FOG WATER CHEMISTRY AND EPIPHYTIC LICHENS AS INDICATORS OF POLLUTANT INPUT TO VENEZUELAN CLOUD FORESTS

by

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ABSTRACT

Atmospheric pollution is generally believed to have played a major role in forest decline in northeastern North America and Europe, particularly at high elevation sites. Recently, fog has been reported to contribute significant acidic and trace metal inputs to these montane forests. However, in tropical montane forests very little is known about fog occurrence or chemistry.

In this study fog incidence and chemistry were examined in two Venezuelan cloud forests adjacent to the Caracas Valley at Altos de Pipe and El Avila National Park. The epiphytic lichen community was characterized and the lichen *Parmotrema madagascariaceum* was chosen as an indicator of trace metal input. Transplant experiments were carried out to evaluate spatial trends in atmospheric deposition of trace metals.

Fog was found to be a very important hydrological and chemical input to these high altitude forests. Fog deposition accounted for an estimated 38% and 78% of annual precipitation at Altos de Pipe and El Avila, respectively, with fog occurring for up to 326 days of the year. Fog was acidic with a mean pH of 4.6-5.0. Nitrate concentrations were very high as were concentrations of trace metals, particularly Pb and Zn. Elevated concentrations of these metals were also seen in lichen tissue and associated bark. Lead levels in lichens reached 190 $\mu g/g$ dry wt. Lichens transplanted from relatively 'clean' to more polluted sites showed an increase in

metal concentrations after several months. This accumulation of metals could ultimately lead to ecosystemic problems. Indeed, the apparent contamination of cloud forest fogs needs to be monitored more widely as does the biological impact.

RESUMEN

La contaminación atmosférica es considerada uno de los factores mas importantes en el deterioro de los bosques de Norte America y Europa, especialmente en los lugares montañosos. Recientemente, se ha reportado que las nieblas ácidas contribuyen a los bosques montañosos con cantidades significantes de ácido y trazos de elementos. Sin embargo en sistemas tropicales montañosos, especialmente en los bosques nublados, estudios se han realizado sobre la incidencia y composición química de la niebla son escasos, a pesar de que los bosques están cubiertos con esta la mayor parte del año.

En esta tesis la composición química de la niebla y su incidencia en dos bosques nublados venezolanos adyacentes al valle de Caracas (Altos de Pipe y El Avila Parque Nacional) se ha examinado. Las mediciones fueron tomadas durante la estación seca y la de lluvias de 1989-90. También, la comunidad de líquenes epifíticos fue determinada para establecer de la riqueza de especies de líquenes y también para identificar una especie que sirva como bioindicador de la calidad del aire.

El líquen epifítico *Parmotrema madagascariaceum* (Hue) Hale fue escogido como el indicador mas apropiado para medir la acumulación de metales en los bosques nublados. Experimentos de transplantes se realizaron para evaluar los patrones de

altitud, espacio y temporada de la deposición atmosférica de metales ocurrida en los sitios de estudio.

Se encontró que la niebla es un factor hidrológico y químico muy importante en los bosques nublados. Medidas preliminares mostraron que la deposición química equivale al 38% y 78% de precipitación anual en Altos de Pipe y El Avila, respectivamente, con una ocurrencia de hasta 326 dias por año. La niebla de los dos lugares presentó caracteristicas acidas con un pH promedio de 4.6-5.0. Las concentraciones de nitrato fueron muy altas y representaron una gran parte de la acidez. En el agua de niebla se encontraron altas concentraciones de metales, especialmente plomo y zinc. También el tejido de los liquenes y su corteza asociada presentaron altas concentraciones de estos metales. Niveles de plomo en líquenes recolectados en el mas alto de los sitios de El Avila alcanzaron hasta 190 $\mu g/g$ peso seco. Varios meses luego de ser tranplantados de sitios relativamente 'limpios' a otros contaminados, líquenes mostraron un aumento de algunos metales, cuando comparados con los niveles de control. Esta acumulación de metales podría causar problemas al ecosistema en los sitios de alta exposición a la niebla. En conclusión, esta aparente contaminación de niebla en los bosques nublados, así como su impacto biológico, requieren un sistema de medición mas extensivo.

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CHAPTER 5 GENERAL DISCUSSION

This thesis provides significant new data on the incidence and chemistry of fog events in the two cloud forests of El Avila and Altos de Pipe, in the northern Coastal Range of Venezuela during the wet and dry season. This study also includes information on the composition and distribution of the corticolous community of epiphytic lichens in these cloud forests. The epiphytic lichen, *Parmotrema madagascariaceum* was selected as a bioindicator species and its elemental content was determined from six subsites at the two cloud forests. One overriding background concern was that polluted air masses originating in the Caracas conurbation may be adversely affecting the rich cloud forests of the surrounding montane areas and that lichens would be a sensitive indicator of this.

Both cloud forest sites support a very rich community of epiphytic lichens. The total number of corticolous foliose lichens was found to be 61. Percentage cover of lichens and bryophytes on the boles of a common cloud forest tree species was close to 100%. Clearly, these forests provide ideal habitats for cryptogamic and vascular epiphytes.

A very high incidence of fog in cloud forests at El Avila and Altos de Pipe was observed during both wet and dry seasons. Preliminary measurements show that fog deposition is an important hydrological input, accounting for a large percentage of annual precipitation i.e., an estimated 78% and 38% at El Avila and Altos de Pipe, respectively. The highest fog frequency was in the early morning hours at both cloud forest sites. The El Avila and Altos de Pipe cloud forests are in fog for an annual mean of approximately 8 hrs and 5 hrs during a 17 hr/day, respectively. Fog events at these sites are estimated to occur up to 326 days per year. Therefore, exposure to atmospheric pollutants in fog may be very high. Such exposure and interception is significant for epiphytic lichens since they are poikilohydric and commence photosynthesis when wetted. Furthermore, atmospheric pollutants in solution can be more damaging compared to dry deposition in dry conditions when lichens are physiologically inactive (Richardson and Nieboer 1981; Coxson 1988).

The fog at both cloud forest sites was slightly acidic, with a high NO_3:SO_4 ratio. The lowest pH measured was 3.70 at El Avila, following 14 days without precipitation. Ratios of NO_3:SO_4 were between 0.57-1.50 and reveal the relative importance of NO_3 inputs compared to SO_4 in fog collected from this region. These ratios can be compared to ratios from temperate fog of between 0.18 and 0.67 for high altitude forests in Quebec (Schemenauer and Winston 1988). Nitrate was often the most significant anion in fog and when compared to other studies, NO_3 concentrations showed comparable values to fog collected from polluted high elevation sites in Germany. The apportionment of F^-, $SO_4^=$ and Ca^{++} ions in fog showed high anthropogenic contributions at both sites. Significant oceanic influences accounted for a large portion of Na^+, Mg^{++}, K^+ and Cl^- in fog collected from both sites, thus perhaps reflecting the close proximity to the Caribbean. Fog ion concentrations were much higher when compared to precipitation from the same site. Fog also was generally more acidic than precipitation. Analysis of bulk deposition and throughfall showed that throughfall generally contained higher ion concentrations with up to 10x greater concentrations of K^+ and Mg^{++} compared to bulk deposition from the same site. Throughfall also had consistently higher pHs compared with bulk deposition. It is suggested that the leaching of bases from canopy surfaces neutralizes incoming wet deposition, resulting in throughfall which exhibits enriched ion concentrations and higher pHs at all sites.

Trace element content of fog showed both El Avila, and to a lesser extent Altos de Pipe, to have substantial inputs of Pb, Zn, B and Mn. These trace elements most probably arise from anthropogenic sources. Very high Pb concentrations of up to 270 μg/L were found in fog collected from El Avila. This is much higher than values from temperate high elevation studies: Weathers *et al* (1988) report levels of 31-62 μg/L in fog collected from Mt Washington, New Hampshire; while fog collected from sites in tropical and subtropical high elevation sites range from only <5-8 μg/L (Schemenauer and Cereceda 1992a; 1992b). High inputs of trace elements were also reflected in tissue chemistry of lichens collected at the two cloud forest sites. Lichens and associated bark showed high Pb concentrations of up to 190 μg/g and 86 μg/g, respectively. This compares with lichen values of up to 77.7 μg/g in *Hypogymnia physodes* collected from an industrial town in Central Scotland (Gailey *et al* 1985) or values of up to 138 μg/g in *H. physodes* from Mt. Sutton, Quebec

(Scott and Hutchinson 1989). The main source of Pb in the present study is almost certainly anthropogenic and most likely arises from the automobile combustion of leaded gasoline. Boron and Mn levels were also very high in lichens and seemed to be of anthropogenic origin. Large amounts of Al, Fe, and Mg were found in lichen tissue and are most probably associated with soil dust and seasalt.

Overall, the El Avila sites were more affected by anthropogenic emissions from the Caracas Valley than the sites at Altos de Pipe. Although Altos de Pipe is located downwind of Caracas, it does not seem to be receiving comparable levels of pollutants. This may be due to mixing of 'clean' air coming from the southeast or east which dilutes air masses containing high concentrations of atmospheric pollutants from the Caracas Valley. Clearly, some atmospheric pollutants, depending on their form and chemical species, are transported only short distances. Lead emitted into the atmosphere via vehicle exhaust is mainly in particulate form from submicrometer to 10 μm diameter (Reiter *et al.*, 1977). Lead associated with larger particles of >1 μm diameter are subject to rapid gravitational fallout. These particles have a very short lifetime in the atmosphere and often are deposited within 100 m from the road. However Pb particulates of <1 μm are small enough to be unaffected by gravitational settling and are dispersed into the boundary layer. (Reiter *et al.*, 1977). From the boundary layer, these particulates may be transported over long distances. Eventually these small particulates are removed from the atmosphere by precipitation and or fog deposition or by dry deposition (Barrie and Schemenauer 1988).

Transplant experiments, described in chapter 4 showed significant increases in trace metal concentrations when lichens were transplanted from relatively 'clean' to more polluted sites. Increases of up to 6.3 μg Pb/g/mo were seen in lichen thalli transplanted from El Avila's San José to Altos de Pipe's IVIC Canchas site. The opposite occurred when lichens were transplanted from polluted sites to 'cleaner' sites with significant decreases in Pb and Zn concentrations. These changes in concentrations were seen over a very short time period of 6 and 10 months and paralleled endemic lichen concentrations at the transplanted sites. This indicated that Pb and Zn levels in lichen tissue are a direct consequence of local atmospheric levels of Pb and Zn. Furthermore, these metals are accumulated rapidly in lichen thalli. No information, to my knowledge, exists on trace metal fluxes in these cloud forest systems. However, based on studies in temperate high elevation sites, the soil organic layer is often the sink of metals such as Pb and Zn, with long residence times for Pb in forest floors being estimated at 500 yr (Friedland and Johnson 1985).

Highest mortality of lichen transplants was seen at the Los Venados site (29%), closest to the Caracas Valley. This suggests that the Los Venados site exhibited biologically significant differences in microhabitat and/or differences in concentrations of phytotoxic substances. Due to daily inversions over Caracas (Sanhueza and Romero 1978), the Los Venados site may be exposed to higher concentrations of gaseous pollutants such as NO_x, SO_2, O_3 and PAN compared to other sites. Thus far, no measurements of these compounds have been taken at these high elevation sites.

Cloud forest ecosystems in Venezuela may be highly susceptible to acidification damage. Soils in this region are naturally acidic and exhibit high exchangeable Al contents and very low Ca levels (Dengo 1951; Garcia-Miragaya and Herrera 1971). Many plant species in Venezuelan cloud forests accumulate Al in either their leaves or roots. Cuenca *et al* (1990) suggest that due to natural acidity and high Al soil content in cloud forest systems, many plants and animals have evolved an acid tolerance. However, these organisms may not tolerate increased acidity, nor an increase in soluble Al which may be occurring due to human activity. Aluminium toxicity has been associated with forest decline in temperate regions, especially at high elevation sites (Smith 1981; Johnson and Siccama 1983).

It seems likely that with long term exposure to atmospheric pollutants, including acidic fog and high concentrations of trace metals, epiphytic lichens may be at risk of significant decline at the two cloud forest sites of El Avila and Altos de Pipe. Although SO_2 levels in Caracas are low in comparison with temperate urban centres, emissions have increased more than two fold between 1977-1981 (Sanhueza *et al.*, 1988). Previous measurements show that on a national scale, NO_x emissions increased 131% between 1970-1984 (Sanhueza *et al.*, 1980). Due to the growing population of the Caracas Valley and the concomitant growth in the number of vehicles, a significant increase in NO_x in the future is probable. As precipitation is naturally acidic in this region, an increase in these anthropogenic inputs of acidic gases would rapidly increase the total acidity (Sanhueza *et al.*, 1988). Fog in the same area may be much more acidic and contribute a threat to sensitive elements of the native flora. Monitoring programs are needed to provide data on changes in fog and rain chemistry over the long term. Epiphytic lichens are widely recognized as sensitive and practical bioindicators of air quality and some authors have proposed them as early warning sentinels of forest decline in temperate regions (Sigal and Johnston 1983; Scott and Hutchinson 1989). Loss of species in parallel with changes in fog and rain chemistry due to pollutant increases would be a major cause for concern regarding the health of the Venezuelan coastal montane rain forests.

An increase in acidity of wet deposition may have profound effects on the distribution and mobility of trace metals, particularly Pb, Zn and Mn in these cloud forests. It is apparent that epiphytic lichens are affected by trace metal inputs via fog and/or dry deposition at El Avila and Altos de Pipe. Lead, in particular, may pose a potential threat to epiphytic lichens, if high inputs persist over the long term. Other epiphytes including bryophytes, liverworts, ferns and vascular epiphytes may also be affected. *Tillandsia* (Spanish moss) an epiphytic member of the Bromeliaceae has been used as a sensitive monitor of Pb and other heavy metals in subtropical areas (Martinez *et al.*, 1971). Bryophytes are also known to accumulate large amounts of heavy metals and have been used as effective monitors of these elements (Ross 1990). Due to their unique morphological and physiological characteristics and particularly their dependency on atmospheric inputs for nutrients epiphytes often show the detrimental effects of air pollutants much earlier than non-epiphytic higher plants. More information is needed on the inputs of gaseous pollutants and their effects on cloud forest vegetation in this region.

Epiphytes are of considerable importance in tropical rain forests. They occur in the foodchains of many vertebrates and invertebrates, and are important in nutrient cycling. Those lichens with cyanobacteria phycobionts can make significant contributions to nitrogen fixation (Forman 1975; Slack 1988). In temperate ecosystems, lichens can be very important in nutrient cycling. Epiphytic lichens are highly efficient in capturing nutrients from wet deposition, occult precipitation (fog) and gaseous uptake (Knops *et al.*, 1991). In previous studies, the importance of lichens in nutrient cycles has been based on biomass (Pike 1978; Lang *et al.*, 1978). However, Knops *et al* (1991) argue that many atmospheric-canopy interactions occur on the basis of surface area and/or morphological form. Due to the highly dissected three-dimensional nature of lichens and other epiphytes, in contrast to the much lower relative surface area of other canopy components such as leaves and branches, lichens may contribute more to atmospheric-canopy interactions than biomass values alone would suggest (Knops *et al.*, 1991). However in addition to the effects on nutrient cycling, the large surface area of lichens and other epiphytes also serves as an increased surface for pollutants in fog.

Lichens and other epiphytes have an enormous moisture interception capacity, especially in the humid tropics. Although epiphyte biomass was not measured in the present study, percent cover was close to 100% at all sites at El Avila and Altos de Pipe. Many tropical montane forests have very large epiphyte biomass values. Nadkarni (1984) reported epiphytic biomass in the Monteverde Cloud Forest in Costa Rica as 4.7 tonnes/ha. In Tanzania, Pócs (1982) measured epiphyte biomass and found that in submontane rain forests (1415 m) it was 2.1 tonnes/ha dry wt and in mossy elfin mist forests (2120 m) biomass reached 13.7 t/ha. This latter figure was calculated to be half the total biomass for the entire forest. Pócs (1982) also reported that 78 g dry weight of corticolous epiphytes had an interception capacity of 471% on tree trunks, 110-120 cm above the ground. Pócs (1982) estimated that water interception reached 30,000 litres/ha absorbed during a single rainfall event. In cloud forests in the Colombian Andes, Veneklaas *et al* (1990) estimated total epiphyte biomass to be 12 t/ha dry wt, made up of bryophytes, poikilohydric ferns, lichens and vascular epiphytes. This study was conducted at an upper montane rain forest at an altitude of 3370 m. Water content was highly variable ranging from 27-591% of dry wt in epiphytes. Veneklaas *et al* (1990) showed that water captured by epiphytes is lost very slowly through drainage and evaporation. Evaporation rates were low considering the large amounts of water which can be stored in the epiphyte mass.

Loss of epiphytes due to increased pollutant input could have very serious consequences for cloud forest vegetation as a whole. In the reduction or absence of epiphytes, water storage capacity would be greatly reduced. This in turn would substantially increase run-off and erosion, especially during the rainy season.

A more serious case is that of deforestation in cloud forest ecosystems. Cloud forests are estimated to cover 500,000 km^2, equivalent to approximately 10% of the total area of tropical rain forests (Stadtmuller, 1987). There is great variability in cloud forests and no scientific definition, to my knowledge, exists. In very general terms, cloud forests are defined by Stadtmuller (1987) as:

> "All forests of the wet tropics which are frequently covered by clouds or fog and thus receiving, in addition to rain, a source of moisture via the condensation and/or capture of small water droplets, influencing the hydrological and radiation balance as well as climatic, edaphic and ecological parameters."

This type of forest is a highly endangered ecosystem in many regions due to increasing population pressures and intensified land uses. Perhaps most critical in this respect are the unprotected cloud forests of Central America and the Caribbean, which are reputed to be disappearing at a rate of 20 ha/min (LaBastille and Pool 1978). This is due to logging and shifts in land use to make pasture and fields for crops. Farmers take advantage of cooler climates at higher altitudes to raise temperate vegetables and flowers. This is clearly exemplified by the villagers of Galipán within the boundaries of El Avila National Park. This village, located on the steep northern slopes of El Avila, has been in existence for approximately 300 years (Gallardo, pers. comm.) and has provided temperate crops and flowers to city dwellers in Caracas for many years. On both sides of the village and associated terraced agricultural fields, large swaths of cloud forest vegetation have been removed. Although development has been halted due to National Park regulations, there are many areas along the Cordillera de la Costa which are unprotected, and clearing of these areas continues.

Large scale removal of cloud forest vegetation has serious repercussions. Pócs (1982) reports that in the Uluguru Mountains of Tanzania, when the protective cover of forest has been removed in large areas, heavy rainfalls have caused destructive large scale landslides. In the mountains of South America, the same phenomenon was reported by Alexander von Humboldt more than a century ago (Humboldt and Bonland 1881). He reported that "once forests on the top and sides of mountains were removed, the moss along with the brushwood disappeared, and then when the rain came it formed sudden inundations which devastated the country" (cited in Puckett 1988). Presently, in the Caracas Valley which is surrounded by hills and mountains, growing populations of squatters are clearing many of the hills for housing. During the heavy rains which occur in the wet season, areas at the base of these hills are often temporarily flooded with large scale erosion taking place down the slopes of the denuded hills.

The conservation of cloud forest ecosystem is not only critical in the prevention of landslides and large scale erosion, but also in the overall watershed regime

(Hamilton *et al.*, 1976; LaBastille and Pool 1978). Deforestation of cloud forests has a large potential impact of the hydrology of watersheds and may cause a substantial decrease in water yield (Zadroga 1981; Veneklaas 1990). Once cloud forest vegetation is removed, the ability to intercept fog water is lost or greatly reduced. This may be especially important in altering the hydrological cycle where fog deposition contributes significantly to annual net precipitation, particularly during the dry season. Consequently, fog incidence and the interception and subsequent redistribution of fog water by vegetation is of great hydrological importance. Cloud forest vegetation may significantly reduce evapotranspiration and increase net precipitation and regulate flow regime (Zadroga 1981). The continuous supply of high quality drinking water from watersheds covered by cloud forests is also an important factor in the conservation dilemma (LaBastille and Pool 1978; Veneklaas 1990).

Furthermore, with the clearing of cloud forest a great loss of biodiversity would follow. Many floral and faunal species are restricted to cloud forest ecosystems. Often these cloud forests are much wetter than surrounding areas that do not receive fog deposition and thus habitats may differ substantially between cloud forest and lower altitude forests.

Many questions remain unanswered and could be addressed in further research. Soil analysis, including elemental concentrations would be useful in assessing the extent of trace metal concentrations in cloud forest sites, especially at El Avila. Clearly, epiphytes and bark substrate show significant enrichment for Pb and other metals however, it is not known whether bark Pb levels reflect surficial deposits or uptake via Pb in soil. In addition, components of higher plants such as leaves, roots and branches could be analysed for trace metal content to determine whether metals are being taken up via soil or are deposited only on canopy surfaces. This information would be useful in assessing the amount of toxic elements to which these cloud forests are currently exposed. Furthermore, it may be useful to analyse throughfall for trace metal content in order to determine concentrations of metals reaching the forest floor via wet deposition.

It may also be important to examine the relative contributions of dry and wet deposition on atmospheric pollutant input at the two cloud forest sites and to quantify concentrations of gaseous pollutants including O_3, NO_x, SO_2 and PAN at these high elevation sites.

As natural acidity of precipitation and surface waters is common in Venezuela, there is a need to distinguish between natural and anthropogenic sources of acidic deposition in fogs. This could be done by analysis of fog collected from non-urban/industrial impacted cloud forests.

Finally, this thesis has provided significant baseline data on fog occurrence and chemistry at two cloud forest sites in northern Venezuela. The corticolous community of foliose lichens at these two cloud forests has been described and a common species was employed as a bioindicator of air quality. Results of this study show that significant acidic and trace metal inputs are reaching cloud forest vegetation and over time these atmospheric pollutants may be a risk to the health of these rich coastal montane forests.

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