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The hydrological significance of cloud forests in the Sierra de las Minas Biosphere Reserve, Guatemala

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Abstract

This paper discusses the hydrological significance of socio-economic practices such as agricultural land use change and forest extraction to communities adjacent to the Sierra de las Minas Biosphere Reserve, Guatemala. Cloud forest hydrology differs from most environments because of the increased frequency of fog interception and fog precipitation. Fog precipitation occurs when intercepted cloud droplets coalesce on foliar and woody surfaces as fog filters through the canopy, and represents a significant proportion of the annual water inputs to cloud forests especially during the dry season. Interception data from this study showed that fog precipitation contributed greater than 7.4% of the hydrological inputs at 2550 m and less than 1% at 2100 m in the Sierra de las Minas. During the dry season fog precipitation contributed 19% of the hydrological inputs to the water budget of the cloud forest. Fog precipitation may be a significant hydrological input to the water resources of the local population. Socio-economic practices such as the conversion of cloud forest to agricultural land may decrease water resources for communities in Guatemala that demand greater quantities of water.

Keywords: Fog precipitation; Hydrology; Cloud forests; Deforestation; Water resources; Guatemala

1. Introduction

The United Nations General Assembly proclaimed 2002 the International Year of Mountains on 29 July 1998, and called for attention to these often neglected regions of the world. In Latin America montane environments are being modified by development as settlers search for new agricultural land (Richards, 1996; Young, 1998; Young and Leon, 2000). These changes in land use can have profound impacts on the water resources, especially in cloud forest environments (Bruijnzeel and Proctor, 1995). This study addresses the significance of cloud forests on water resources and the importance of fog precipitation as a hydrological input in the Sierra de las Minas Biosphere Reserve, Guatemala.

The hydrology of cloud forests differs from other environments because of the presence of fog precipitation. Fog precipitation occurs when fog droplets pass through the canopy of the forest and are filtered by vegetative surfaces. Fog precipitation can occur in any environment where fog persists long enough for cloud droplets to coalesce on vegetation surfaces and drip to the forest floor. Working in a Colombian cloud forest, Cavelier and Goldstein (1989) found that 48% of the annual water input to the forest floor was from fog precipitation; annual fog interception was 796 mm and annual precipitation was 853 mm. Local factors influencing the quantity of fog precipitation include canopy height (Kittredge, 1948), canopy architecture (Kimmins, 1987), wind velocity (Lovett et al., 1982), foliar surfaces (Smith and McClean, 1989), hillslope orientation (Ellis, 1971; Zadroga, 1981), and orientation of foliage and branches (Cavelier and Goldstein, 1989).

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Fog precipitation occurs in diverse regions of the world as a result of advection of warm moist air masses over cool surfaces (Schemenauer and Cereceda, 1992) and adiabatic cooling of air forced up the slopes of mountains (LaBastille and Pool, 1978; Henderson-Sellers and Robinson, 1986; Stadtmüller, 1987). In Central America, the northeast trade winds carry moisture from the Caribbean Sea to mountain ridges (Sanford et al., 1994; Hartshorn, 2000). Fog precipitation is common in these montane forests at elevations from 840 to 3475 m (LaBastille and Pool, 1978).

Fog precipitation has been measured by (1) constructing fog gauges (Vogelmann, 1973; Schemenauer and Cereceda, 1994), (2) comparing throughfall and precipitation (Stadtmüller and Agudelo, 1990), (3) measuring discharge from watersheds (Zadroga, 1981; Harr, 1982), and (4) developing canopy-fog deposition models (Collett et al., 1991). Means (1927) compared soil moisture between a location in the open and a location under pine and eucalyptus trees to estimate fog precipitation. One research team used stable isotope analysis in Kenya (Ingraham and Matthews, 1988) and California (Ingraham and Matthews, 1995) to find that fog precipitation is a source of groundwater recharge and a source of water for transpiration.

Removal of cloud forests reduces the contribution of fog precipitation to the hydrological budget of the watershed. Deforestation of a montane cloud forest may decrease water yield because of the decrease in fog precipitation (Zadroga, 1981). Several montane cloud forests were felled for local fuelwood (Richards, 1996), subsistence and export agriculture (Colchester, 1991; Southgate and Basterrechea, 1992; Castellon, 1996; Critchley and Bruijnzeel, 1996; Young, 1996), construction of rural roads (Young, 1994; Ziegler et al., 2000; Olander et al., 1998), logging (Richards, 1996), and the expansion of grazing lands (Myers, 1992; Nations, 1992). Often cloud forest vegetation is progressively replaced with agricultural land or coffee plantations which expand from lower elevations to higher elevations. The last-remaining cloud forests often occur on ridge crests and the higher mountain peaks (Daugherty, 1973). With changes in species composition and stand characteristics, the filtering of water droplets to produce fog precipitation may be directly affected and fog precipitation inputs will likely change.

Federal law in Guatemala prohibits logging for economic activity without a permit from the Instituto Nacional de Bosques (INAB), an agency of the Guatemalan government established to reduce deforestation and encourage reforestation projects, however fuelwood gathering and clearing land for agriculture is common. In parts of Guatemala, deforestation threatens the watersheds for some major cities (Barry, 1992). The deforestation rate in Guatemala is 900 km^2 per year (Nations, 1992). The forest cover as a percentage of the national territory dropped from 67% in 1959 to 35% in 1990, and the projected loss of all forest cover is between 25 and 40 years (Barry, 1992). In Guatemala, the major cause of deforestation is the conversion of forests to pastures in frontier regions of the Department of El Petén in the northern region of the country. While this trend of increasing migration to northern Guatemala poses a threat to the sustainability of the natural ecosystems of the northern region, the majority of the population in Guatemala reside in the central highlands where secondary forests are actively managed and forest extraction is common (Veblen, 1976; Veblen, 1978; Pira et al., 1999; Holder, 2004a).

Guatemalan cloud forests have been one of the last forest types to be seriously threatened by human activity (Tum and Budowski, 1997). Many of the mountainous regions of Guatemala were previously unapproachable by vehicle. Because of the economics of commercial logging of valuable hardwoods and pines, it has become feasible to construct temporary roads into mountainous regions, extract the desired timber (usually by felling the entire forest), and leave the roads and surrounding mountainside to erode heavily during the first rainy season after logging operations are completed. The cloud forests of the Sierra de las Minas in eastern Guatemala have a history of extensive logging operations (Lehnhoff and Núñez, 1998). They have been protected in the past by unstable and steep slopes, cool temperatures, heavy precipitation, and soils that often are relatively nutrient-poor. The major tracts of cloud forest are presently in danger of deforestation. Small remnants of cloud forests remain in ravines and on crests.

The lower portion of the cloud forest has long been known to be well-suited for coffee plantations and as that industry continues to expand the cloud forest inevitably retreats upslope. As the population of Guatemala increases and the inequities of land distribution persist (Colchester, 1991), agricultural land is encroaching on forested mountain slopes previously either inaccessible or considered unsuitable for agriculture.

The objectives of this study are to address the degree to which fog precipitation adds a significant proportion to water resources of communities in Guatemala and to discuss the hydrological significance of cloud forests to the communities adjacent to the Sierra de las Minas Biosphere Reserve.

2. The Sierra de las Minas Biosphere Reserve

An examination of fog precipitation was conducted within the Sierra de las Minas Biosphere Reserve, Guatemala, 15 km east of the village of Chilascó, Salamá, Baja, Verapaz (Fig. 1). The Sierra de las Minas Biosphere Reserve of Guatemala was established in 1990 to protect the highly biodiverse cloud forest of

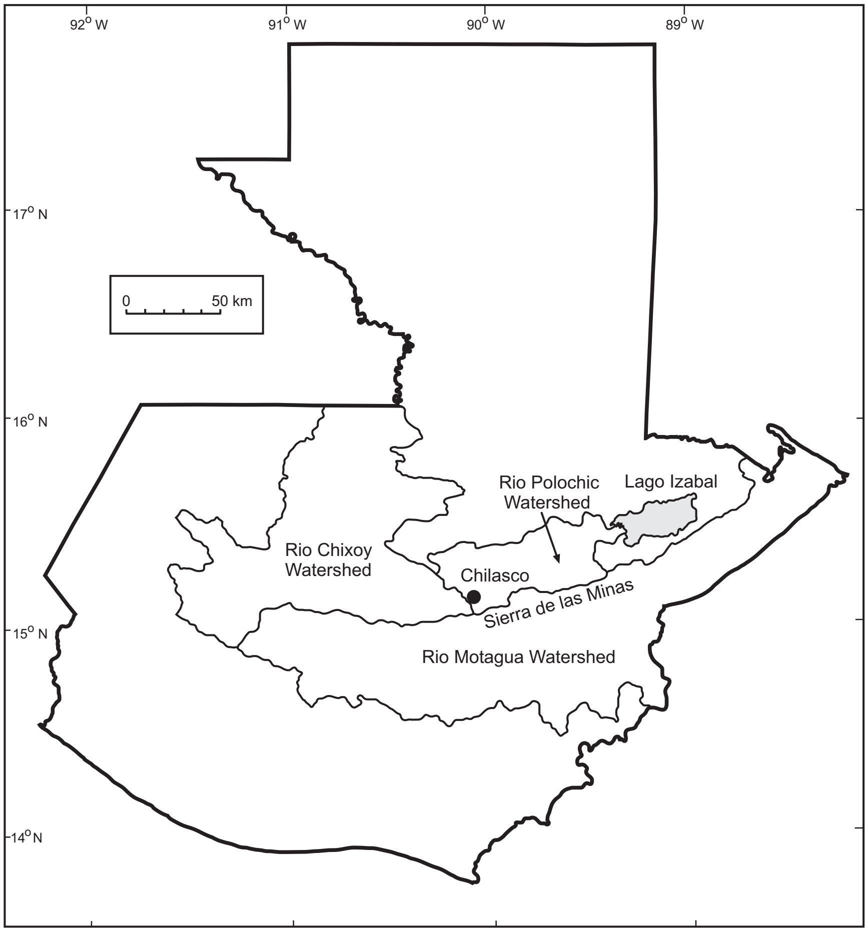

Fig. 1. Location of the major watershed Sierra de las Minas in eastern Guatemala.

approximately 2400 km^2 (Ack and Lehnhoff, 1992; Lehnhoff and Núñez, 1998). Because of inadequate government support for protected areas, a number of non-governmental organizations (NGOs) are involved in protected area administration. An example of such a NGO is Defensores de la Naturaleza, an environmental organization based in Guatemala City. Defensores de la Naturaleza manages the Sierra de las Minas Biosphere Reserve, and a government commission overseas the managers (Lehnhoff and Núñez, 1998). Defensores de la Naturaleza has developed management plans for wildlife protection, environmental education, scientific research, and sustainable development within the biosphere reserve. International groups and private companies such as the World Wildlife Fund, the Nature Conservancy, the MacArthur Foundation, CARE, and the RARE Center for Tropical Conservation have contributed substantially to (1) the operating budget of Defensores de la Naturaleza, (2) sustainable development projects in villages surrounding the biosphere reserve, and (3) the preservation of the cloud forests within the core zone of the biosphere reserve.

The Sierra de las Minas extends in roughly an east–west direction for approximately 130 km in east-central Guatemala across portions of five departments: Zacapa, El Progreso, Baja Verapaz, Alta Verpaz, and Izabal (Fig. 1). The northern and southern slopes of the mountain range are drained by tributaries of the Río Polochic, the Río Chixoy, and the Río Motagua. The ridge extends unbroken above the 2100 m contour for 65 km. Cerro Pinalón and Cerro Raxón have elevations greater than 3000 m. The Sierra de las Minas is bounded to the west by the Salamá basin within the Río Chixoy watershed, while in the east the mountains gradually lose elevation and southeast of Lago de Izabal the mountains decrease to less than 200 m.

The Río Polochic valley is inhabited by Kekchí people and plantation agriculture is common at the valley bottom (Castellon, 1996). The village of Chilascó near the intersection of the three major watersheds is the largest community at the western end of the Sierra de las Minas Biosphere Reserve (Figs. 1 and 2). The Río Motagua valley is south of the Sierra de las Minas. Ladinos make up greater than 95% of the population.

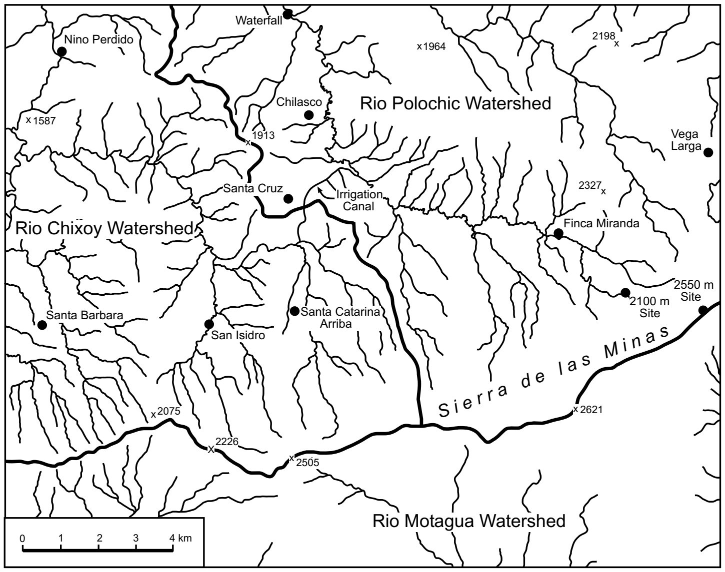

Fig. 2. Location of study area with watersheds and major tributaries.

Industrial development and plantation crops are common at the valley bottom, although the valley bottom is the driest region of Central America (Brown et al., 1996). More than 150 villages within and surrounding the Sierra de las Minas Biosphere Reserve rely on the water resources from 63 permanent streams and other natural resources of the cloud forest for survival.

The temperature in the Sierra de las Minas is determined largely by elevation. Nightly low temperatures at a nearby cloud forest nature preserve (Biotopo Mario Dary located at 1520 m approximately 20 km northwest of the Sierra de las Minas) range from 5 to 15 °C, regardless of season. Slightly lower temperatures occur during the winter months. Elevations as low as 1300–1500 m in the Sierra de las Minas may experience occasional frost.

Northeast trade winds create wet conditions along the northern slope of the Sierra de las Minas. From low elevations up to about 1300 m a tropical forest prevails and above this elevation precipitation exceeds 5000 mm annually in some areas where cloud forest dominates (Campbell, 1982). The Sierra de las Minas creates a rain shadow for the southern side of the ridge. Wet montane cloud forests occur above 2000 m, then dry pine–oak forests extend down to 1500 m. In the middle Motagua valley pine forest descends to about 800 m; below this level less than 500 mm of precipitation is received annually, and distinct subhumid vegetation extends to the valley floor. The west to east dip in elevation of the crest of the Sierra de las Minas plays an important role in the rainfall pattern of the lower Motagua valley. The higher crests of the Sierra de las Minas create rainshadow conditions in the middle Motagua Valley where less than 500 mm of precipitation is received annually. There is a rather abrupt increase in rainfall to the east of Gualán due to the low crest of the Sierra de las Minas to the north of that region.

The biota as a whole is of tropical origin, but many of the often immense dominant trees are of temperate origin. The diversity of plants growing in cloud forests is overwhelming. On the forest floor are numerous selaginellas, ferns, small palms, liverworts, mosses, terrestrial bromeliads and orchids, begonias, and several other herbaceous plants. The limbs and trunks of trees support a luxuriant epiphytic growth that includes algaes, mosses, ferns, lichens, bromeliads, and orchids. Along the 2000 m contour bamboos and small palms sometimes are common in the Sierra de las Minas.

Perhaps the most characteristic cloud forest plants in the Sierra de las Minas are the giant tree ferns that may reach heights of over 10 m. These are represented in the Sierra de las Minas by the families Cyatheaceae and Dicksoniaceae. Although tree ferns occur at less than 300 m in the Montañas del Mico to the northeast of the Sierra de las Minas, the northern slope of the Sierra de las Minas, and other areas where local conditions are relatively wet the year round, tree ferns reach their greatest abundance between 1500 and 2200 m. Several amphibians and reptiles are endemic to the Sierra de las Minas (Campbell and Smith, 1998). Tree ferns and herpetofauna are important indicator species of cloud forests (Hartshorn, 2000; Campbell, 2001).

Most cloud forests have a moderate amount of humus covering the forest floor. The soils of the Sierra de las Minas have a spongy layer of humus greater than 1 m deep in several locations. The mat formed by this humus gives it an almost trampoline quality as one proceeds through the forest. The humus layer may be thin in some areas but tends to be continuous, and an abundance of epiphytes, mosses, lichens, and other small moisture-loving plants cover the forest floor and vegetative surfaces.

3. Fog precipitation in the Sierra de las Minas

This section provides a summary of previously published data on fog precipitation from the Sierra de las Minas (Holder, 2003; Holder, 2004b). Five precipitation gauges were positioned in a site cleared of cloud forest near the summit of Montaña de Miranda (15°05′N, 90°01′W) at 2550 m on 24 July 1995. Data from the precipitation gauges at Montaña de Miranda were collected for 44 weeks until 11 June 1996. Fifty eight throughfall gauges were positioned in the cloud forest at an elevation of 2100 m within the cloud forest, and 36 additional throughfall gauges were positioned in the cloud forest at 2550 m near the summit of Montaña de Miranda. The gauges were monitored approximately every week. Because the 2100 m site did not have large enough canopy openings to position precipitation gauges data from the precipitation gauges at the 2550 m site were applied to the 2100 m and 2550 m sites. Because precipitation varies widely across an area and along an elevational gradient, the results of this study should be viewed as estimates of hydrological fluxes in the cloud forests.

Fog precipitation was determined from the equation for interception (I), $I = (P_g - T)$, where P_g is gross precipitation and T is throughfall. If I is a negative number fog precipitation is present. In this study, the sum of all negative quantities of interception is the quantity of fog precipitation occurring in the cloud forest watershed. The limitation of this study is that not all of the fog precipitation quantity is determined within the watershed. Fog precipitation is not reported until throughfall is greater than gross precipitation. Mature cloud forest canopies may produce fog precipitation even though throughfall is less than precipitation, but this study has used a conservative estimation of fog precipitation to account for evaporation from vegetative surfaces.

Based on the precipitation data, the dry season is estimated to be approximately six months from November to the end of April (Fig. 3). The rainy season occurs for approximately six months from May to the end of October. Seventy-nine percent of precipitation at the summit of Montaña de Miranda occurred during the rainy season over the 44-week period (Table 1). Throughfall based on the average of all gauges during each sampling period at 2100 m measured 1641 mm for the 44-week period. Over the 44-week period 35% of precipitation was intercepted by the canopy at the 2100 m site. Only 4.3% of precipitation was intercepted at the 2550 m site over the 44-week period. Veneklaas and van Ek (1990) found interception ranged from 12.4% to 18.3% of precipitation in cloud forests in Colombia ranging in elevation from 2550 m to 3370 m. Cavelier et al. (1997) reported interception totals of 37.2% of precipitation in a cloud forest of Panama. Interception totals were lower at the 2550 m site than the 2100 m site in all but two sample intervals. Interception is lower at 2550 m

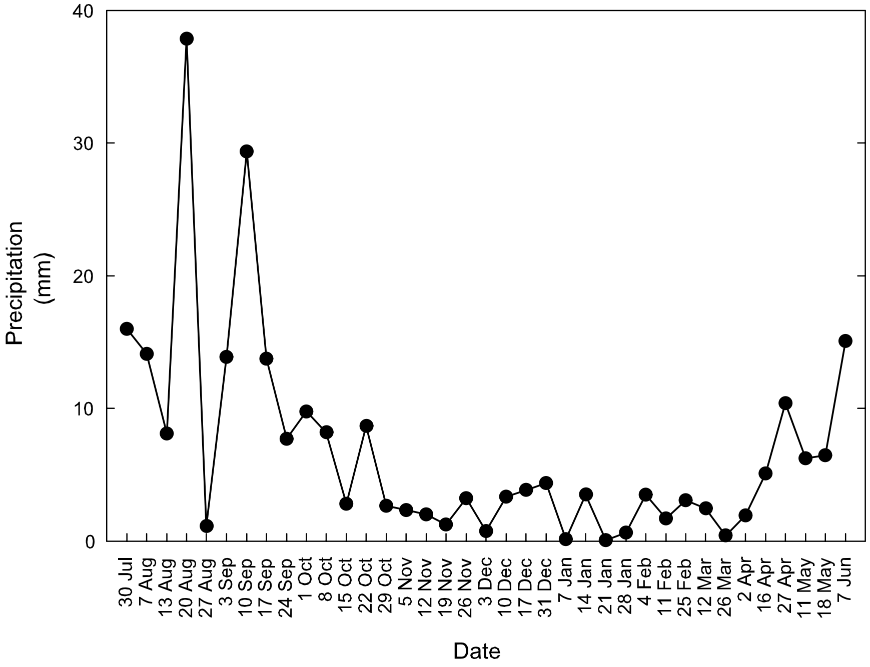

Fig. 3. Precipitation in the Sierra de las Minas near the summit of Montaña de Miranda (2550 m).

Table 1
Seasonal hydrological inputs at 2100 m and 2550 m in the Sierra de las Minas from 24 July 1995 to 7 June 1996

	2100 m	2550 m
Precipitation (mm)		
Rainy season	2165	2165
Dry season	394	394
44-week period	2559	2559
Throughfall (mm)		
Rainy season	1392	1688
Dry season	249	565
44-week period	1641	2253
Interception (mm)		
Rainy season	781	486
Dry season	137	−179
44-week period	918	307
Fog precipitation (mm)		
Rainy season	0	8
Dry season	23	196
44-week period	23	204

because of the persistence of fog, and greater quantities of fog precipitation found in throughfall measurements (Table 1).

Total fog precipitation at 2100 m for the 44-week period was 23 mm or less than 1% of total water input to the forests. The average fog precipitation over the entire period totaled 0.01 mm day^{-1}. Total fog precipitation at 2550 m was 204 mm which accounts for 7.4% of the total water input to the forest. The average rate of fog precipitation recorded by the throughfall gauges at 2550 m was 1 mm day^{-1}. Fog precipitation did not account for as large of a percentage of total water input as previous studies (Ellis, 1971; Vogelmann, 1973; Juvik and Ekern, 1978; Cavelier et al., 1996). Because fog precipitation was conservatively measured by identifying fog precipitation when throughfall exceeded precipitation, the contribution of fog precipitation to the annual water budget of the Sierra de las Minas would be greater than 7.4% as reported in this study.

The data from the Sierra de las Minas show a trend in fog precipitation with elevation. Fog precipitation increased 0.4 mm for every 1 m in elevation in the Sierra de las Minas over the 44-week period. Cavelier et al. (1996) and Cavelier and Goldstein (1989) reported similar findings in Panama and Colombia, respectively. Fog precipitation increased 0.2 mm m^{-1} in Colombia (Cavelier and Goldstein, 1989). Maximum adiabatic temperature differences between the two sites were 4.5 °C. This temperature difference can produce fog conditions only at the summit of Montaña de Miranda whereas the mid-elevation ranges are not submerged in fog. The upper slopes of the Sierra de las Minas receive more water input from fog precipitation than the mid-elevation slopes and the windward base of the mountain range.

Standardized interception ($[P_g - T]/P_g$) was different between the two study sites for the entire sampling period (Fig. 4). Based on the sum of average gauge measurements during the study period, standardized interception was 0.38 at 2100 m and 0.03 at 2550 m. Fog precipitation data show a seasonal pattern most evident at the 2550 m site (Fig. 4). Fog precipitation was greatest during the dry season at both sites, however the seasonal difference in fog precipitation totals was only significantly different at 2550 m (Holder, 2003). The dry season has the coolest months of the year when

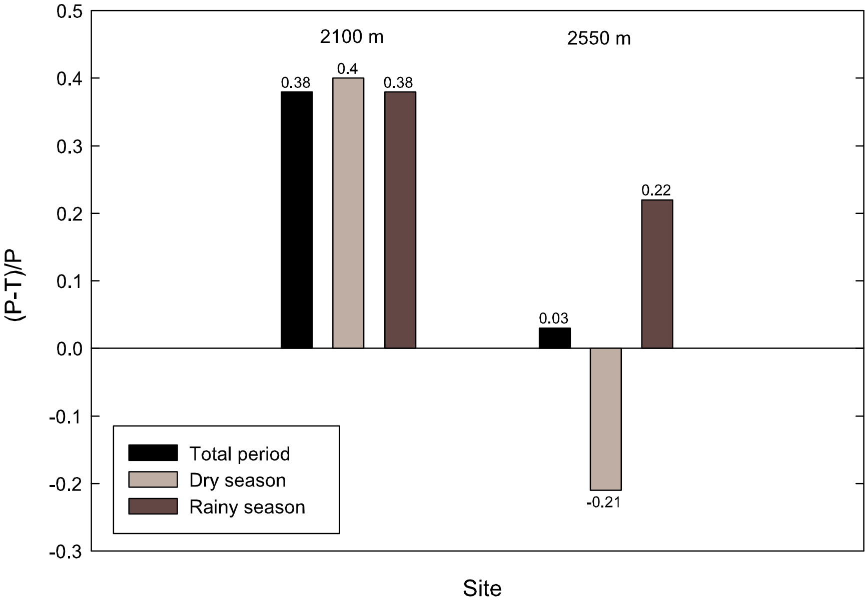

Fig. 4. Seasonal differences in standardized interception at two sites in the Sierra de las Minas.

evaporative water loss from the canopy is least. The canopy is more likely to maintain the maximum water storage in the dry season when temperatures are cool than during the rainy season when temperatures are warmer. Fog precipitation occurs most often when cool temperatures prevail and the canopy is saturated. In cloud forests with pronounced dry seasons such as in the Sierra de las Minas, fog precipitation is a significant moisture source. Fog precipitation may significantly influence surface and subsurface water resources during the dry season (Zadroga, 1981).

4. The significance of fog precipitation

4.1. Water resources in relation to cloud forest stands

The watersheds of the Sierra de las Minas consist of a large area of pristine cloud forest with abundant surfaces for cloud droplet impaction although logging has occurred in selected regions (Lehnhoff and Núñez, 1998). A reduction in the canopy surface area (deforestation) would reduce quantities of fog precipitation. The data collected from the watershed in this study was representative of the larger region of the Sierra de las Minas, and communities are harvesting water from cloud forest catchments. In the more populated and more arid leeward slope of the Sierra de las Minas, people depend on the additional water inputs of fog precipitation in cloud forests, especially in the six-month dry season. Because the dry season has a significant quantity of fog precipitation, management of the cloud forest is particularly important in maintaining water resources for arid lowland communities that ration water during the dry season.

The Sierra de las Minas Biosphere Reserve has an area of 2400 km^2. The core zone of the biosphere reserve containing mostly cloud forests has an area of 1050 km^2. Given the importance of the core zone for generating potable water to lowland communities, the preservation of the remaining cloud forests should be prioritized. The core zone of the biosphere reserve generates greater than 250 million l day^{-1} of fog precipitation (Holder, 2004b). Most of the region less than 2100 m has been depleted of cloud forests, however remnant cloud forests do exist outside of the core zone. Because major water-demanding industries such as bottling plants have moved into the arid Rio Motagua Valley and the population of the valley is increasing, fog precipitation in regions greater than 2100 m will become important in the near future. The hydrological inputs in cloud forests are vital to the livelihood of people in the lowland regions, and more data are needed to make direct connections between the water balance of high elevation cloud forests of the Sierra de las Minas and the water resources of communities surrounding the cloud forests.

Water resource availability is an increasing problematic issue in developing countries in the tropics (Cairncross, 1990). Twenty-four percent of towns have municipal water systems (not including Guatemala City) with treated water (Barry, 1992). Most villages in the rural landscape have untreated water. Thirty-nine percent of the population of Guatemala is without easy access (in house or community spigot) to potable water and 41% of population is without sewage services (Barry, 1992). The need for water is seen as an important concern for several development organizations participating in activities in Guatemala. Over the past 10 years, communities in the arid eastern highlands have begun to ration water during the dry season even as large water-demanding industries such bottling plants and agroindustry operate in the driest valley of Central America. Deforestation of municipal water catchments, population growth, and increased water demand for irrigation and industries have reduced the quantity of water resources available for domestic use, especially during the dry season.

More than 150 villages surround the margins of the cloud forest of the Sierra de las Minas Biosphere Reserve and depend on the cloud forest as a source for municipal water. Management of cloud forests is important for these communities because of the implications of land use change for water resources and future forest extraction practices.

4.2. Land use trends in Chilascó

Chilascó, the community I lived in during the course of this study, is among one of the more than 150 communities surrounding the cloud forest, and the village is typical of the other communities adjacent to the Sierra de las Minas Biosphere Reserve. The village of Chilascó lies near the watershed divide of the Río Polochic, Río Chixoy, and Río Motagua (Fig. 2). Water is transported to the community through pipes from springs within the cloud forests of the Sierra de las Minas. Chilascó is located approximately 10 km west of the western border of the Sierra de las Minas Biosphere Reserve. I chose to live in Chilascó because of the relative accessibility to the cloud forests, and because Defensores de la Naturaleza worked with the community. Four park guards employed by Defensores de la Naturaleza live in Chilascó. Additionally, my investigation was relevant to the community because Chilascó relies on the cloud forest for water and as an extractive reserve for raw materials to build houses and to make household items such as baskets (see Section 4.5). Living in one of several communities that depend on the cloud forest for their livelihood helped clarify the environmental, social, and political issues surrounding the Sierra de las Minas Biosphere Reserve.

The population of Chilascó in 1992 was 2084 (378 families). Five years previously in 1987, Chilascó had 358 families (Margoluis and Ramirez, 1993). People in Chilascó grow corn and beans during the rainy season from April to November. Also, people plant broccoli in three crops from July to December. During the driest months (January–March), the land is prepared for cultivation by burning debris and applying chicken manure that is shipped in from outside Chilascó. The cool temperature and high precipitation of Chilascó along the margins of the cloud forests are able to support non-traditional agricultural crops introduced by development organizations and export agriculture businesses. Broccoli production started in the early 1990s and rapidly replaced staple crops such as corn and beans as the principle crop in the village. Broccoli is a land intensive crop, and as a result, farmers have applied more chemical fertilizers and pesticides on the crops in recent years than in the past. Broccoli has provided more resources to the village, but applying chemical fertilizers and pesticides appears to have decreased soil productivity by damaging naturally occurring soil microfauna. The development organization, CARE, sponsored a study by a research team from the University of Georgia and found that soil nitrogen levels were declining and that the frequency of pesticide use has been increasing because of stronger strands of insects (Dix, 1997). The community of Chilascó has regularly discussed plans to extend broccoli production to communal land closer to the margins of the cloud forests and the border of the core zone of the biosphere reserve.

The village of Chilascó was settled in the 1940s when the Guatemalan government issued a tract of land to the people to be regulated by a communal committee. The original colonizers lived 8 km upstream from Chilascó adjacent to the cloud forest. The original inhabitants wanted land closer to the main road and land which was more productive. The land previously occupied by the inhabitants is still communally owned by the village. As broccoli production increased over the past 10 years, the land surrounding Chilascó has also been allocated for broccoli production. People from Chilascó have begun to cultivate subsistence crops on their original land near the cloud forest. Broccoli for export is grown in the prime agricultural land in Chilascó, and subsistence crops are grown on steep-sloped, marginal land often bordering the cloud forest of the Sierra de las Minas Biosphere Reserve. In one particular case, I observed the felling of cloud forest for subsistence agriculture. The production of broccoli for export is indirectly applying pressure to clear the cloud forest as the current trend is toward resettling the marginal agricultural land near the cloud forest boundary.

Deforestation or the conversion of cloud forests to agricultural land decreases fog precipitation. Deforestation of the cloud forest will impact this hydrological input and will reduce water resources of the surrounding arid valleys of Sierra de las Minas and the surrounding lowlands during the dry season. Fog precipitation contributes approximately 1 mm day^{-1} to the hydrological budget of the Sierra de las Minas. During several days of the dry season, fog precipitation becomes the only hydrological input to the watershed. In watersheds with cloud forests that supply water for domestic and industrial use in arid valleys, this quantity of water is significant. For every hectare converted from cloud forest to agriculture, the watershed may lose more than 1.8 million l of water from fog precipitation annually assuming that the production of fog precipitation is minimal in agricultural fields or pastures (Holder, 2004b).

4.3. Indigenous rights vs. biosphere reserves

In an attempt to preserve the cloud forests and water resources of the Sierra de las Minas, Defensores de la Naturaleza and the international environmental community often make locally unpopular decisions that conflict with the rights of indigenous people. Until the late 1970s, Chilascó was the closest settlement to the west of the large tract of cloud forest which in 1990 became the Sierra de las Minas Biosphere Reserve. In the late 1970s, a small group of indigenous families fleeing political unrest were granted title to a large tract of land in the middle of the cloud forest within the present boundary of the core zone of the biosphere reserve (Fig. 5). The community became known as Vega Larga (Fig. 2). The people of Vega Larga depended on Chilascó for trade and communication. Their staple crops had very low productivities because of the climate and soil nutrient deficiencies. As a result, people from Vega Lar-

Fig. 5. The community of Vega Larga surrounded by cloud forest within the core zone of the Sierra de las Minas Biosphere Reserve.

ga often harvested broccoli as day-laborers for meager salaries in Chilascó.

Shortly after the Sierra de las Minas Biosphere was established and the environmental NGO Defensores de la Naturaleza was given authority to manage the reserve, the 30 families of Vega Larga were pressured to leave their land. Only one individual in Vega Larga spoke Spanish well enough to negotiate the terms of resettlement. The people of Vega Larga were very skeptical of any negotiations to leave the land because the community had just settled in the cloud forests as political refugees who had previously lost their land.

Defensores de la Naturaleza wanted Vega Larga to resettle to an abandoned finca in the Río Polochic valley although the NGO did not have the money to buy the finca for the community. Defensores de la Naturaleza solicited the help of international environmental organizations. The Nature Conservancy responded by initiating a campaign under their Habitats at Risk program (Lehnhoff, 1999). In their campaign The Nature Conservancy stated that the longer it takes to raise the money, the longer the community will be forced to stay within the core zone and continue "damaging practices." The reality is that the community of Vega Larga never wanted to leave. Under pressure from Defensores de la Naturaleza and international environmental groups, the community gave up claim to the land and resettled in the Río Polochic valley in 1998.

Vega Larga should serve as a case study in negotiating rights to land and resources with communities surrounding the Sierra de las Minas Biosphere Reserve. The establishment of national parks, biosphere reserves, and biological corridors to protect biodiversity and natural resources is often contested by locals because of the perceived, and sometimes real, threat of sacrificing communal rights to natural resources (McCay, 1996; McKean, 2000; Becker, 2003). The case of removing the community of Vega Larga from the biosphere reserve became a question of the power of communal, state, and international governance over natural resources. In the case of Vega Larga communal governance and rights to the natural resources of the cloud forests (including the land, forest, water, etc.) lost to the power of the state and international institutions. Although the community of Vega Larga was powerless to insist on remaining in the cloud forest in the mid-1990s, a sensitivity by international institutions (e.g. The Nature Conservancy) and the state (e.g. Defensores de la Naturaleza via the Guatemala government) of contested rights over natural resources will be demanded by local communities with increasing concern of globalization on the use rights to natural resources.

4.4. Ecotourism development vs. water rights

Another dispute between communal and state rights of natural resources is emerging in the village of Chilascó. A committee in Chilascó developed a proposal for an ecotourist site at a waterfall on the Río Chilascó downstream from the community (Fig. 2). The community hopes to build a hotel and bring in tourist money to develop the infrastructure of the village. The development of the waterfall as an ecotourism site has resulted in a conflict for rights to water in the river passing through Chilascó. During the dry season, more than 50% of the Río Chilascó is diverted upstream from Chilascó to be used for irrigation in dry lowlands near the towns of Salamá and San Jeronimo before the water reaches the waterfall (Fig. 2). Additionally, a hydroelectric plant was constructed between Santa Barbara and Niño Perdido in 1999 resulting in the construction of another diversion channel adjacent to the first irrigation canal to increase the discharge of a stream to increase the generation of electricity. The Guatemala government permitted a Spanish company to construct several small hydropower plants in tributaries from the Sierra de las Minas and sell the electricity generated to locals. The diversion of the river significantly reduces the water reaching the waterfall causing a trickle of flow during the dry season.

Negotiations for water rights have begun between Chilascó and the lowland communities benefiting from irrigation and the hydropower industry. The negotiations, however, have not included the management of the cloud forests upstream from the point of stream diversion. The proper management of the cloud forest watersheds and reduction in deforestation may increase the dry season discharge at the point of diversion, and allow all parties to achieve their objectives.

4.5. Forest extraction for supplemental income

The village of Chilascó depends on the natural resources and environment of the cloud forest for their economic and cultural survival. An income source for people of Chilascó is fern production for flower arrangements in the United States and Europe. Large privately-owned fern factories have moved into Chilascó and employ more than 50 people (primarily women) from the village. Fern factories are constructed by first removing vegetation over a 2-ha area on the slopes of hills. Second, fiberglass mesh is placed over the entire slope to provide shade for the growing ferns. Because ferns are common species in cloud forests, fern factories have entered regions where cloud forests once flourished. Cloud forests are threatened because fern factories remove all of the vegetation and encroach on the margins of the cloud forest. Extracting ferns sustainably from the forest may minimize the threat to the cloud forest, but this practice has not been introduced because of efficiency in production. The use of pesticides and fertilizers in the fern factories may also affect the quality of water in communities downstream.

Women in Chilascó supplement household income by making baskets from vines that grow only in the cloud forest. People from Chilascó and Vega Larga harvest the vines from the cloud forest and sell the raw material to women who make the baskets and sell them during market days in Salamá. The commodification of the baskets in the markets has increased the rates of vine harvesting in the cloud forest. People have reported traveling greater than 15 km into the cloud forest to find sources of vines because of declining resource areas due to over-extraction (Flores, 1997). In other regions of the Sierra de las Minas Biosphere Reserve over-extraction of tree ferns and bryophytes for export has left the forest depleted of tree ferns or the branches stripped of epiphytes.

5. Conclusions

Cloud forests in the Sierra de las Minas are hydrologically different from the lowland vegetation in the surrounding valleys because cloud forest vegetation passively collects water from passing fog. Fog precipitation represented a greater proportion of hydrologic input in the cloud forest in the dry season (19%) than the rainy season (less than 1%). Although fog precipitation likely occurs in the rainy season as suggested from other published studies, fog precipitation in the rainy season could not be accurately estimated based on the methodology chosen in this study. Fog precipitation is underestimated in this study because fog precipitation was only measured when throughfall exceeded precipitation. Mature cloud forest canopies may produce fog precipitation even if interception is less than gross precipitation because fog precipitation is most common when the canopy is saturated. Therefore, fog precipitation is expected to be higher than what is reported in this study.

The reduction in deforestation rates and the sustainable management of timber and non-timber forest product extraction is vital to the cultural and economic livelihood of communities adjacent to cloud forests. Cloud forests are sources of municipal and industrial water, and the phenomenon of fog precipitation supplements water resources. Converting cloud forests to agricultural land or over-extracting timber and non-timber products may result in the reduction of water resources for communities.

The outlook for the communities adjacent to the Sierra de las Minas Biosphere Reserve is promising despite the land use changes occurring within a few watersheds. The majority of the core zone of the biosphere reserve is well-protected and managed by Defensores de la Naturaleza. The sustainable use and buffer zones where communities like Chilascó are located, however, have experienced the most transition. As current socio-economic patterns continue in the sustainable use and buffer zone communities of the Sierra de las Minas Biosphere, further study of the negotiations between communal, state, and international governance of forest and water use will provide insight into how contested natural resources can be sustainably managed.

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