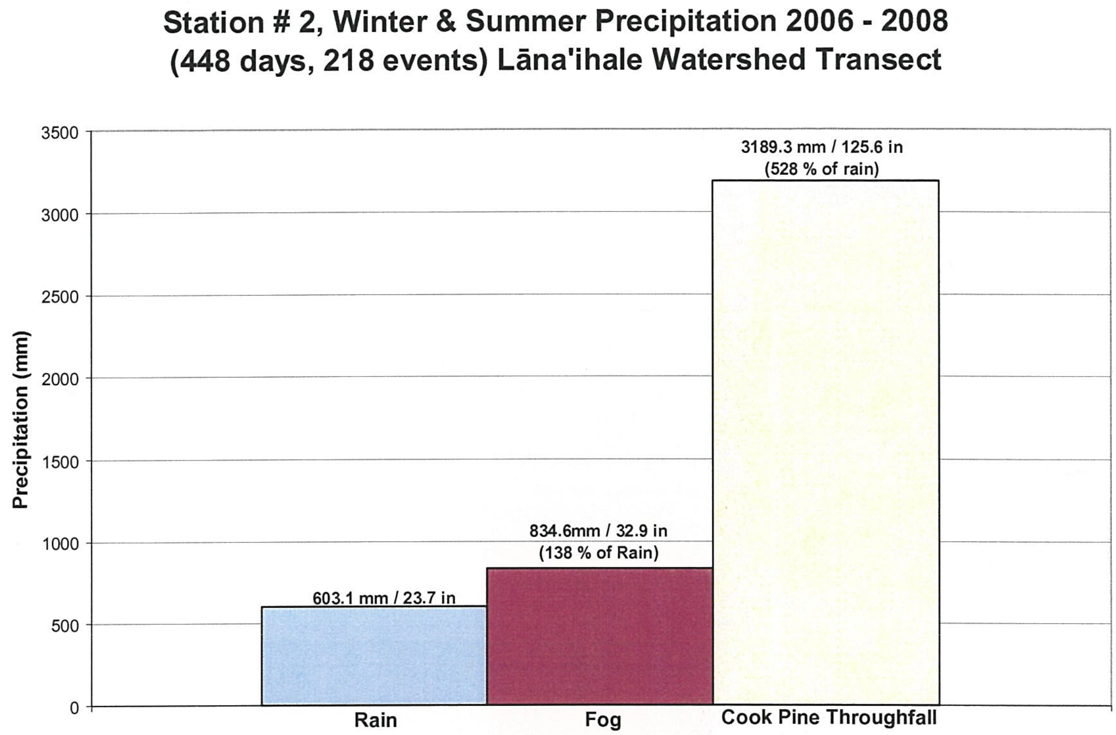


Figure 23. Rain, fog, and throughfall (Station #2)

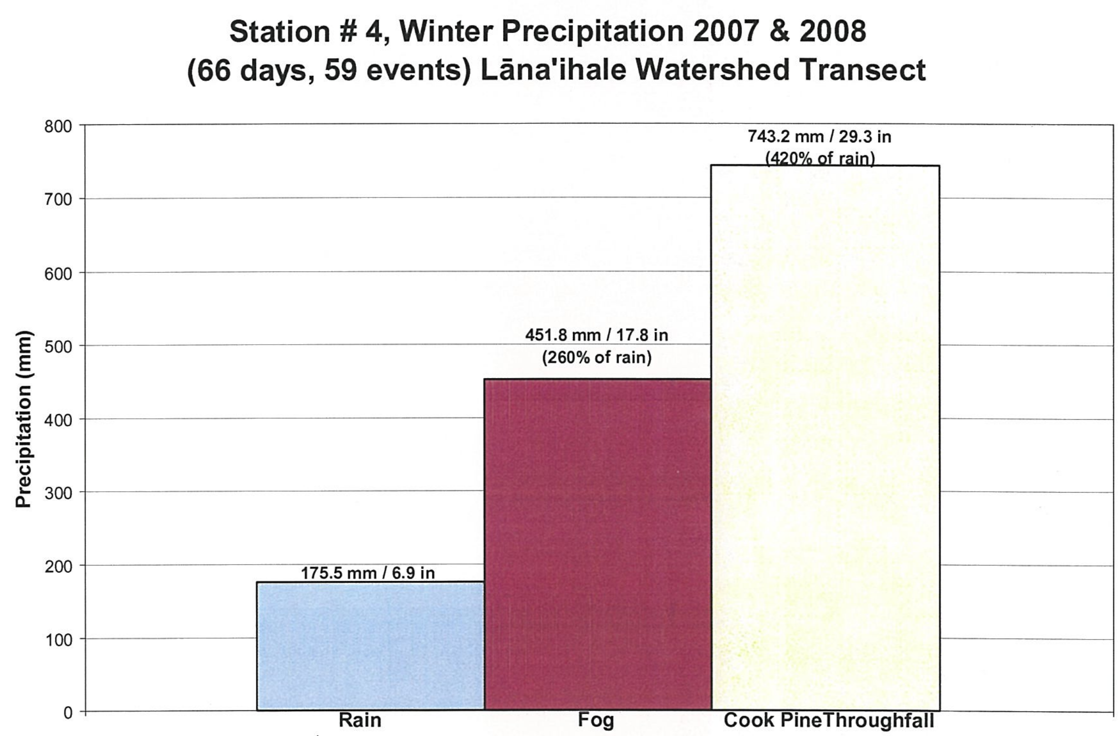


Figure 24. Rain, fog, and throughfall (Station #4)

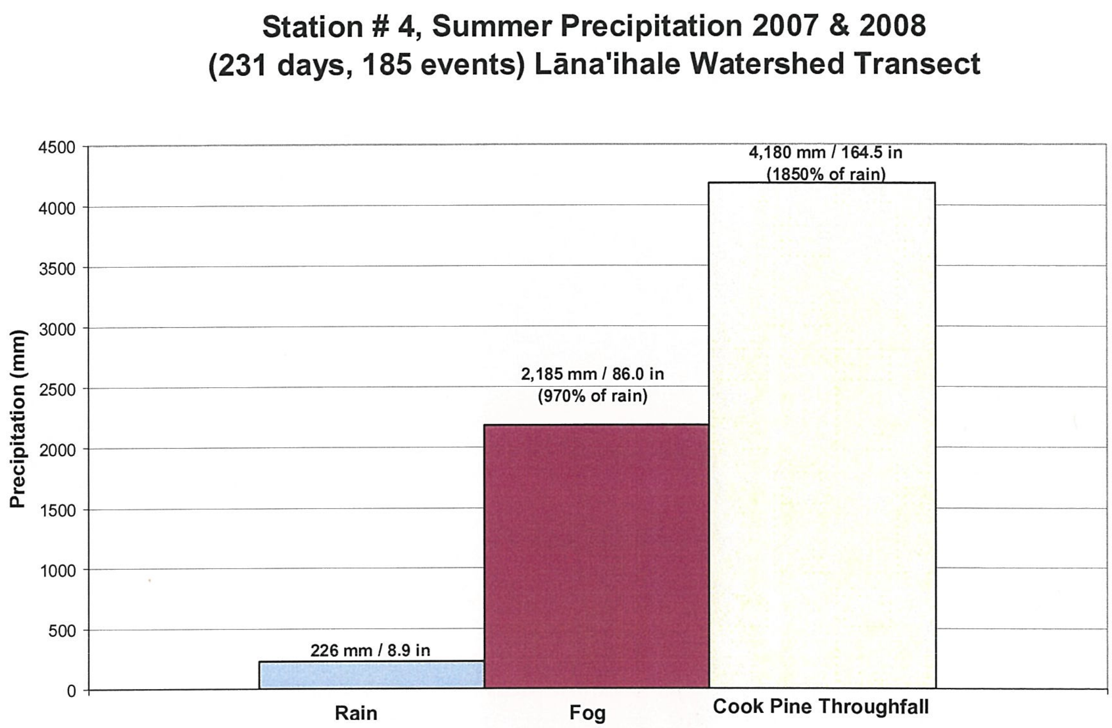


Figure 25. Rain, fog, and throughfall (Station #4)

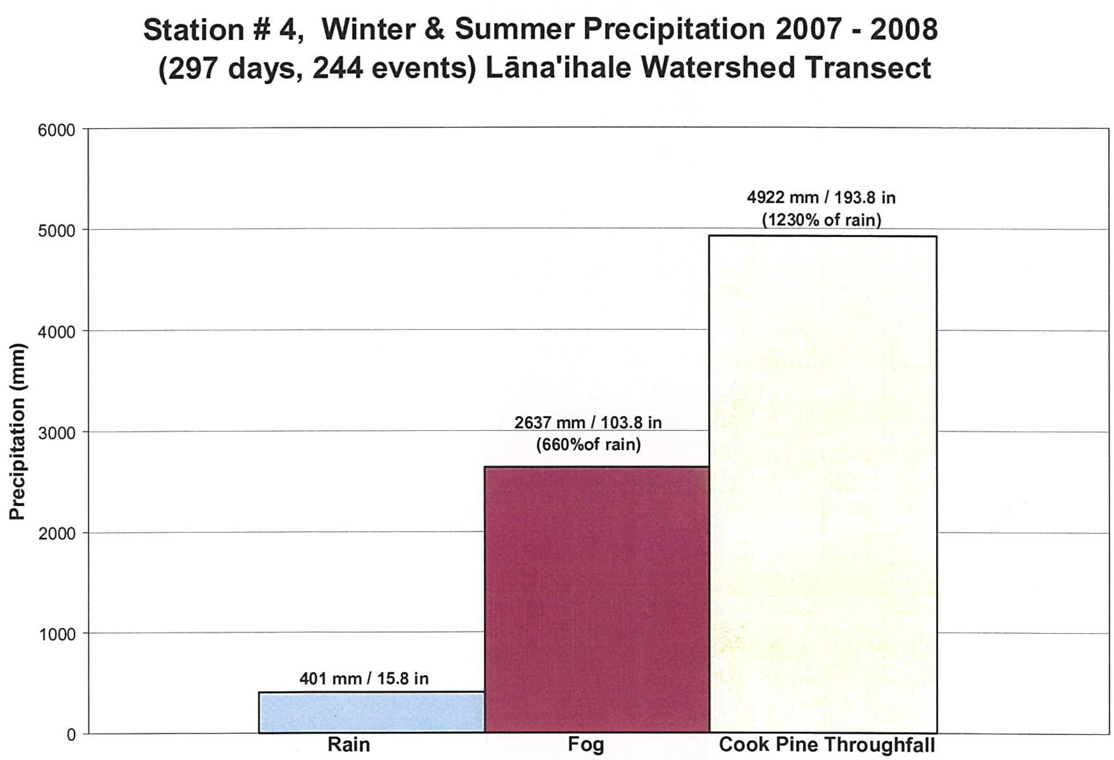


Figure 26. Rain, fog, and throughfall (Station #4)

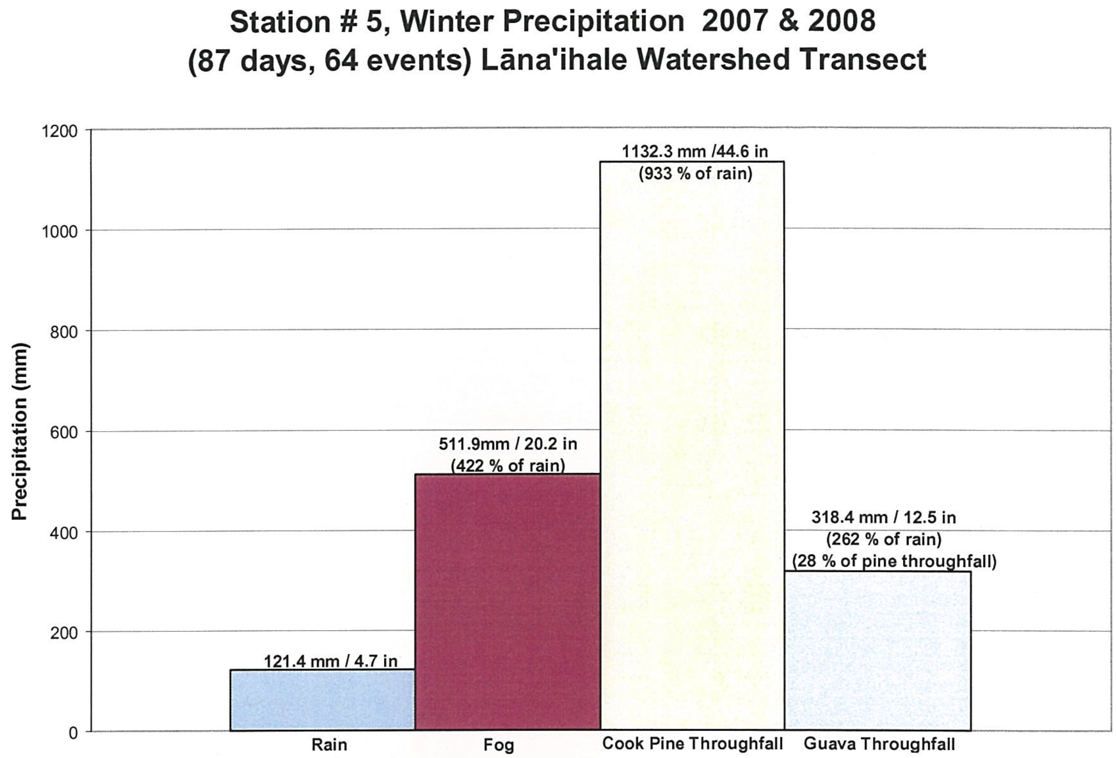


Figure 27. Rain, fog, and throughfall (Station #5)

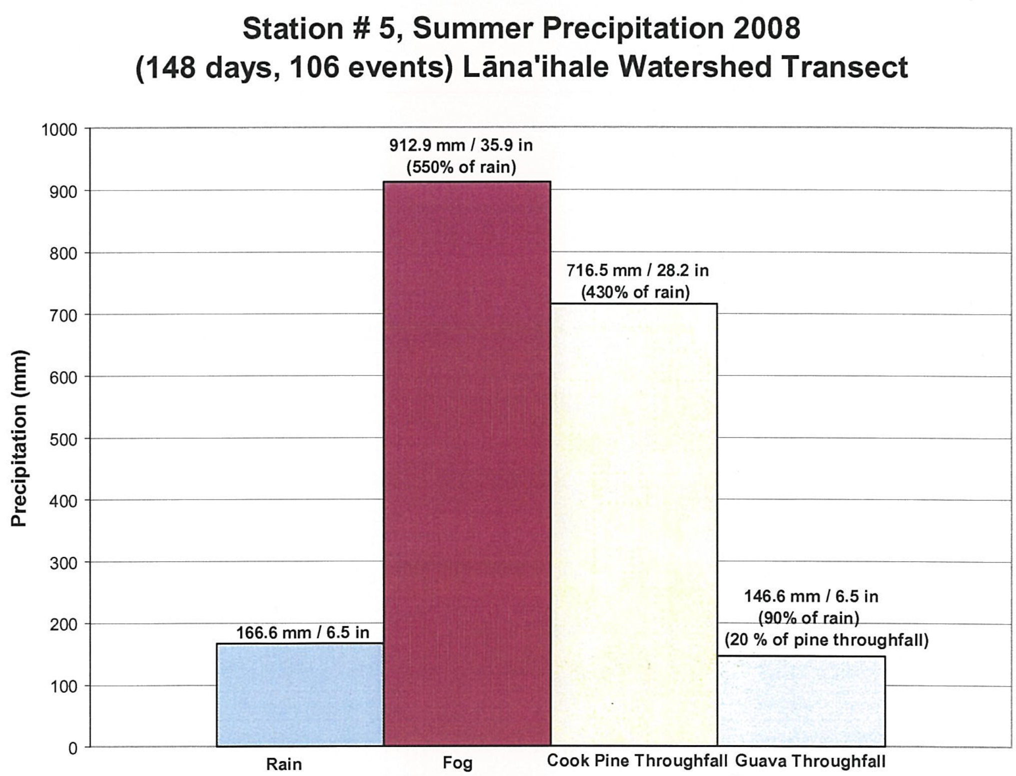


Figure 28. Rain, fog, and throughfall (Station #5)

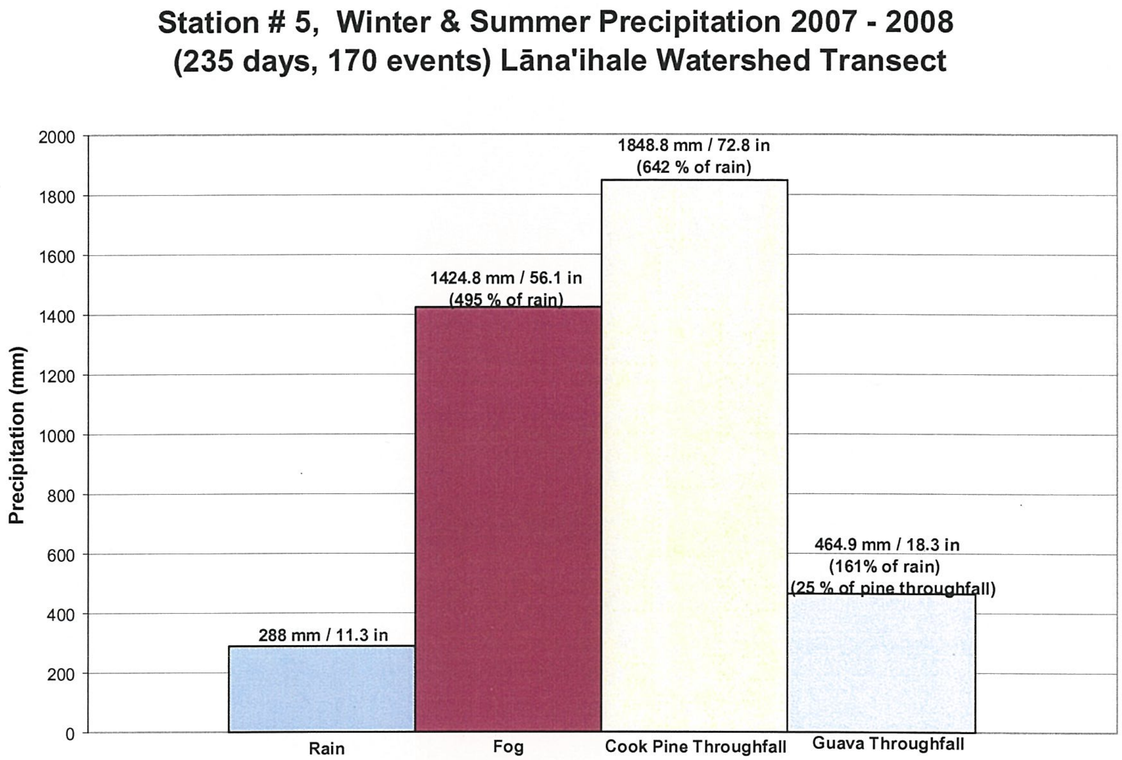


Figure 29. Rain, fog, and throughfall (Station #5)

Table 6. Station #5 precipitation - October 2007.

Precipitation Characteristics	Open site rainfall	Open site fog catch	Under canopy throughfall
Days with precipitation	2	23	21
Total monthly precipitation (in.)	0.13	4.13	11.7
Ratio of Fog Catch and Throughfall to Rainfall	-	31.8	89.9

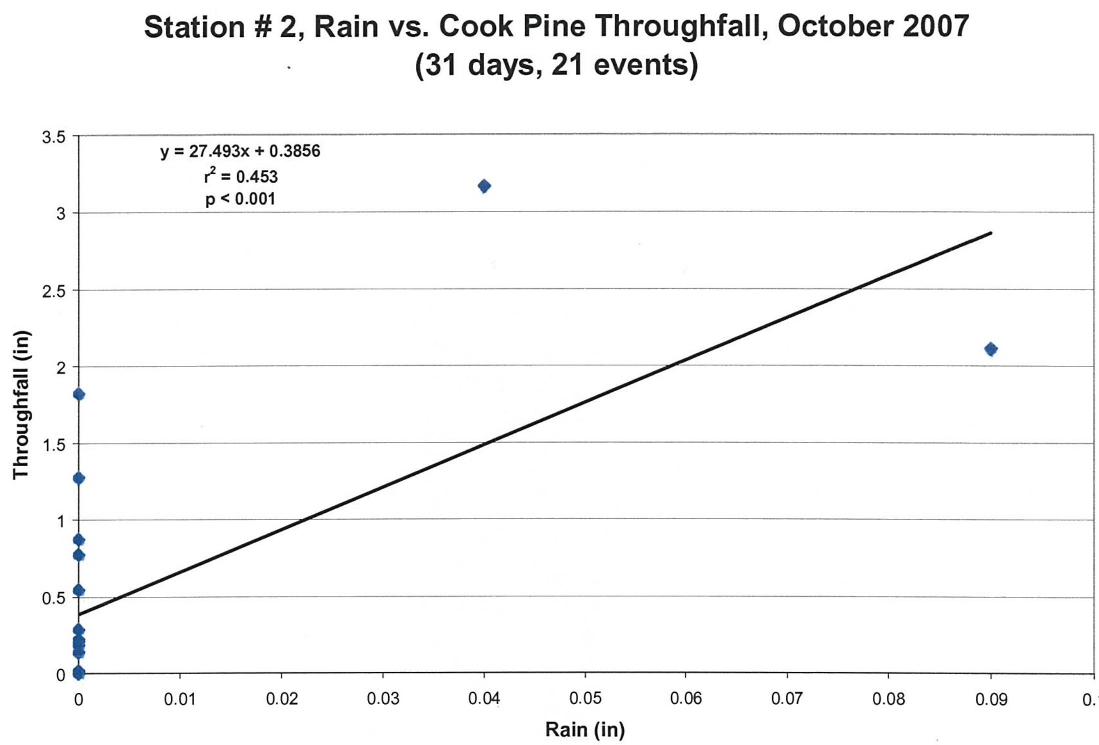


Figure 30. Rain-throughfall relationship for Station #2.

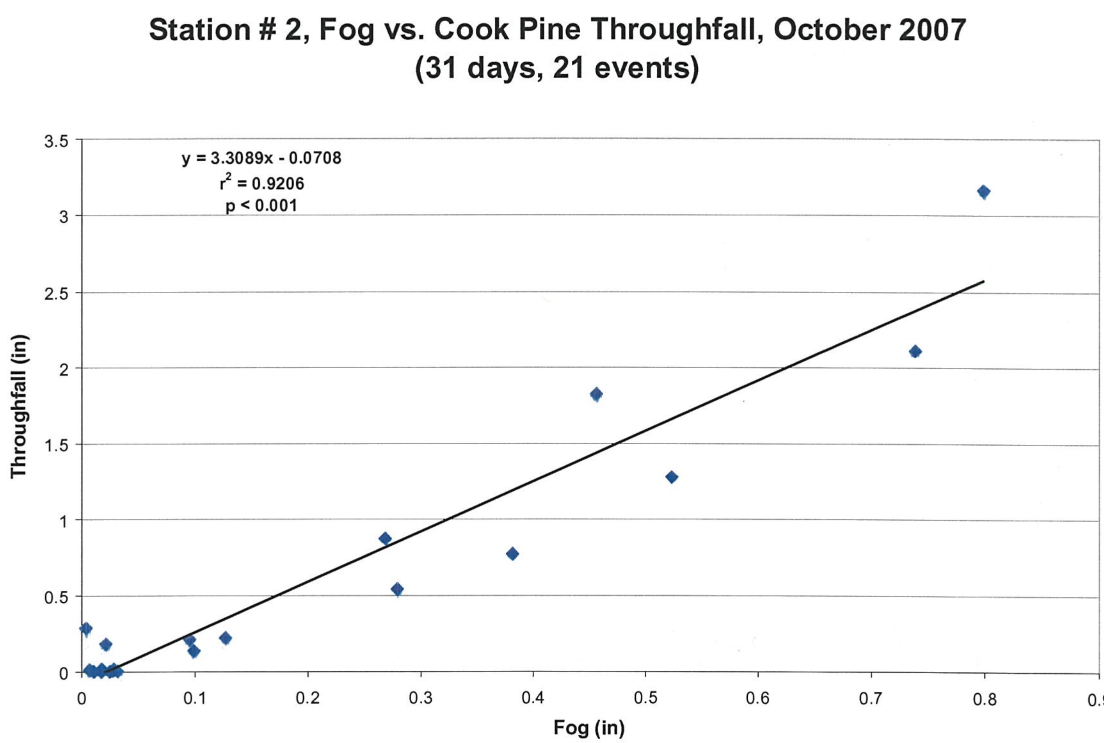


Figure 31. Fog-Throughfall relationship for Station #2.

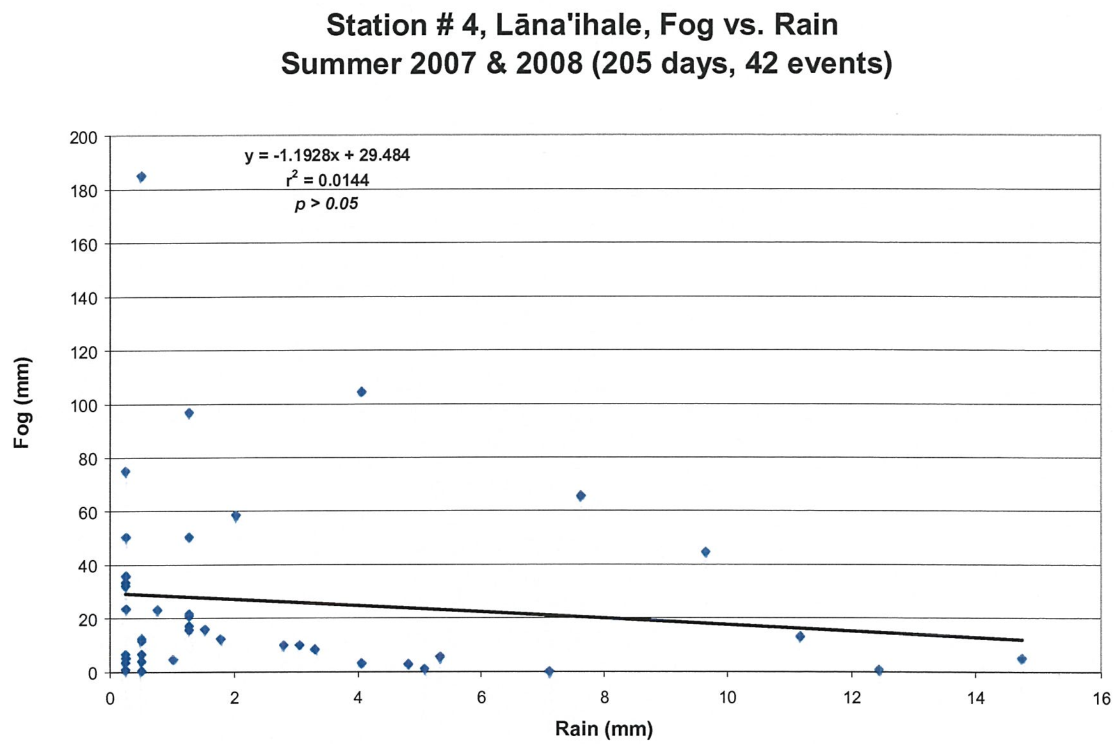


Figure 32. Rain-Fog relationship for Station #4.

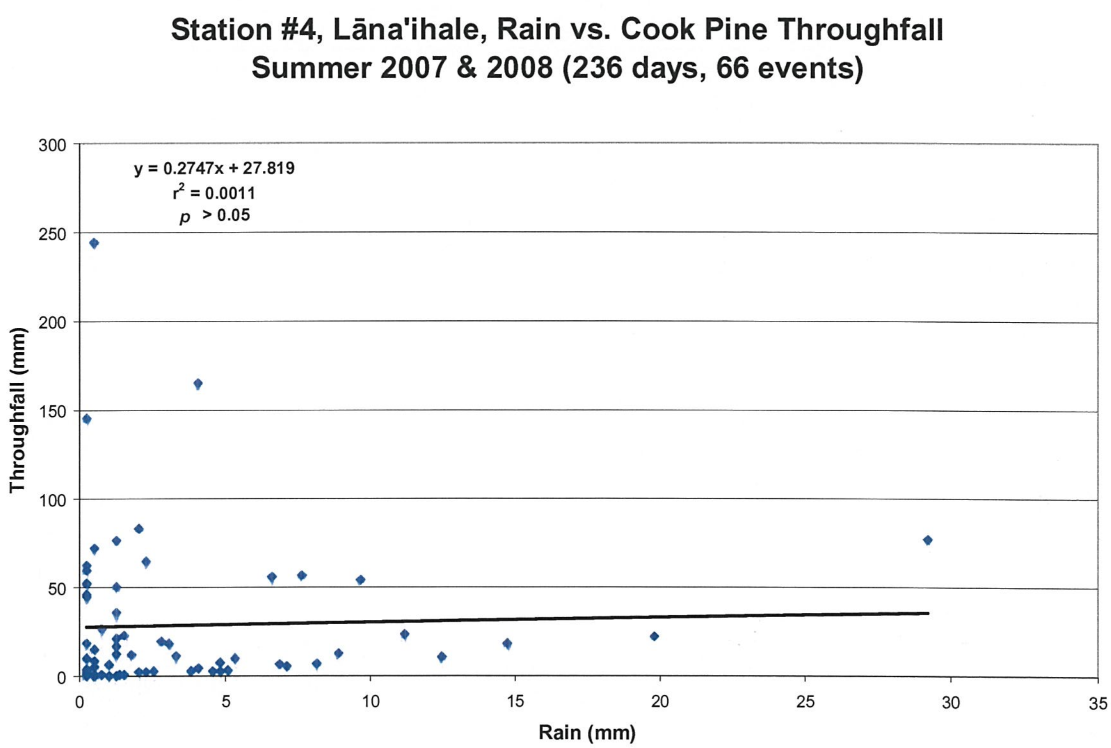


Figure 33. Rain-Throughfall relationship for Station #4

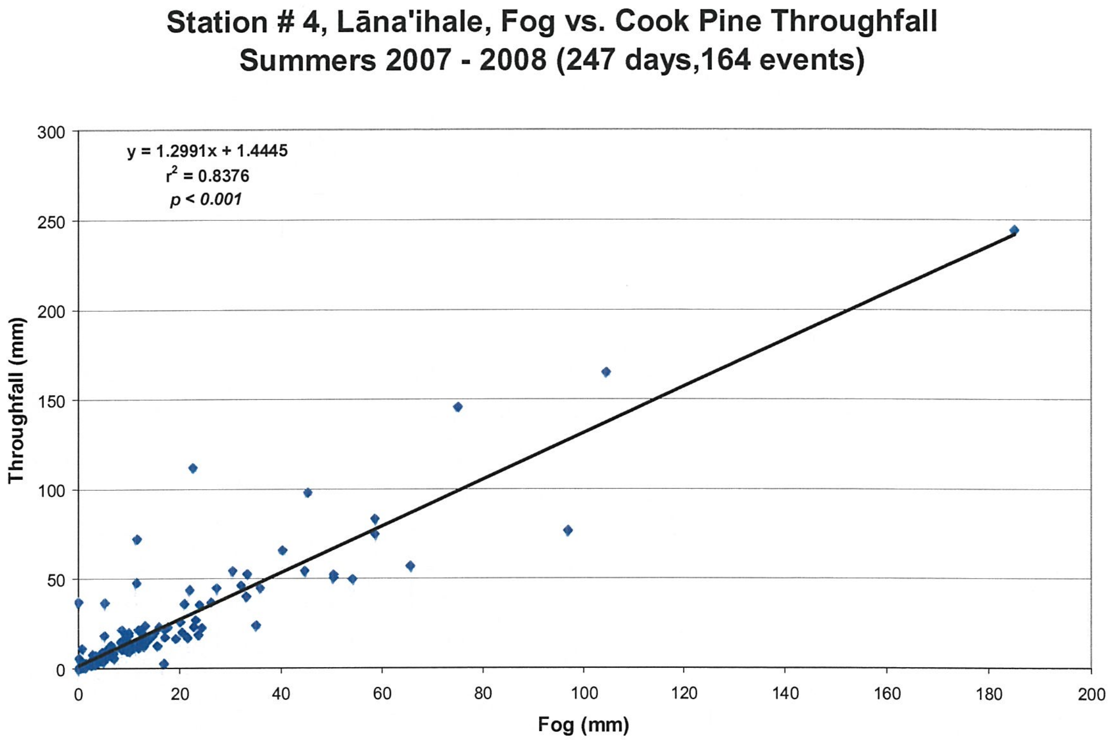


Figure 34. Fog-throughfall relationship for station #4

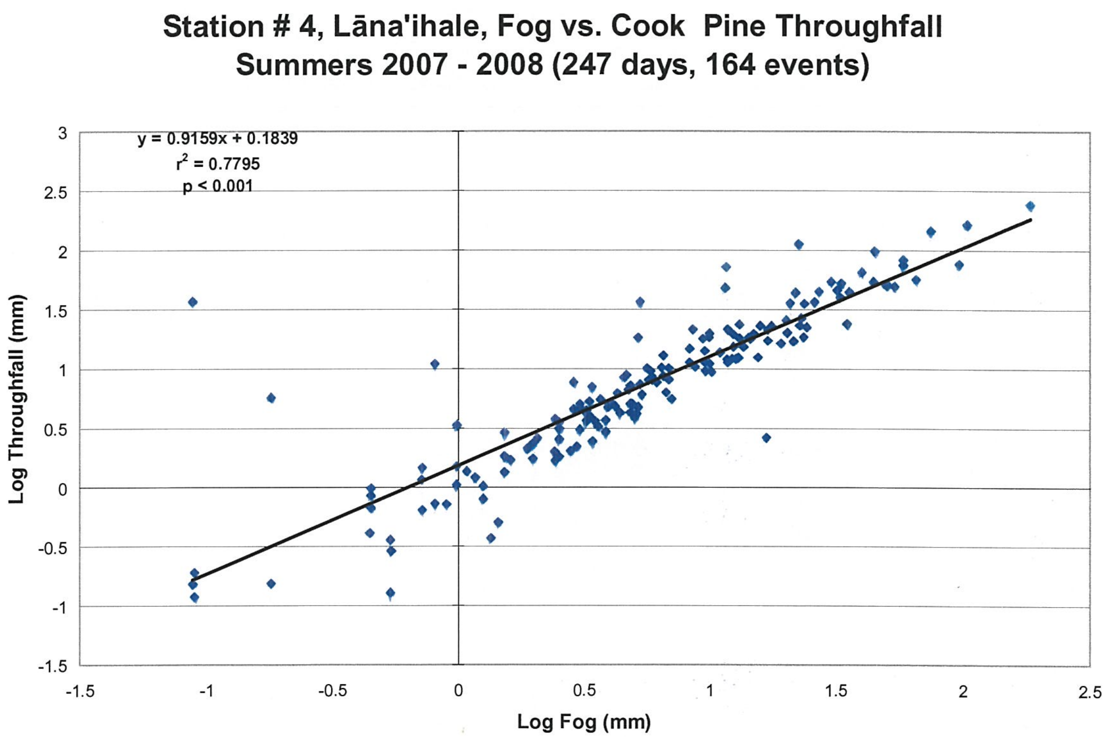


Figure 35. Transformation (log/log) of Figure 34 fog-throughfall relationship.

C. Throughfall from *Eucalyptus* and *Guava*

A single sampling site for *Guava cattleianum* throughfall was established at Station #5 adjacent to the Cook pine also being monitored at this location (**Figure 9**). *Guava* thickets form dense continuous canopies of comparatively low statue (6 – 15 ft. or 2-5 m tall) in the Lāna'ihale summit region. As such air flow (and associate cloud-water) is more likely to be deflected over the canopy rather than through it, reducing the potential for fog drip. As will be seen in **Figures 27-28** in comparing both summer and winter periods *Guava* throughfall ranged between 90-262% of open site rainfall, averaging 161% (**Figure 29**). In comparison with the adjacent Cook pine throughfall the *Guava* throughfall catch ranges from 20-28% of Cook pine (average 25%, **see Figure 29**). It should be noted that this comparative experiment relating Cook pine and *Guava* throughfall was restricted to one lower, less foggy locations along the transect (station #5 at an elevation of 2,510 ft). These results lead us to conclude that, at least for exposed summit ridge *Guava* stands, a much smaller but still significant fog drip contribution can be expected.

In a short term experiment we also monitored throughfall under a mature *Eucalyptus robusta* stand (**see Figure 10**) adjacent to the monitored Cook pine at Station #1. As will be seen in **Figure 36,** for this short sampling period *Eucalyptus* throughfall equaled only 82% of period open-site rainfall, in spite of the fact that significant fog and Cook pine throughfall (in excess of rainfall) occurred during the same period. It appears, at least for the limited period of record, that canopy interception loss for E*ucalyptus* exceeds any potential gains from fog catch. Further research would be required to determine if these limited results are representative of E*ucalyptus* / fog relationships in other parts of the upper watershed, where this species is relatively abundant.

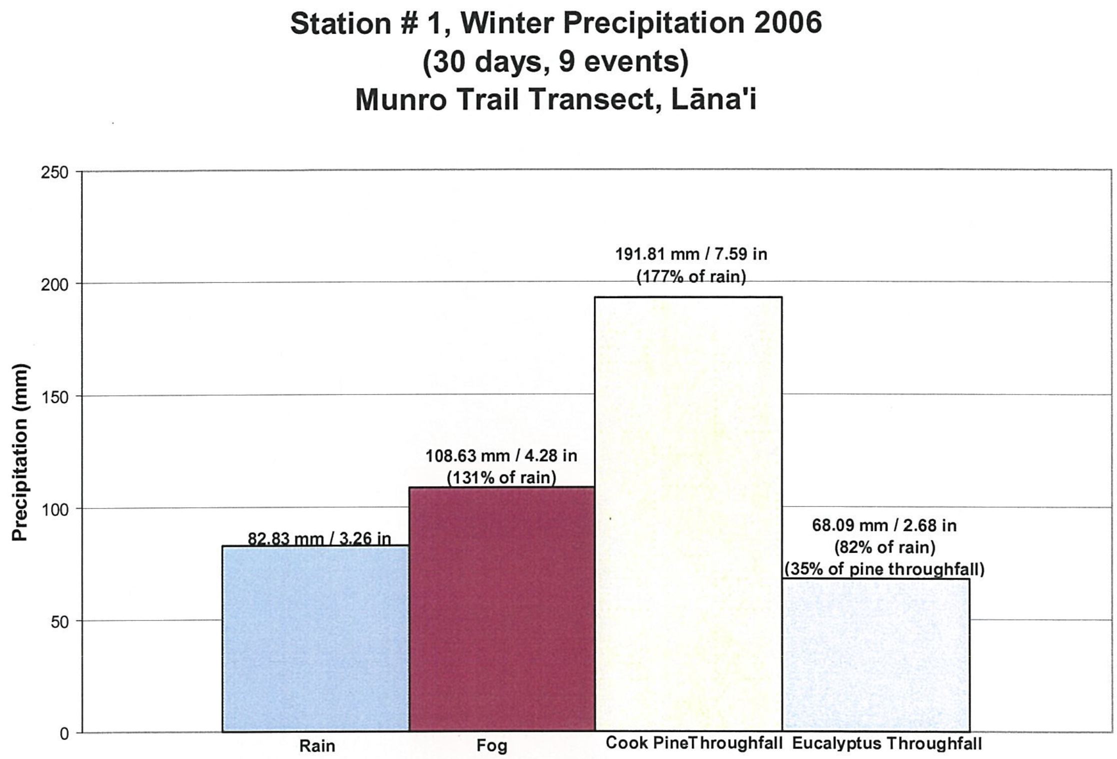


Figure 36. Station #1 precipitation including *Eucalyptus* throughfall

D. Cook pine water balance

i. Evapotranspiration

There is only limited pan evaporation data for the Island of Lāna'i. A single year (1957) of recorded pan evaporation measurements are available for Lāna'i City, totaling 26.63 in. (Ekern and Chang, 1985). This one-year record shows considerable non-seasonal, inter-month variability, suggesting caution in any attempt at spatial or temporal extrapolation of this data to general evapotranspiration conditions in the adjacent upper Lāna'ihale watershed.

In the present study potential evapotranspiration (*PET*) for the summit ridge was estimated on a daily basis according to the relationship developed by Penman (1948). Net radiation (R_n) for the *PET* calculation was derived from measured solar radiation *R* using an empirical formula developed by Chang (1969). The period of record for analysis varied among our ridge-line stations. **Table 7** provides a summary of the mean values of the variables used in the *PET* estimates from selected stations. **Table 8** presents the *PET* estimates with rainfall (*RF*) measured during the period of record. PET exceeds rainfall R at the lower elevation stations but actual evapotranspiration *AET* can be expected to be a smaller fraction of PET at these moisture-limited sites than at locations with greater rainfall and above the cloud-base. Recent studies of evaporation using eddy covariance techniques at tropical- maritime forest sites with high rainfall (or perhaps frequent fog) suggest that *AET* can exceed Penman-based estimates, and that evaporation of intercepted water from the canopy is a significant source of moisture for evaporation which can be about 30% higher on days when the canopy is wet (Giambelluca et al. 2009).

Table 7. Mean values for variables related to the *PET* calculation where R is solar radiation (w/m^2), R_n is net radiation (w/m^2), T_a is air temperature (°C), *U* is wind speed (m/s), and *RH* is relative humidity (%).

Station	Elevation	*R*	R_n	T_a	*U*	*RH*
2	908	148	103	17.5	2	92
3	1022	126	84	16.6	2.5	92
4	922	125	84	17.4	2.6	92
6	679	126	85	17.9	1.8	91
7	503	176	131	20.3	2.7	90

Table 8. Rainfall (*RF*) and potential evapotranspiration (*PET*) summary with values (inches)

		Total		Daily		Annual	
Station	Days	*RF*	*PET*	*RF*	*PET*	*RF*	*PET*
2	462	47.44	45.47	0.10	0.10	37.52	35.94
3	257	42.72	20.28	0.17	0.08	60.71	28.82
4	336	33.82	26.81	0.10	0.08	36.77	29.17
6	159	12.13	12.87	0.08	0.08	27.87	29.57
7	355	14.84	45.83	0.04	0.13	15.28	47.13

Annualized rainfall and *PET* values for stations 2-7 (**Table 8**) are graphed in **Figure 36.** Stations (#3-4 & 6) in the western, most humid, cloud shrouded areas of the upper watershed yielded consistent annual *PET* of near 30 in, with *PET* values increasing at both lower elevations (Station #7) and on the dryer eastern end of the ridge (Station #2). Because of our limited record and lack of any strong or consistent seasonal signal in the data, we could not justify the calculation of definitive "monthly" *PET* estimates. For individual tree water-balance calculations in the upper watershed we used the 30 in annual *PET* value. It should be noted that for two reasons this is a liberal estimate of tree water-use, because: 1) The *PET* calculation is based on "open-water" evaporation and does not include the influence of leaf (needle) stomatal resistance in the suppression of transpiration below the "potential" open water rate; and 2) the wetting of canopy leaves during frequent fog events implies that significant *PET* demand can be met from direct leaf evaporation rather than tree transpiration (water drawn from root zone soil moisture). Such reduced transpiration demand potentially leaves more fog drip soil moisture available for enhanced ground water recharge under Cook pine.

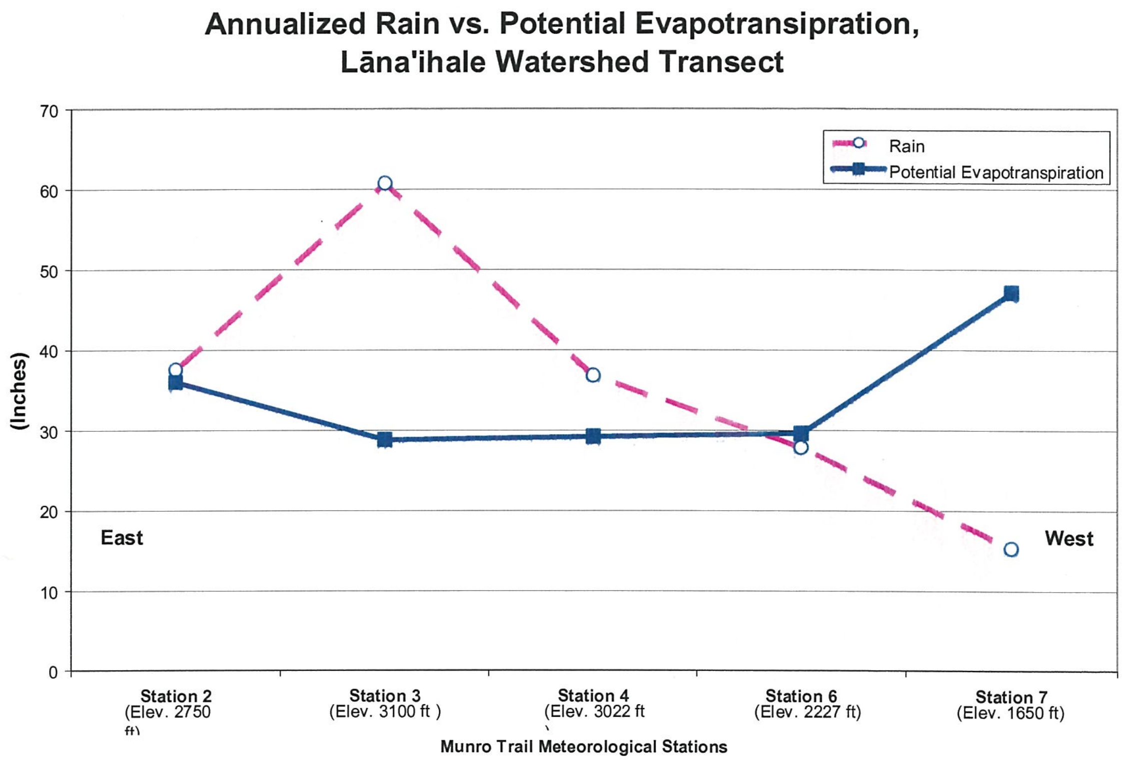


Figure 37. Annualized Potential Evapotranspiration (open-water) and rainfall.

ii. Soil moisture, runoff and recharge

We did not quantitatively monitor direct surface water runoff as a component of this study. However, frequent field observations, during both rain and fog events in the Lāna'ihale watershed leads us to conclude that direct runoff under our monitored Cook pines during fog drip events was a very small proportion of total throughfall. This conclusion is based on two components: 1) most of the planted Cook pines occupy ridge top or plateau sites with slight to moderate slopes >10%) not conducive to heavy runoff; and 2) fog drip events produce relatively modest but sustained rates of throughfall; rates that typically do not overwhelm the infiltration capacity of the ridge top soils. In contrast, during infrequent but intense rainfall episodes the infiltration capacity of the clay-dominated soils in the area can easily be exceeded, yielding much higher, but short duration, direct runoff. Although runoff was not monitored as part of this study it is likely to be in the vicinity of 5% or less for "slow-drip" fog episodes under Cook Pine.

Figure 38 provides a clear illustration of comparative open-site (under grass & shrub) and under Cook pine soil moisture fluctuation, and the implications for runoff and recharge. For the Station #2 sample month illustrated (November-December 2006), open site soil moisture (-4 in) content exhibited distinctive spikes associated with the two major rainfall events (November 14th and December 12th) occurring during this period. This soil dried rapidly after each event as the warmer, exposed site rapidly returned water to the atmosphere through bare soil evaporation and transpiration from the herbaceous vegetative cover. The average monthly moisture content for this open site soil averaged only 0.39 in/ft (about 3% water content). Such small amounts of water are typically held fairly tightly in the soil and are unavailable for sustained, gravity driven downward percolation for ground water recharge. In contrast, soil under the nearby Cook pine (**Figure 38**) remained at, or near field capacity (effective saturation of soil pore spaces) throughout the month, with an average monthly soil moisture content of over 4 in/ft (33% water content). Such a sustained, high level of soil moisture content would provide for continuous ground water recharge throughout the month. The above example was replicated at other sampling sites across the watershed. **Figure 39** illustrates open site and Cook pine soil moisture relationships for both comparatively wet (Station #4) and dry (Station #1) summit ridge stations over the six-month period March-August 2008. At the fog immersed summit area (Station #4), Cook pine soil moisture remained at near field capacity (33%) throughout the period, providing an unambiguous confirmation of sustained groundwater recharge during this dry summer season. At this same site the adjacent open site soil moisture values fluctuate between 17-25%. Even at Station #1 (**Figure 39**) with substantially less rain, fog and throughfall (see **Figures 15 & 17**) there is still significant soil moisture enhancement under the Cook pine.

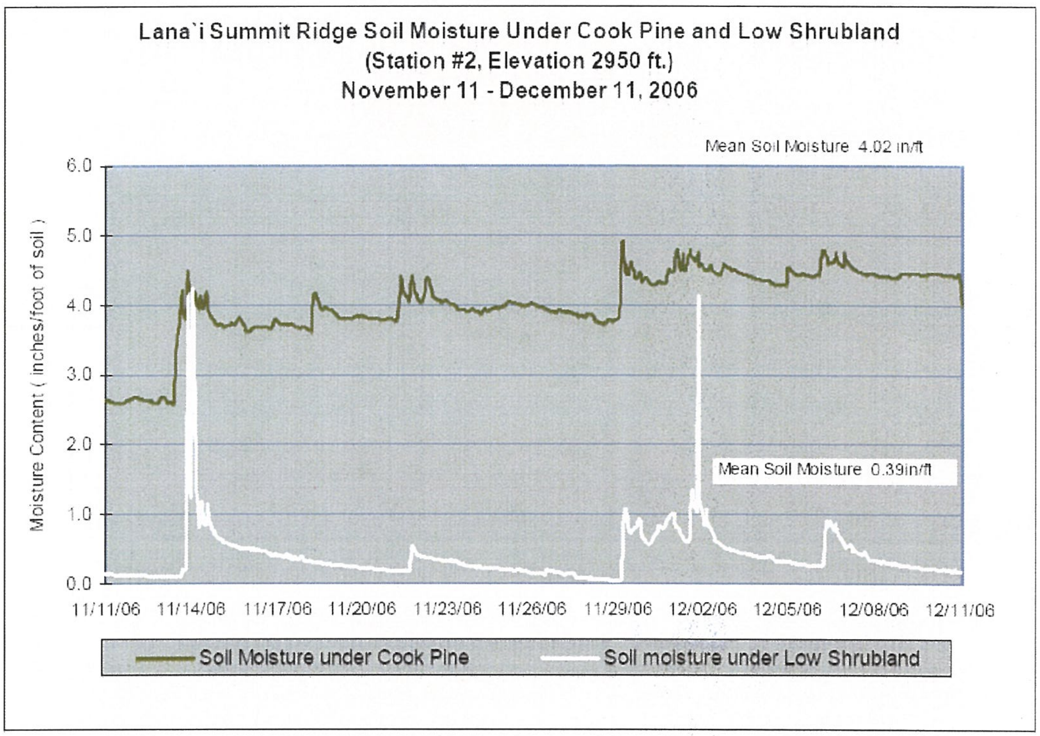


Figure 38. Soil moisture at Station #2, November-December 2006

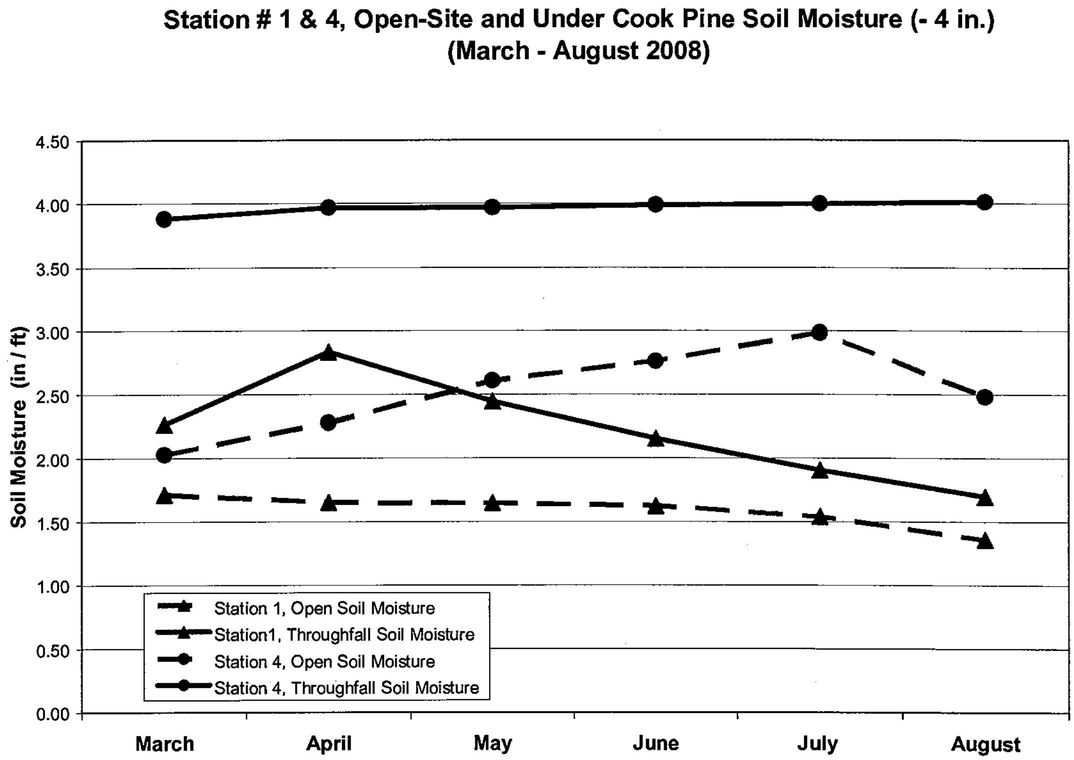


Figure 39. Summer soil moisture at Stations #1 and #4.

iii. Tree water balance

Combining the runoff estimates derived above, with rainfall, non-vertical rainfall and throughfall values measured or estimated for station #4, we have developed a simplified Cook pine water balance model that solves for ground water recharge, with and without the contribution of fog drip (**Figure 40**). In the absence of any fog input the mature cook pine would receive approximately 52 inches (40 in direct and 12 in non-vertical) of rainfall catch. Water losses from this tree system through evapotranspiration (30 in), interception loss (6 in) and runoff (8 in) total 44 in, yielding, by subtraction an annual recharge estimate of 8 in/tree. If estimated annual fog drip (340 in, see page 20 for derivation) were added to the tree input (**Figure 40**, right), recharge increases more than 40-times to 323 in /yr.

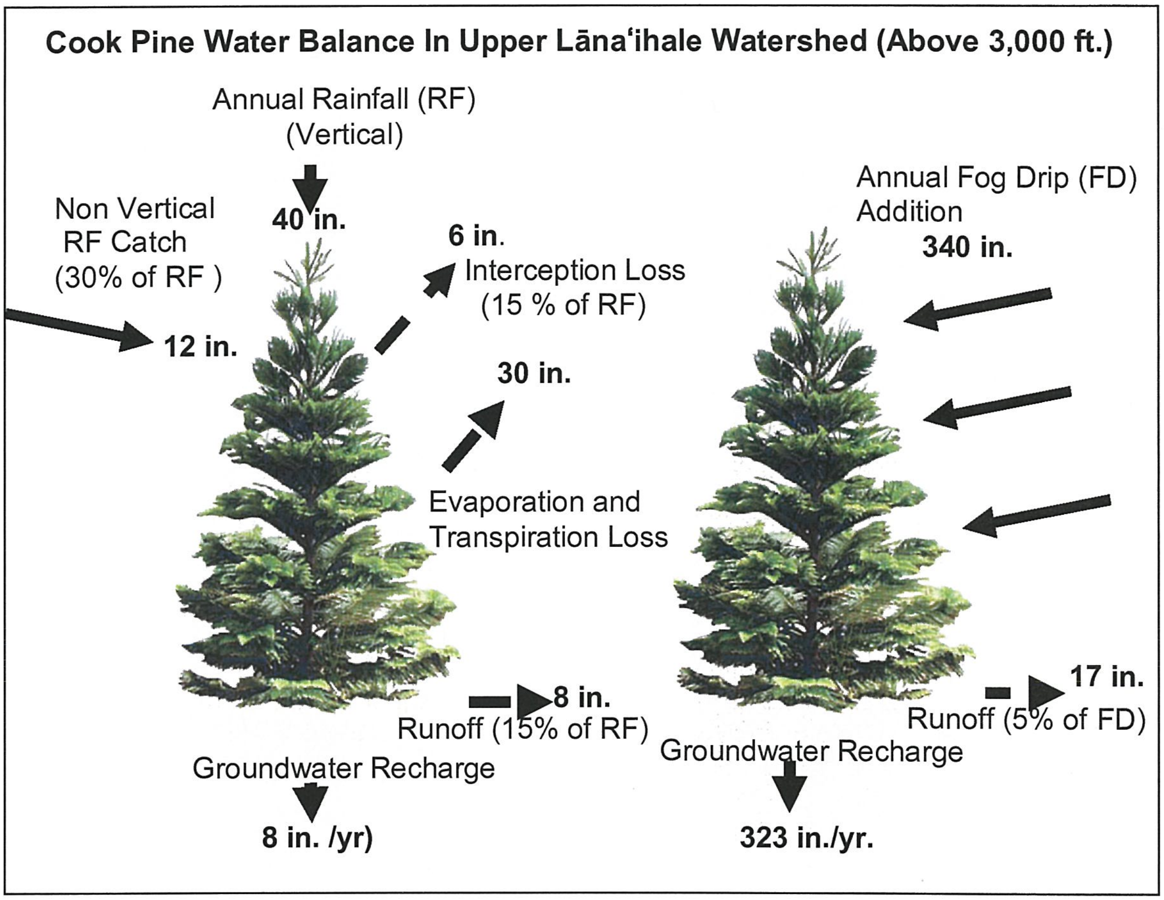


Figure 40. Cook Pine water balance in the upper Lāna'ihale watershed (Station #4)

6. Cook Pine reforestation in the Lāna`ihale watershed

As can be seen from the forgoing analysis, there are very high levels of fog drip associated with well exposed, mature Cook pines in the upper Lāna`ihale watershed. However, extrapolating these sample results to the entire watershed would require further work. There are thousands of Cook Pines in the upper watershed and many of these trees are of different sizes, canopy condition and local terrain exposure, compared to the limited number of sampled trees. Further sampling of throughfall for these different Cook Pine cohorts would be required to reasonably extrapolate the overall contribution of fog drip across the entire watershed. Additionally, there are\well exposed areas of the upper watershed where there are currently either no Cook Pine or senescent trees with damaged canopies. The current (DLNR approved) forest management plan for the Lāna`ihale watershed allows additional replanting of Cook pine in addition to restoration of native species. We used computerized GIS and digital elevation models of the watershed to evaluate ideal areas for future Cook pine reforestation where fog drip can be maximized. We developed an "integrated fog incidence and terrain suitability model" (**Figure 41**) to classify the complex topography of the upper watershed according to: slope angle, site convexity and aspect (windward exposure). Slopes of $< 30^{\circ}$ were considered inaccessible for tree planting; ridge-tops (convex) were considered superior to concave depressions or gulches; and direct exposure to trade winds (easterly aspect) was valued over more sheltered terrain sites. The application of these criteria (via GIS) to a digital elevation map of the watershed results in a spatial classification of discrete suitability classes for Cook pine restoration (**Figure 42**). It will be seen from this map (and table inset) that 135 acres are identified as highly suitable for restoration in the summit zone (>2, 900 ft). This map provides a blueprint for future Cook pine reforestation, and also an opportunity to potentially combine the goals of increase water yield with native ecosystem restoration. In addition to expanded replanting of Cook pine (which would have to be balanced against native petrel ***`Ua`u*** habitat conservation), the opportunity also exists to establish demonstration scale, native plant restoration plots irrigated by water collected under existing Cook pine, using small under-canopy catchments (see **Figure 7**).

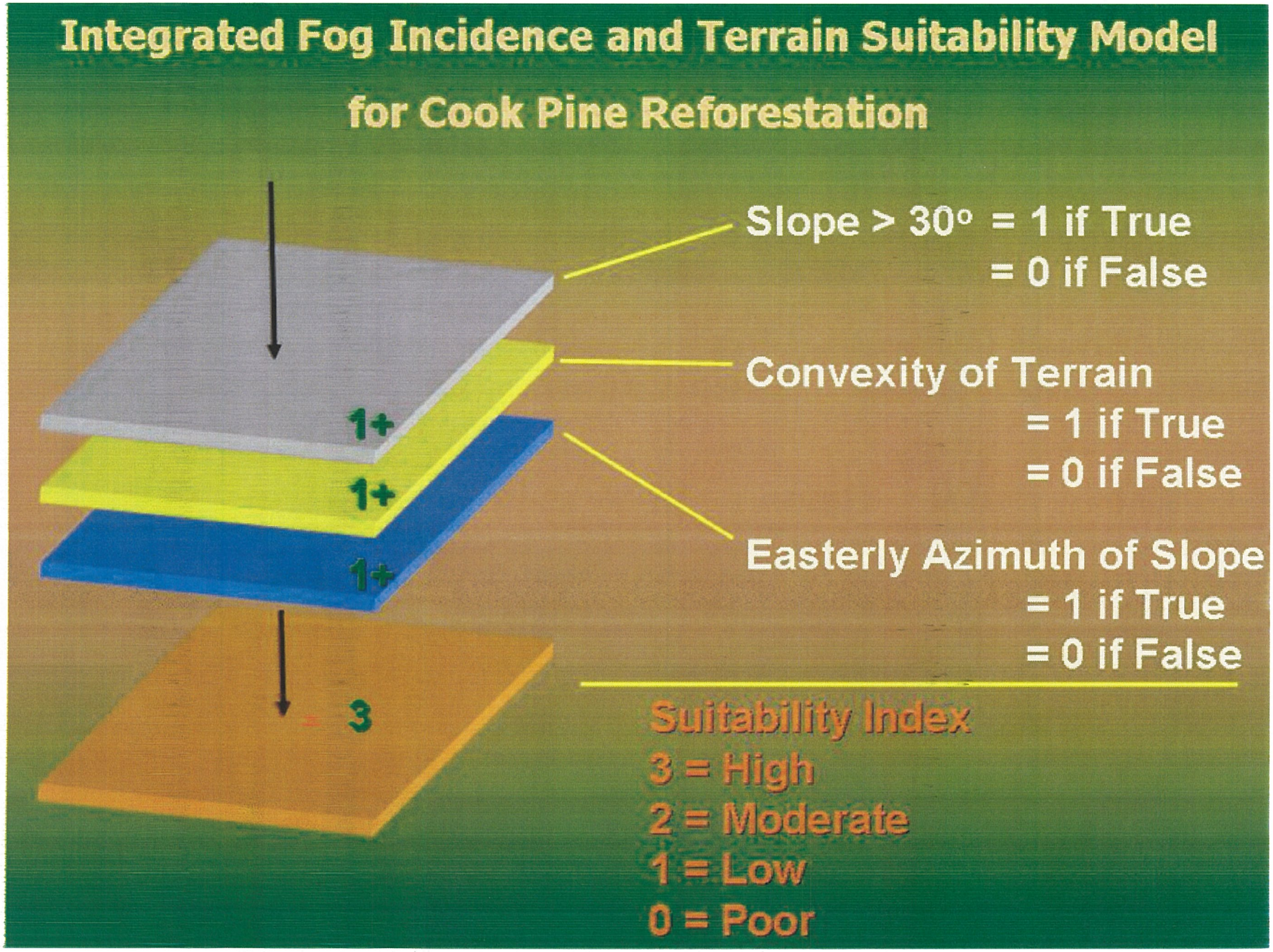
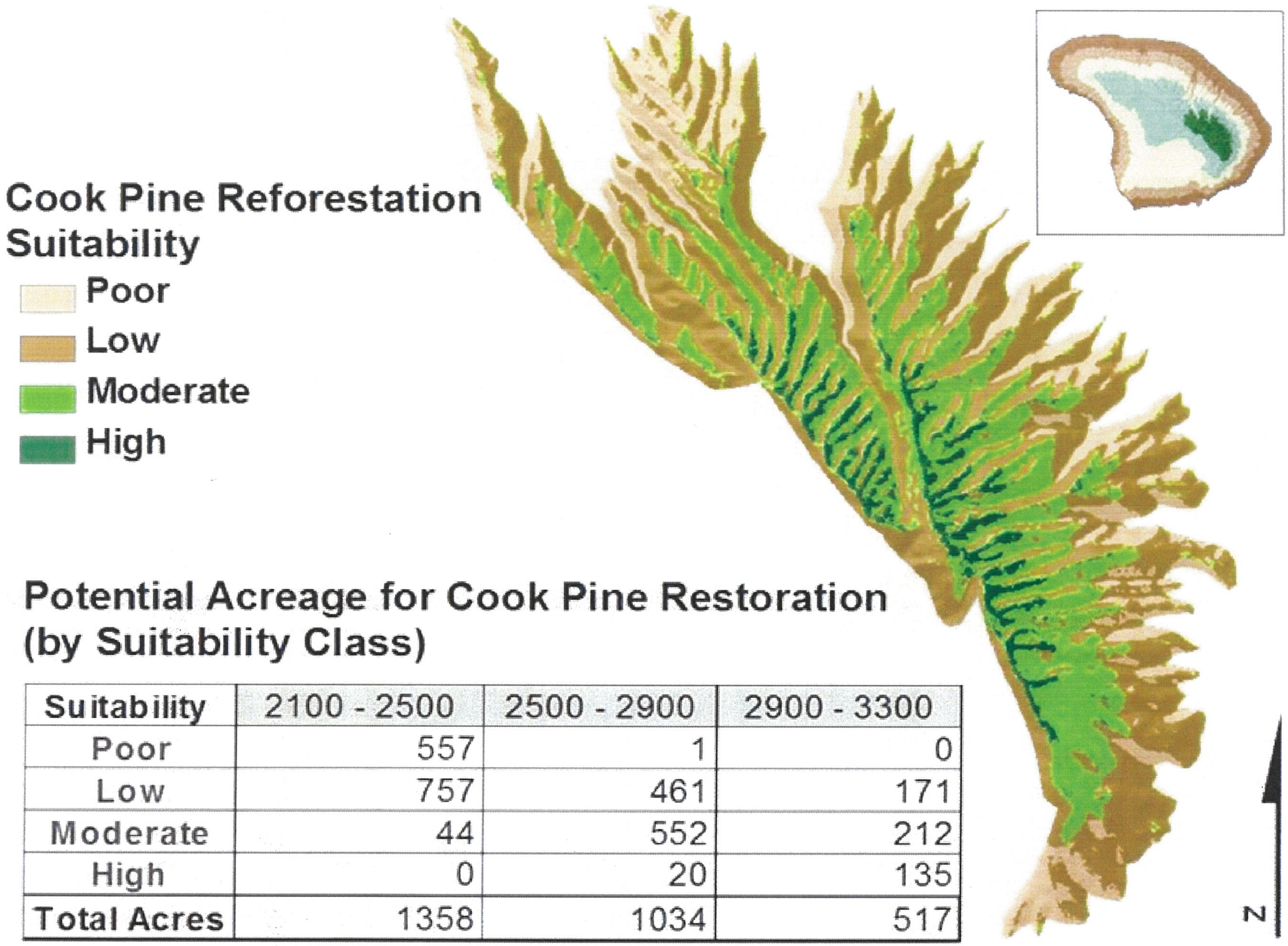


Figure 49. Terrain Suitability model for Cook Pine restoration.



Potential Acreage for Cook Pine Restoration (by Suitability Class)

Suitability	2100 - 2500	2500 - 2900	2900 - 3300
Poor	557	1	0
Low	757	461	171
Moderate	44	552	212
High	0	20	135
Total Acres	1358	1034	517

Figure 50. Suitability map for Cook pine reforestation.

7. Conclusions

a) The current study has documented a substantial cloud-water (fog drip) resource in the upper Lāna`ihale watershed above 2,500 ft. In the Lāna`ihale summit region the measured fog drip from mature Cook pine can reach several hundred inches per year at well exposed sites. These values far exceed earlier measurements associated with the PRI study during the 1950s. Differences can be attributed to the fact that Cook pines are now much larger, and the cloud-water resource has been found to increase exponentially at higher elevations above the original PRI study site at 2,750 ft.

b) We are able to successfully model Cook pine throughfall using open-site fog gauge measurements. This offers the potential for comparatively inexpensive and simple long term monitoring of the cloud-water resource and fog drip recharge in the Lāna`ihale watershed without direct, cumbersome measurements of actual throughfall.

c) Soil moisture content under Cook pine in the upper watershed typically remained at or near saturation even during low rainfall periods implying substantial gravitational water movement into recharge as a consequence of frequent fog drip.

d) Evapotranspiration rates in the upper water are estimated at 29-30 in/yr.

e) A simple water-balance model for mature Cook pines in the upper watershed indicated as much as 300+ in of canopy cloud-water throughfall contribution to run-off and groundwater recharge, compared to only about 16 in canopy throughfall from direct rainfall.

f) Further studies would be required to evaluate the "cumulative" fog drip impact of the substantial Cook pine plantings in areas of the watershed where fog exposure may be somewhat less than the "ideal" summit ridge sites monitored as part of this project.

8. Recommendations:

a) Plant more Cook Pine. This study has documented the substantial fog drip contribution to Cook pine throughfall in the upper Lāna`ihale watershed above 2,500 ft, and further mapped areas highly suitable for reforestation. Aggressive reforestation with Cook pine offers the potential for substantial increases in ground water recharge in the decades ahead, and if combined with simultaneous native ecosystem restoration (perhaps using some Cook pine fog drip water for native species irrigation) can provide enhanced ecosystem services in an uncertain climate change future.

Some global warming models predict a gradual lifting of the cloud-base level in Hawai`i (so called Monte Verde effect, named for the Costa Rican cloud forest imperiled by reduced fog drip). Other models suggest a global warming will strengthen the trade winds , and the related upper level trade wind inversion that restricts vertical cloud development and reduces rainfall. At the same time these models predict reduced winter rainfall from frontal storms that constitute a significant component of annual rainfall in sheltered leeward areas such as Lana`i. Future stronger trade winds (with a stronger inversion; i.e. thinner cloud layer) would favor increased cloud water delivery to the Lāna`ihale watershed but reduced rainfall, magnifying the future importance of Cook pine fog drip. Consider expanded Cook pine reforestation as a potential buffer against future climate change.

b) Combine aggressive Cook pine reforestation with sustained companion efforts for native ecosystem restoration in the watershed. Even if many native plants may not be exceptional fog drip collectors, in addition to their intrinsic and cultural values, they anchor soil and can substantially reduce the considerable erosion threats remaining in the watershed. Ongoing fencing and ungulate & feral animal removal are important steps toward this end. However, examples abound in Hawai`i of aggressive alien plant invasions even in well fenced and protected areas.

c) Implement sustained precipitation monitoring in the Lāna`ihale watershed. The long term monitoring of rainfall at the Lanai hale summit was discontinued in 2004. Modern watershed management requires precipitation input data in addition to the monitoring of ground water levels (source wells, springs, etc.) The following is suggested as a minimum monitoring plan for the watershed:

i) Reestablish continuous rainfall measurement at the Lana`ihale summit site, and at least two other locations along the summit ridge at different elevations. This can be done with relatively inexpensive manual rain gauges, read periodically (monthly) by watershed personnel in conjunction with their other duties in the watershed,

ii) Maintain at least one active fog gauge in the summit area (either read manually or linked to a recording data logger) as a long term "sentinel" for detecting subtle changes or trends in cloud water delivery to the summit Lāna`ihale watershed. Based on relationships established in this study this fog gauge output can also be used to in provide ongoing, robust estimates of fog drip input into groundwater recharge and sustainable water use.

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