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HAZARD ASSESSMENT ARTICLES

Conceptual Ecological Model of the Chiquibul/Maya Mountain Massif, Belize

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ABSTRACT

The Chiquibul/Maya Mountain Massif (CM3) is an approximately 1.25 million-acre area in southwestern Belize and is among the most intact tropical forests north of the Amazon. The CM3 has a variety of habitats that contribute to its valuable environmental services and high aesthetic value, but despite its protected area status, the CM3 is under increasing pressure from extraction of natural and cultural resources as a result of transboundary incursions on the western border and increased land-use changes from industrial activities that include agriculture, hydropower development, logging, and mining. Conceptual ecological models (CEM) are effective planning tools for organizing existing information about natural systems for determining gaps in knowledge and research priorities, and for developing objectives and measures of success for management and monitoring programs. The CEM of the CM3 describe ecological relationships among major stressors and attributes of the system and presents performance measures to quantify potential change to attributes. Attributes were derived from defining characteristics of the massif and chosen as valuable ecological and cultural components of the massif. Ecological linkages between stressors and attributes highlight priorities for conservation, management, and research that will ensure continued protection of the CM3.

Key Words: conservation management, ecological indicators, ecosystem attributes, environmental stressors, landscape model, Maya Mountains.

INTRODUCTION

The Chiquibul/Maya Mountain Massif (CM3) is part of the largest block of intact, connected tropical forest north of the Amazon, totaling some 1,260,800 acres and

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accounting for 22.2% of the land mass of Belize (The Nature Conservancy 2007; Figure 1). The massif lies within UTM Zone 16 in southwestern Belize, and extends from the Vaca Forest Reserve at its northernmost point to the Columbia River Forest Reserve in the south, sharing a 45-km border with Guatemala to the west and contributing to the Chiquibul-Montañas Mayas Biosphere Reserve, Guatemala. CM3 watersheds feed into coastal waterways to the east and maintain the health of the Belize Barrier Reef. The area is the most dominant land feature of Belize and is composed of 14 sub-units under a variety of protected area designations that include eight forest reserves (Chiquibul, Columbia River, Deep River, Maya Mountain, Mountain Pine Ridge, Sibun, Sittee River and Vaca), two national parks (Noj Kaax Me'en Eligio Panti and Chiquibul), the Bladen Nature Reserve, the Cockscomb Basin Wildlife Sanctuary, the Caracol Archaeological Reserve, and the Victoria Peak Natural Monument (Walker and Walker 2009).

The defining characteristics of the CM3, that is, the major ecological components that collectively describe the ecosystem and differentiate it from other natural areas, are its: (1) contiguous forested area, (2) species richness and habitat diversity, (3) archaeological history, (4) environmental services, and (5) aesthetic landscape. However, as the natural areas of the massif are affected by a growing human population, associated land use changes, and economic pressures, these fundamental components of the system are changing. This article describes the development of the Chiquibul/Maya Mountain Massif Conceptual Ecological Model (Figure 2), which was created to provide a guideline for effective preservation, comprehensive conservation, and sustainable management of this ecosystem for ecological and cultural diversity.

Conceptual ecological models have been used as a communication tool between scientists and managers to identify major stressors and working linkages that impact vital ecological attributes of an area that are then used to direct research and monitoring efforts for effective management (Gentile *et al.* 2001; Ogden *et al.* 2005). These models have been used to respond to rapid ecosystem degradation (Harwell *et al.* 2010), evaluate restoration plans of systems that have undergone stress (Barnes and Mazzotti 2005; Davis *et al.* 2005), measure the success of restoration programs, and direct future efforts (Doren *et al.* 2009). In unique cases they are used as predictive models to identify stressors to an area that is not yet entirely degraded but that has potential for improved management and conservation (Mazzotti *et al.* 2005).

The conceptual ecological model of the CM3 (Figure 2) is a result of a workshop, supported by the Belize Foundation for Research and Environmental Education (BFREE) and Friends for Conservation and Development (FCD), which involved agencies and scientific experts and drew on multi-stakeholder input of the Conservation Action Plan (The Nature Conservancy 2007) developed for the Forest Department of the Government of Belize. Participants identified external drivers to the system, major stressors involved, and ecological responses of valued ecological and cultural components of the system.

In addition to the workshop, two documents lay the foundation for development of this conceptual ecological model: the *Technical Assessment of the Maya Mountain Massif: Summary Report* and all associated final reports (Walker *et al.* 2008) and the *Chiquibul National Park Management Plan* 2008–2013 (Salas and Meerman 2008). The

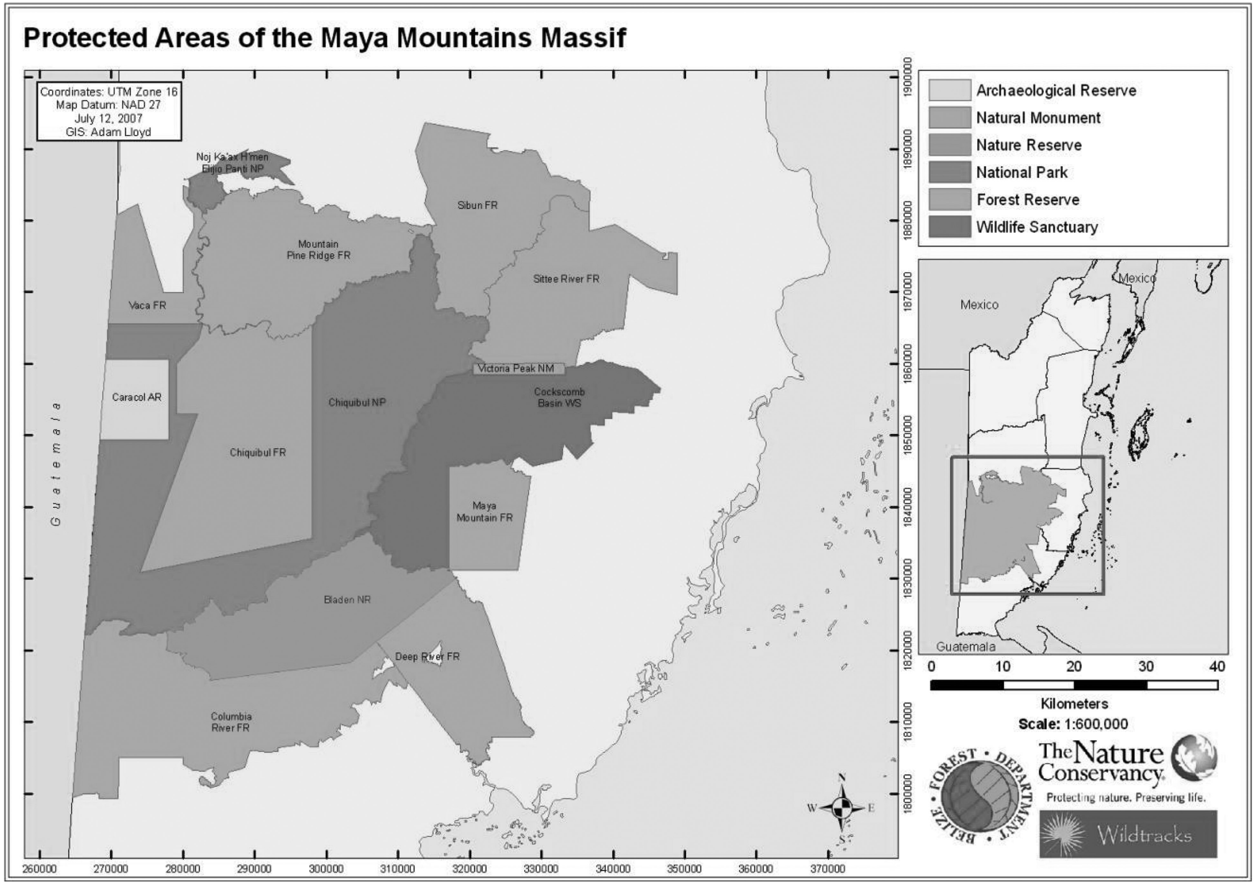

Figure 1. Map of the protected areas of Chiquibul/Maya Mountain Massif, Belize taken from Walker *et al.* (2008). (Color figure available online.)

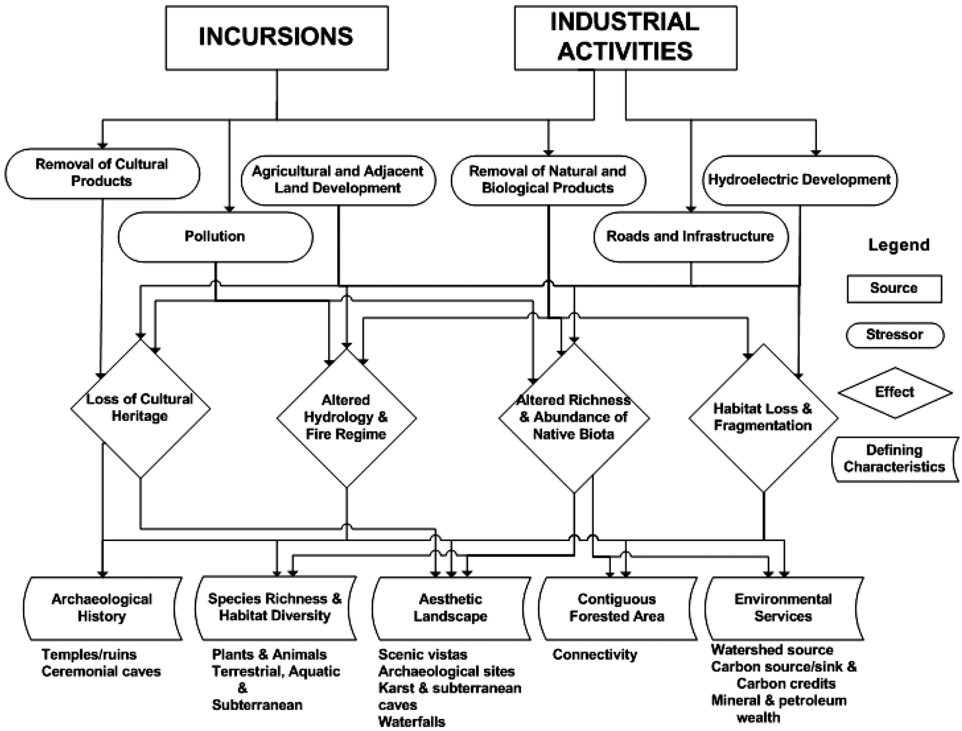

Figure 2. The conceptual ecological model of the Chiquibul/Maya Mountain Massif, Belize.

objectives of this conceptual ecological model are to: (1) determine the baseline value of the CM3 as defining characteristics, (2) identify stressors and attributes of the system, and (3) hypothesize ecological linkages between stressors and attributes that contribute to the development of a research, modeling, and monitoring (RMM) plan for the CM3 to protect and preserve the region's natural and cultural resources.

EXTERNAL DRIVERS AND ECOLOGICAL STRESSORS

This conceptual model identifies two principal drivers to the CM3 system, both of which are anthropogenic: incursions and industrial activities. Incursion refers to the illegal entry of Guatemalans into remote areas of western Belize, whose presence results in large-scale deforestation for agriculture and unsustainable rates of resource extraction (Walker *et al.* 2008). Belize's overall low population density is currently experiencing the highest growth rate in the region due in part to the influx of immigrants into more remote areas of the Cayo and Toledo districts (SIB 2010; Ramos 2009a). Corporate and industrial actors both from within and outside of Belize are also important sources of ecological changes to the massif. Industrial activities including agroindustry, hydroelectricity, logging, and mining are responsible for large-scale land clearance and the development of roads and infrastructure for increased accessibility (Walker *et al.* 2008). The regional scientific experts who contributed to the development of this model also identified climate change as an important driver to the CM3 system. However, because of the complexity and uncertainty of its potential impacts, we recommend the development of a separate model for the CM3 focusing on effects of climate change.

Each external driver generates several stressors that impact the natural system of the massif; stressors have been identified either as ongoing pressures (*e.g.*, agricultural and hydroelectric developments) or as early signs of potential negative impacts (*e.g.*, removal of natural and biological products and pollution). Stressors are presented here and further discussed in the section on ecological linkages below.

Agricultural and Adjacent Land Development

Agricultural development is the principal reason for an altered landscape in the massif and is driven both by incursions and industrial activities. First, illegal agricultural incursions on the western border with Guatemala, mostly from the Petén, have resulted in at least 13,510 acres of national protected forest being cleared (possibly as much as 20,000 acres; 7 News 2011a). Some of this land is impacted and degraded by agricultural fires even though it is not in an agricultural system (R. Manzanero personal observation; 7 News 2011b). There is a stark contrast between the intact, forested area of the massif and the adjacent developed land on the western side (Bridgewater *et al.* 2006). Second, politically granted, private concessions to clear forest for citrus plantations in the fertile river valleys of the Sibun/Sittee Forest Reserves contribute to agricultural development within the protected area of the massif (Walker *et al.* 2008). Lastly, land is cleared for agricultural use by small-scale, subsistence farmers from communities near the Vaca and Columbia River Forest Reserve within Belize (Walker *et al.* 2008). As the demand for arable land increases, the protected areas of the CM3 are steadily being converted to meet the needs of a growing population. When land is severely altered, the connectivity of contiguous forest diminishes and the entire system is affected, including dependent native biota (Schumaker 1996).

Roads and Infrastructure

Traditionally, road expansion into the more remote areas of the CM3 has been for timber extraction and mining, evident by the myriad criss-crossing "forestry" roads in the Maya Mountains, which intersect with roadways leading toward military training grounds (Walker *et al.* 2008). The construction of access roads to the Mollejon Dam, the widening and upgrading of old logging tracks into the Ceibo Chico area and access roads leading into the Vaca region have raised concern (Walker *et al.* 2008). Recent road construction to increase tourist access has also facilitated a major movement of farmers, particularly in the Vaca area (FCD 2011), and increased illegal hunting (E. Bedran pers. comm.). The effects of roads and infrastructure include forest fragmentation and loss of connectivity (Vasquez and Allen 2004), damage to forest trees (*e.g.*, growth patterns, species composition and distribution; Gullison and Hardner 1993), barriers and conduits affecting population dynamics and survival (Findlay and Bourdages 2000), heightened exotic species invasion, increased human contact with flora and fauna with the potential for increased exploitation, greater spread of diseases, and altered natural processes such as fire regimes and watersheds (Gullison and Hardner 1993).

Hydroelectric Development

The construction of the Chalillo Hydroelectric Dam on the Upper Macal and Raspaculo Rivers that run through the CM3 sparked international controversy for its widespread ecological effects (Guynup 2002). The dam is located 12 km downstream from the confluence of the Macal and Raspaculo Rivers and created a reservoir 20 km upstream of both rivers, inundating approximately 2,800 acres of forested and riparian ecosystems (Meadows and Meerman 1999). The dam is also 48 km upstream from the towns of San Ignacio and Santa Elena, which together contain about 15,000 residents. There are now an additional two other dam curtains, Mollejon and Vaca, which have been added along the waterways of the western rivers. Damming for hydroelectricity alters the direction and volume of water flow that threatens the aquatic and riparian areas of the CM3, threatens archaeological sites with inundation, compromises watershed integrity, fragments the massif, impacts the Mesoamerican Biological Corridor, and polarizes public support for the conservation of biodiversity (Walker *et al.* 2008).

Pollution

Belize does not have a large urban population; however, an increasing human presence throughout the country and particularly in remote areas like the CM3 increases pollution and improper waste disposal at multiple spatial scales (Young 2008). Preliminary studies indicate contamination of the massif by agrochemicals transported in the water column from agro-industries of the coastal plain, both through orographic precipitation and to a lesser extent through direct drift (Walker unpubl.). Water pollution also results from hydroelectric development; for example shock sediment discharge from the Chalillo Dam in 2009 led to health concerns for a number of villages downstream of the Macal and Raspaculo Rivers (Young 2008; Ramos 2009b) and more recently, mercury levels in several fish species along the Macal River exceeded normal levels by more than three times because of rotting vegetation cleared with the Chalillo Dam development (Amandala 2011). As a result, the Ministry of Health issued a public health advisory against eating bay snook (*Petenia splendid*) from the Macal River to avoid chronic health effects associated with mercury exposure (Belize Press Office 2011). Also in areas surrounding the CM3 (including in some protected areas), slash-and-burn farming is common and when combined with extensive forest fires is likely the main cause of air pollution to the system that also contributes to water pollution from high levels of dissolved ash (Akimoto 2003; Amandala 2011). Visual pollution is also evident in the massif, where exposed hillsides and rock faces, devoid of vegetation and native flora, are a result of mineral exploration and road construction for access into remote areas for hydropower, logging, mining, and tourism (Walker *et al.* 2008). The landscape is also dotted by large machinery used in these activities, often parked on roadsides disturbing the natural beauty of vistas.

Removal of Natural, Biological Products

Xate

The over-harvesting of xate leaves in Mexico and Guatemala for the floral trade in Europe, Japan, and the United States has spurred xate leafcutters to extend illegal harvesting into the protected areas of Belize and is the principal source of income for several communities in Guatemala (Bridgewater *et al.* 2006). The CM3 has been identified as a hotspot for xate abundance and by 2008 an estimated 1000–1500 xateros were operating illegally in the area, using a network of foot trails and larger horse trails to remove several thousand leaves at once (Walker *et al.* 2008). Plants are being stripped entirely of their leaves, reducing the chance of regeneration, which is compounded by the removal of seeds and seedlings (Bridgewater *et al.* 2006). In the Chiquibul forest the number of xateros continues to increase, creating a greater problem because they are sometimes armed and violent, for example, recent shooting at local hunters and Belizean defense soldiers (Channel 5 News 2010, 2011a). These incidents coupled with increasingly regular hold-ups along major roadways by ex-Guatemalan militia are the main security risks when venturing into the massif (Channel 5 News 2011b).

Hunting

Alongside adverse effects of illegal xate harvesting is associated indiscriminate hunting activity within protected areas of the CM3 (Bridgewater *et al.* 2006). Many game species, including some not usually hunted for consumption such as Baird's tapir (*Tapirus bairdii*), spider monkeys (*Ateles geoffroyi*), black howler monkeys (*Alouatta pigra*), and scarlet macaws (*Ara macao cyanoptera)* have been found at xatero camps within the massif (Walker *et al.* 2008; N. Bol pers. comm.). Guatemalan poachers raid nests to supply the pet trade's demand for yellow-headed parrot (*Amazona oratrix*) and scarlet macaw nestlings, and juvenile spider and black howler monkeys (Walker *et al.* 2008; FCD 2011). Illegal hunting is primarily linked to xatero activity but also occurs in the massif from within Belize (Walker *et al.* 2008.). Illegal bushmeat hunting reduces wildlife populations, such as the white-lipped peccary (*Tayassu pecari*), which has been extirpated from the Chiquibul, an area that was once the species' primary stronghold in Belize (Kelly 2003). The term "Empty Forest Syndrome" (Redford 1992) is becoming increasingly applicable to the Chiquibul forest (Kelly 2003).

Timber

Timber has played an important role in Belize's economic history beginning with logwood (*Haematoxylon campechianum* L.) and later switching to mahogany (*Swietenia macrophylla* King). However, despite a decline in harvesting and reduced contribution to Gross Domestic Product (GDP) (0.5% SIB 2010), the high demand for exotic woods on local and international markets drive the continued spread of illegal logging, which greatly impacts the forested areas of the massif regardless of protected area status (J. Briggs pers. comm.). Other ecologically vulnerable hardwoods such as cedar (*Cedrela odorata* L.), Sapodilla (*Manilkara zapota*), Santa Maria (Calophyllum brasiliense), and Nargusta (Terminalia amazonia) are illegally logged for commercial purposes in Mexico and Guatemala and to build homes, furniture, fence posts, and provide firewood especially in border settlements (Channel 5 News 2008; J. Briggs pers. comm.). Recently, government concessions have been granted to a handful of companies with political affiliations to log within the southern and western portions of the protected areas of CM3 (Walker *et al.* 2008). Recent findings show that the Columbia River Forest Reserve (CRFR) appears devoid of traditional commercial timber species, whereas there are relatively good timber stocks in Western Chiquibul but current harvesting levels are unsustainable (Cho *et al.* 2011). Physical removal of timber reduces seedling recruitment and canopy cover, creating light gaps for other plant species thereby altering species composition and creating a cascade of effects on forest dynamics.

Non-Timber Forest Products

Forested areas of the massif provide multiple non-timber forest products (NTFPs) that include but are not limited to seeds, leaves, flowers, fruits, bark, latex, resins, pulp, roots, and oils (Ticktin 2004). Historically, chicle (from the sapodilla tree: *M. zapota*) harvesting and chocolate production from cacao trees (*Theobroma cacao*) dominated the NTFP market in Belize but these have since declined and been replaced by a variety of palms. These palms serve a prominent role in traditional Belizean cultures, and harvesting tends to be harmful to the plants' persistence. The cohune palm (*Orbignya cohune*) produces oil-rich nuts, an edible heart that is also used for wine, and sturdy leaves and fiber for thatching and craft-making; the leaves of the bay palmetto (*Sabal mauritiiformis)* are also used for thatching (O'Hara 1999; Balick *et al.* 2000). At current rates, there is a potential for over-harvesting, which would likely affect species abundance and population health (Walker *et al.* 2008) and have negative impacts on seedling recruitment, nutrient cycling, and soil erosion (O'Hara 1999). In Belize, up to 75% of the primary health care needs of rural people are provided by traditional practitioners who rely on naturally occurring medicinal plants and herbs (Balick and Mendelsohn 1992). However, studies have shown that harvesting methods can be unsustainable and due to the remote nature of much of the CM3, this type of biological extraction goes unchecked and is a steady and increasing stressor to the system (Balick and Mendelsohn 1992).

Oil and Mineral Extraction

Oil and mineral exploration have occurred in the CM3 for decades and though there have been no major oil field discoveries, the rich stratigraphy of the Maya Mountain Divide and Little Quartz Ridge indicate substantial mineral deposits, and the geological profile of the coastal zone of Deep River Forest Reserve indicate potential petroleum deposits (Walker *et al.* 2008). The latter is now the site for intensive oil exploration despite its protected area status (Ramos 2011). The National Protected Areas Act prohibits extractive mining but because of a lack of cohesive planning and policies, the Ministry of Natural Resources continues to grant permits within the protected areas of the massif (Walker *et al.* 2008). Mineral extraction is localized in areas of the CM3 and is mostly for sand and gravel used in civil works and construction (Doan 1999). Prospecting for gold has occurred for years mostly via stream panning but there is now an increase in gold and quartz mining (Wacaster 2010) and illegal gold panning by Guatemalans in the Ceibo Chico region of the Chiquibul National Park (FCD 2011). Invasive methods of mineral extraction involving complete removal of vegetation from concession areas lead to forest fragmentation that is compounded by construction of access roads (Walker *et al.* 2008). Heavy traffic involved with hauling sediment and/or oil creates visual pollution, alters soil compaction and hydrology, often adds sediment to waterways (Vasquez and Allen 2004), forces animal populations to relocate, and opens up areas for increased human presence (which has its own corollaries).

Removal of Cultural Products

Ancient artifacts were removed from many of the massif's Mayan sites with permission during the colonial period, and today are still housed in museums and collections abroad (Walker *et al.* 2008; Awe 2010). In addition, some rare finds discovered by archaeologists have ended up in personal collections and have garnered exorbitant prices on the black market (Matsuda 1998; Walker *et al.* 2008). Present-day looting comes in many forms. Local looters may raid a temple or unearthed mound by tunneling in and removing articles to sell in local villagers or to foreign visitors (Matsuda 1998). With the increase in tourism and commodification of Mayan culture, visitors to temples and ruins occasionally take pieces of pottery or remains as souvenirs (Walker *et al.* 2008), the impact of which may go unnoticed for some time. Xateros are particularly destructive looters because they are skilled at locating ancient Mayan dwellings overgrown by the forest and they are opportunistic in removing all items with market potential (Awe 2010). Looting of cultural articles is a lucrative business because wealthy collectors are willing to pay tens of thousands of dollars for a jade figurine or a piece of ancient pottery. This intense demand for exotic antiquities fuels the growing trade despite prohibitive laws on collecting illicitly recovered objects and the issue of cultural property (Matsuda 1998; Walker *et al.* 2008).

DEFINING CHARACTERISTICS AND ECOLOGICAL ATTRIBUTES

For each of the five defining characteristics of the CM3 system (contiguous forested area, species richness and habitat diversity, archaeological history, environmental services, and aesthetic landscape, Figure 2), key ecological attributes were identified to serve as indicators of ecosystem response to changes caused by the various stressors described. Attributes were chosen to indicate responses at various temporal and spatial scales and a variety of taxonomic and hierarchical levels. Much like target viability in bottom-up models, attributes are a reflection of the health of an ecosystem and if missing or altered would lead to the outright loss or degradation of the system. Performance measures for each attribute are tools for monitoring potential change in the health of the ecosystem, which are both logistically and financially feasible (The Nature Conservancy 2007; Walker *et al.* 2008). Here both attributes and their associated performance measures are presented.

Contiguous Forested Areas: Connectivity

Belize's forested expanse covers 67% of the country and the forested area of the CM3 has been recognized as the largest intact block in Central America providing critical ecosystem function at both national and regional levels (Walker *et al.* 2008). The tropical broadleaf forest, a feature of northern Mesoamerica that is reduced elsewhere in its range, is intact in the CM3 in part because of Belize's historically low population density and the country's network of protected areas (Cherrington *et al.* 2010; Figure 1). In isolation, however, the massif is too small to protect wide-ranging species in the long term and the need for dynamic forested patches means that connectivity with other forest tracts is critical to maintain biodiversity. True connectivity by linking with Guatemala to the Selva Maya has already been lost, but connectivity still persists in Belize via the Manatee Forest Reserve up through the Central Corridor Route to the Rio Bravo Conservation Management Area.

Maintaining connectivity between forests is critical to survival of species and the natural ecological processes of a system that depend on a heterogeneous landscape. Forest connectivity can be derived from validated geographic information system (GIS) data using a combination of satellite images and digital aerial photography mosaics (Meerman 2004) where performance measures such as patch area and perimeter are computed and plugged into FRAGSTATS (http://www.umass.edu/landeco/research/fragstats/fragstats.html; McGarigal *et al.* 2002) to evaluate the functional joining or connectedness of neighboring patches in a landscape (Schumaker 1996).

Species Richness and Habitat Diversity

The CM3 includes a range of topographical and geomorphological features, that when combined make for complex habitats. The range of intact ecosystems over an altitudinal gradient from the mountainous regions of the massif to the coastal estuaries of Deep River ensures that habitat diversity and biodiversity are rich (Meerman and Sabido 2001). Mesoamerica has been identified as one of the richest biodiversity areas on the planet, ranking second only to the tropical Andes in terms of diversity and endemism with 17% of all known terrestrial species (Walker *et al.* 2008). Belize plays an integral ecological role in Mesoamerica by providing critical intact habitat and ensuring viable populations of at least 37 globally threatened species (Walker *et al.* 2008; Table 1). Of these threatened species, 3 are considered "critically endangered," 19 are classified as "endangered," 9 are classified as "vulnerable," and 23 are endemic to the massif (Meerman 2005; Walker *et al.* 2008; IUCN 2010; Tables 1 and 2).

Plants

Some 662 plant species have been recorded in the massif and this number is constantly updated with ongoing field expeditions (Meerman and Matola 2007; Calonje *et al.* 2009). Species of conservation concern include a critically endangered endemic cycad (*Zamia decumbens*), endangered fiddlewood (*Vitex gaumeri*), big-leaved mahogany (*Swietenia macrophylla*) that is considered vulnerable in this area (Walker *et al.* 2008; IUCN 2010; Table 1). Of 41 recorded endemic plants of Belize, 37% occur in the CM3 and are found in the highly restricted Belizean Pine

Table 1. Species of global concern found within the Chiquibul/Maya Mountain Massif, Belize.

Common name	Scientific name	Status	Author
Flora			
	Ceratozamia robusta	EN	Miquel
	Pithecellobium johansenii	EN	Standl
	Quiina schippii	EN	Standl
Mountain Pimento	*Schippia concolor*	VU	Burret
Large-leaved mahogany	*Swietenia macrophylla*	VU	King
Small-leaved mahogany	*Swietenia mahagoni*	EN	Jacques
	Trichilia breviflora	EN	Blake & Standley
Fiddlewood	*Vitex gaumeri*	EN	Greenm
Cycad	*Zamia meermani*	EN	Calonje
Cycad	*Zamia prasina*	CR	Bull
Cycad	*Zamia variegata*	EN	Warsz
	Zanthoxylum procerum	EN	Donn
Fauna			
Morelett's treefrog	*Agalychnis moreletii*	CR	Duméril
Yucatán Black Howler Monkey	*Alouatta pigra*	EN	Lawrence
Yellow-headed parrot	*Amazona oratrix*	EN	Ridgway
Scarlet macaw	*Ara macao cyanoptera*	EN	Wiedenfled
Central American Spider monkey	*Ateles geoffroyi*	EN	Kuhl
Tomas's sac-winged bat	*Balantiopteryx io*	EN	Thomas
Bromeliad treefrog	*Bromeliohyla bromeliacia*	EN	Schmidt
Treefrog	*Craugastor psephosypharus*	VU	Campbell, Savage and Meyer
Treefrog	*Craugastor sabrinus*	EN	Campbell and Savage
Treefrog	*Craugastor sandersoni*	EN	Schmidt
Great curassow	*Craxrubra*	VU	Linnaeus
American crocodile	*Crocodylus acutus*	VU	Cuvier
Cerulean warbler	*Dendroica cerulea*	VU	Wilson
Central American river turtle	*Dermatemys mawii*	CR	Gray
Keel-billed motmot	*Electron carinatum*	VU	Du Bus and Gisignies
Frog	*Eleutherodactylus leprus*	VU	Cope
	Cruagastor psephosypharus	VU	Campbell, Savage and Meyer
Maya knobtail	*Epigomphus maya*	EN	Donnelly
Baird's tapir	*Tapirus bairdii*	EN	Gill

Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) status. Adopted from BERDS 2011 and IUCN 2011. Available at http://www.biodiversity.bz/ and http://www.iucnredlist.org/, respectively.

Eco-region and its fire-adapted savanna ecosystems (Balick *et al.* 2000; Table 2). As a way to measure plant diversity of the massif, continued surveys are needed to further document plant species richness. Abundance estimates of threatened species, such as the xate palm, can also be used to track impacts of poaching on surviving populations.

Table 2. Endemic species of the Chiquibul/Maya Mountain Massif, Belize.

Common name	Scientific name	Author
Flora		
	Anemia bartlettii	Mickel
	Amyris rhomboidea	Standl
	Axonopus ciliatifolius	Swallen
	Telanthophora bartletti	Rob and Brettel
	Calyptranthus bartlettii	Standl
	Galactia anomala	Lundell
	Gymnanthes belizensis	Webster
	Koanophyllon sorensenii	King and Rob
	Mimosa pinetorum	Standl
	Neurolaena schippii	Rob
	Oxandra proctorii	Lundell
	Pisonia proctorii	Lundell
	Pleurothallis duplooyi	Luer & Sayers
	Scutellaria lundellii	Epling
	Syngonanthus bartlettii	Moldenke
	Zinowiewi pallid	Lundell
Fauna		
Mountain Molly	*Poecilia teresae*	Greenfield
Cave chulin	*Rhamdia typhla*	Greenfield & Woods
Maya Mountain frog	*Lithobates juliani (Rana juliani)*	Hillis and De Sa
Cayo Tarantula	*Citharacanthus meermani*	Reichling and West
Maya Tarantula	*Psalmopoeus maya*	Witt
Sedge Wren	*Cistothorus platensis russelli*	Dickerman
NA	*Cyllopsis wellingi*	Miller

Adopted from BERDS 2011. Available at http://www.biodiversity.bz/

Animals

The animal diversity of the CM3 is unrivalled within the country with a recorded 786 species (Salas and Meerman 2008; BERDS 2005). This species list is not exhaustive, particularly for birds, fish, and insects, but includes the critically endangered Morelett's treefrog (*Agalychnis moreletii*), the endangered Baird's tapir (Belize's national animal), the jaguar (*Panthera onca*), the endemic Maya Mountain frog *(Lithobates juliani* previously *Rana juliani*), and two species of endemic fish: the Cave Chulin (*Rhamdia typhla)* and the Mountain Molly *(Poecilia teresae)* (Salas and Meerman 2008; Walker *et al.* 2008; Tables 1 and 2). The area is host to the endangered black howler monkey, the endangered Central American spider monkey, and is the only known nesting area for the endangered northern subspecies of scarlet macaws (McReynolds 2005). Based solely on its location within the migratory bird corridor, the CM3 also ensures a significant avifaunal diversity (Meerman 2005).

A successfully used quantitative measure of the importance of biodiversity is the Marxan Analytical Tool (Chan *et al.* 2006; Meerman 2007) where the status of endangered and/or endemic species is investigated alongside species of national concern. In addition, monitoring abundance, reproduction, and movements of vital species such as the jaguar (a top predator and umbrella species), the scarlet macaw (a conservation icon), and the Maya Mountain frog (an endemic species), can provide effective performance measures of animal diversity within the massif.

Habitats

Terrestrial. A total of 85 terrestrial ecosystems have been identified in Belize (Meerman 2004) and the CM3 accounts for a complex mosaic of 44 tropical broadleaf, pine forest, and aquatic ecosystems under UNESCO's classification (Walker *et al.* 2008). Thirteen of these ecosystems are found nowhere else in the country, another 11 have more than 80% of their national extent in the massif, and 18 are considered rare and underrepresented within the national protected area system (Walker *et al.* 2008). The Belizean Pine Forests found in the Mountain Pine Ridge and along the coastal plains as well as the Petén-Veracruz Moist Forest of the Macal River valley are classified as critically endangered eco-regions found within the massif (WWF 2001).

A widely used performance measure of landscape characteristics to quantify tropical habitat diversity within the CM3 is patch size distribution (Loehle and Wein 1994). This is measured as the number of patches of different habitat types per unit area. Land cover data can be derived from accurate GIS data using both satellite images and aerial photographs that have been validated by ground-truthing to verify forest cover types (Meerman 2007; Walker *et al.* 2008) that are then used to calculate landscape distribution statistics using FRAGSTATS (http://www.umass.edu/landeco/research/fragstats/fragstats.html; McGarigal *et al.* 2002). This program incorporates calculations on how each habitat is spatially arranged and how it differs in composition relative to the landscape (Loehle and Wein 1994).

Aquatic. There are 46 aquatic ecosystems in Belize and the Macal River Valley of the CM3 is host to unique riparian habitat that does not occur anywhere else in the world and accounts for the largest protected wetlands in Centeral America (Walker *et al.* 2008; FCD 2011). The several small high-elevation headwater streams of the CM3 make up one of the most extensive aquatic ecosystems in the country and comprise 41% of the total linear distance of its rivers (Esselman *et al.* 2005). The diverse wetlands of the CM3 support high biodiversity, especially invertebrates, amphibians and migratory birds (Salas and Meerman 2008) as well as more than 229 floral species (Urban *et al.* 2006). Aquatic biomonitoring of the health of waterways typically are calculated using the ephemeroptera plecoptera trichoptera (EPT) index, which is a species richness measure of three orders of aquatic insects (Ephemeroptera: mayflies, Plecoptera: stoneflies, and Trichoptera: caddisflies; Lenat 1988). Waterways subject to land alteration and pollution are typically absent of EPTs and are dominated by Dipterans (flies), especially Chironomids (midges).

Subterranean. At least 50% of Belize's bedrock is carbonated, of which 22% forms a karstic landscape that is found in several of the protected areas and is most pronounced in the Cretaceous limestones of the CM3 (Miller 1996). Of all karstlands of Central America and the Caribbean, the 68% of karst that is protected in the massif is unparalleled for size and quality and provides unique subterranean habitat for a suite of plant and animal species (Reddell and Veni 1996). The Chiquibul Cave

System in the CM3 is the longest and largest known cave system of Central America, extending into Guatemala and linked by underground waterways (Meerman and Moore 2010). For karst and cave systems, the proportion of pristine to disturbed caves is a viable measure of the condition of these ecosystems. Disturbance may be defined as presence of refuse or degradation of physical structures seen as footprints, graffiti, and broken karst fragments.

Archaeological History

Belize has a rich cultural heritage dating back to the Pre-ceramic Period (10,000–1200 B.C.) when Mayan populations were thriving. Because of the logistical difficulty of working in the mountains, the CM3 represents one of the most poorly studied archaeological regions of the country (Walker *et al.* 2008). However, this area is thought to contain hundreds of archaeological sites with unearthed temples and ruins (Meerman and Moore 2010). Friends for Conservation and Development (FCD) with training from Institute of Archaeology have begun the task of documenting the cultural caches of archaeological sites (FCD 2011).

Temples/ruins

Four geo-cultural sub-regions have been identified in the massif. The Mountain Pine Ridge sub-region has been identified as a valuable source of granite and slate for Mayan production of household items such as mortars and grinding stones and non-utilitarian decorative objects (Walker *et al.* 2008). The nutrient-rich soils of the Chiquibul sub-region encouraged the development of agricultural terracing and the establishment of Caracol, now one of the most well-known archaeological reserves in the country. In the southern region, more than 200 sites have been identified, indicating that settlements were based on resource exploitation and trade thus giving rise to many regional trading centers along the foothills of the Maya Mountains (Walker *et al.* 2008). As a measure of the integrity of the massif's rich archaeological heritage, the proportion of disturbed to undisturbed archaeological sites can be calculated. More remote areas may support a greater number of undisturbed sites, but these may not be entirely unaffected by looting of artifacts.

Ceremonial caves

The Vaca sub-region is interwoven with an intricate cave system thought to have been important in Maya culture, which today houses remains and archaeological artifacts and is a popular tourist destination (Walker *et al.* 2008). Numerous cave systems have been designated as ancient Mayan ceremonial centers; one of these, Actun Tunichil Muknal is a national monument, with several cave altars and large ceremonial stages and more than 400 ceramic jars and the sacrificial remains of at least 14 individuals (Awe 2010). The Chechem Ha caves are located high on the plateau of the Macal River in the Vaca area, area ceremonial center for after-life and sacred rituals (Awe 2010). Signs of ceremonies are also found in the extensive Chiquibul Cave System, which has been nominated as a world heritage site (Meerman and Moore 2010; FCD 2011). This intricate subterranean system includes at least 60 mapped caves and more than 55 km of passages including the largest known passage and cave room in the Western Hemisphere (Meerman and Moore

2010). The performance measure for ceremonial caves can be the same as that used for other subterranean systems, that is, the presence of refuse and the degradation of physical structures and should also include a measure of the non-removal of cultural artifacts.

Environmental Services

Watershed source

The Belize River Watershed is the largest, most important source of water for the country and is comprised of 14 watersheds originating in the CM3 and flowing into the Caribbean Sea (Walker *et al.* 2008). The two main sub-drainage systems of the Macal and Mopan Rivers differ in their surface drainage patterns: in the Macal sub-watershed, there are abundant small streams whereas in the Mopan, the watershed exists largely underground (Salas and Meerman 2008). The waters of the Maya Mountains support at least 128 communities and more than 130,000 Belizeans, and more than 100,000 Guatemalans in approximately 180 communities of the Petén (BERDS 2005; The Nature Conservancy 2006; FCD 2011). The CM3 is the upper watershed catchment for more than 55% of the land mass of Belize providing essential watershed services such as clean water, flood control, and hydroelectric power; maintaining quality of fish stocks and habitats for diverse flora and fauna; and contributing to health of the offshore Belize Barrier Reef (Walker *et al.* 2008). Lastly an intact watershed of the massif provides numerous recreational and tourism services. A measure of watershed functionality is stream flow or discharge, that is, the volume of water that moves from the watershed to the stream channel, which is often expressed as cubic feet per second over a fixed period of time (Murdoch and Cheo 1996). Stream flow is an important factor in the aquatic ecosystem, impacting the physical structure of the stream as well as its chemical and biological components, and should be monitored on a continuous basis.

Carbon source/sink and carbon credits

As the largest block of forest in Belize, the CM3 has great potential as a target for *Payment for Environmental Services*, as a source of carbon credits and as a participant in Reducing Emissions from Deforestation and Degradation (REDD) programs (Walker *et al.* 2008; Cho *et al.* 2011). It is generally believed that natural forest stands, like the CM3, sequester more carbon than forest plantations because they contain greater biomass and a viable understory (Jansson *et al.* 2010). Cho *et al.* (2011) found that biomass stocking, particularly in the area of Columbia River Forest Reserve, has been much reduced by timber extraction, but relative to tropical forests in other countries the massif has high biomass stocks and thus a high potential for carbon sequestration (Cho *et al.* 2011). Reforestation efforts that lead to carbon sequestration credit trading may emerge faster from the southern region of the CM3 where subsistence farmers are being encouraged to plant commercially viable native species such as mahogany and cedar for both domestic and international markets (Walker *et al.* 2008). Performance measures for carbon include above-ground biomass surveys and below-ground (soils) surveys. These are coupled with statistical sampling, computer modeling and remote sensing to estimate carbon sequestration and sources of carbon emissions affecting a system (Houghton *et al.*

1998). More detailed studies can supply necessary data for the Caribbean Center for Combating Climate Change to determine available carbon levels in the biomass of the massif, extrapolate the number of tons per acre of carbon credits that could be traded, and engage the CM3 in a viable carbon trading program that meets the guidelines of the Clean Development Mechanism (Walker *et al.* 2008; Cho *et al.* 2011).

Mineral and petroleum wealth

The CM3 is bounded by volcanics to the south and Upper Cretaceous limestones to the north, and includes the Little Quartz Ridge, which contribute to a unique geology and provides natural resources for mineral interests. The area is host to a variety of mineral deposits, including gold, semi-precious stones, heavy metals, and vast quantities of raw materials such as granite, dolomite and marble, among others (Doan 1999). Gold, bauxite, barites, and cassiterites are found but not in commercially viable quantities; however, more recently gold-bearing gravel was mined in the Ceibo Chico area of the Cayo District, for which production is slated to increase along with quartz mineralization (Wacaster 2010). Raw materials, such as basalt and dolomite limestone are used for construction and for fertilizer in the agro-industries and in the southern region of Deep River Forest Reserve a potential petroleum source has been identified (Walker *et al.* 2008). The bedrock of the CM3 has been subject to prospecting and seismic surveys for decades (Doan 1999) and thus a valid performance measure of mineral and petroleum wealth is to quantify mineral composition and distribution. This will determine how mineral profiles change with mining efforts. The amount of petroleum reserves can be measured by number of barrels produced per day.

Aesthetic Landscape: Scenic Vistas, Archaeological Sites, Subterranean Caves, Waterfalls

The CM3 has a range of diverse habitats making for an aesthetically pleasing landscape with lush greenery surrounding the highest peaks of the country, sweeping panoramas of unbroken forests in the heart of the Chiquibul, open expanses of pine savannah, impressive natural monuments, and other striking scenic features. Waterfalls tucked amidst the forests of the massif provide some of the most breathtaking views, and include Belize's longest waterfall (Thousand Foot Falls), and the highest in Central America (Hidden Valley Falls). The massif is also home to Mayan cultural sites and the intricate Chiquibul Cave System, which are valuable for recreation and ecotourism (Meerman and Moore 2010). An effective performance measure of the aesthetics of a landscape is the presence of litter and the amount of visual pollution. These can be quantified by the number of plastic bottles, wrappers and other items of trash, as well as the number of man-made structures and heavy machinery per kilometer. Discarded refuse alters the aesthetics of a landscape and is an indicator of the perceived attractiveness of the area; thus these performance measures can be incorporated into the scenic beauty estimate that gauges public perception of landscape beauty (Daniel and Boster 1976).

CRITICAL ECOLOGICAL LINKAGES

The proposed hypothesis clusters detailed below and included in the conceptual model are a consensus of regional scientific experts on the most significant and parsimonious effects of stressors on each defining ecological characteristic (and its attributes) of the CM3. By identifying these critical linkages, effective monitoring and management can be implemented using appropriate performance measures to address effects of stressors to the massif.

Habitat Loss and Fragmentation

Illegal agricultural incursions on the western border are the primary source of habitat destruction in the CM3 (Cherrington *et al.* 2010; FCD 2011). The other major sources of habitat loss and fragmentation are related to industrial activities, particularly the Chalillo, Mollejon, and Vaca Hydroelectric Dams; logging operations; and oil and mineral exploration. This land conversion is responsible for the decline of forest connectivity between the CM3 and the Mesoamerican corridor, and an increase in edge effects by exposing natural habitats to a dramatically altered landscape. Impacts include changes to ecosystem functions and trophic cascades, limits to animal dispersal, and diminished watershed integrity (Cherrington *et al.* 2010). As land is altered, soil composition and moisture gradients change and there is an increased fire hazard along boundaries (Myers 2002). Of even greater concern is the loss of habitat connectivity for umbrella species such as the jaguar, which requires large tracts of land to maintain genetically viable populations. *Hypothesis:* increased habitat loss and fragmentation through agricultural and adjacent land development and hydroelectric development decrease the spatial extent of the forested landscape, decrease tropical habitat diversity, reduce wildlife populations, and alters the aesthetics of the landscape.

Road and infrastructure development that allows access to remote areas directly removes natural and biological products and results in reduced forest connectivity, expands the human footprint and threatens the mineral wealth of the area. *Hypothesis:* increased roads and infrastructure reduce connectivity of forested area, reduce habitat patch size, increases resource extraction and impact landscape aesthetics.

Lastly, as habitat is lost, the potential for the CM3 to be a valuable source of *Payment for Environmental Services* by way of carbon sequestration that is locked up in forest biomass (Cho *et al.* 2011), and the ability to trade carbon credits using intact forests with industrialized countries, significantly diminishes (Walker *et al.* 2008). Thus habitat loss is likely to produce a vicious cycle whereby further deforestation will lead to decreased carbon stores and further reduced potential for trading carbon credits. *Hypothesis:* increased habitat loss and fragmentation decrease carbon source stores and reduce availability of tradable carbon credits.

Altered Richness and Abundance of Biota

Incursions and industrial activities bring native biota in closer contact with humans and as forest resources are removed, populations of commodity species are increasingly threatened and biodiversity levels are negatively impacted. The most notorious ongoing case of natural resource exploitation within the CM3 is that of xate palm removal (Walker *et al.* 2008; FCD 2011). Other palms (O'Hara 1999) and medicinal plants (Balick and Mendelsohn 1992) are also being harvested at unsustainable rates. Unsustainable harvesting of hardwood trees for timber is another growing threat, driven mainly by illegal incursions and private logging concessions (Walker *et al.* 2008). The removal of biological products change forest structure and reduces forest connectivity and carbon stores, which then decreases habitat diversity and richness and abundance of plant species. This leads to a cascade of effects including degradation of waterways and reduction in nesting sites for iconic species such as the scarlet macaw. In addition, over-exploitation of native fauna via illegal hunting may be linked to decreasing densities of game species, which have been reported based on sightings and camera-trap data (Kelly and Caro 2003; N. Bol pers. comm.). *Hypothesis:* continued and increased resource extraction involved in agricultural and hydroelectric development and the removal of floral species (poaching) reduce tropical habitat diversity as well as wetland and aquatic habitat, reduce forest connectivity and carbon sequestration stores, and ultimately reduce landscape aesthetics. *Hypothesis:* increased biological removal of both flora and fauna reduce abundance and population distributions of animal species.

Loss of Cultural Heritage

Within the last decade the Institute of Archaeology identified several factors that threaten the rich cultural history of the CM3, the most prominent of which is looting or illegal removal of cultural artifacts (Walker *et al.* 2008). Unearthed ancient structures may contain hundreds of cultural artifacts, but as archaeological exploration probes more deeply into forested interiors there is an increasing risk of loss of cultural objects. Despite laws prohibiting collection of illicitly recovered objects and the issue of cultural property, the loss of cultural heritage by looting of temples and caves is a pervasive threat within remote areas of the massif (Matsuda 1998; Walker *et al.* 2008). Additional threats to cultural heritage within the CM3 include removal of railway and locomotive parts, constructed during the British colonial occupation, for scrap metal export by Guatemalan companies, particularly in the areas of the Vaca Forest Reserve (Walker *et al.* 2008). *Hypothesis:* the intentional removal of cultural products reduces the region's archaeological heritage found at temples, ruins, and caves.

The cultural heritage of the massif is further affected by deforestation and land conversion from agricultural incursions and industrial activities. Numerous illegal land clearances for farmland and the illegal harvesting of xate in and around both Caracol Archaeological Reserve and the Chiquibul Cave System predispose the area to further looting and surface degradation (Walker *et al.* 2008; Meerman and Moore 2010). Logging concessions in the southern region of the massif threaten unearthed cultural sites, as do roads built for mineral exploration in central regions. Some sites have also been subject to the threat of flooding with the altered water flow from the construction of the Chalillo Hydroelectric Dam (Walker *et al.* 2008). Culturally sensitive sites, such as Rio Frio Cave, Actun Tunichil Muknal, and Caracol show physical signs of degradation as a result of increased visitation, and pollution is an ongoing threat to the preservation of intact, culturally meaningful historical sites (Meerman and Moore 2010). *Hypothesis*: increased incursions and industrial activities reduce cultural heritage and decrease the integrity of archaeological sites.

Altered Hydrology and Fire Regimes

The riparian and aquatic ecosystems of the CM3 are intimately connected to the hydrology and geomorphology of associated rivers and perform vital functions that include flood control and storm protection (Meerman 1999). This became apparent when the Chalillo Dam overflowed and flooded villages in October 2008 (Reporter 2008). Of further concern is the silt and sediment entrapment that occurs when multiple dams, such as the Mollejon and Vaca plants, are built on the same river, increasing turbidity that destroys wetland vegetation and promotes over-abundance of tolerant species that out-compete naturally occurring species (Kingsford 2000). Additionally, agricultural incursions, road construction, and land use changes negatively impact hydrological patterns within the massif by removing vegetation needed to maintain soil erosion, altering soil moisture gradients and affecting fire regimes (Myers 2002). *Hypothesis*: land use changes associated with industrial activities and incursions alters hydrology patterns, reduces watershed functionality, and affects species composition of resident biota.

Fire, its impacts on biodiversity, and the balance it can provide when prescribed have not been widely documented in the CM3. Altered hydrological patterns affect fire regimes because fires are more prone to ignite in areas that have a reduced water supply or shortened hydroperiods (Myers 2002). The sweeping wildfires of 2011 in the Pine Ridge area of the massif destroyed several thousand acres of pine and savanna forest (Meerman 2011; 7 News 2011b); this has further reduced landscape aesthetics within the CM3. Additionally, manmade fires have become more frequent with the slash-and-burn system that dominates the agricultural incursions on the western border, and illegal poachers may also have been responsible for some fires that were documented on high elevation areas of the CM3 in 2011 (FCD 2011).

Altered fire regimes impact native flora (either promoting the spread of hardy, fire-resistant species or inhibiting seedling germination of species that require fire), facilitating a shift in floral species dominance that then changes the ecosystem affecting faunal distribution and abundance (Myers 2002). *Hypothesis:* altered fire regimes have the potential to reduce habitat diversity and wildlife populations.

SUMMARY

The Chiquibul/Maya Mountain Massif is the most dynamic, ecologically diverse land mass in Belize and extends its regional importance into the Mesoamerican Biological Corridor. These protected areas are designated to conserve the natural and cultural heritage of Belize in perpetuity for future generations and provide valuable environmental, social, economic, and cultural goods and services. Despite its protected status, however, the CM3 is impacted by anthropogenic threats across its expanse. The greatest stressors result from incursions on the western border with Guatemala followed by industrial activities within the country. The single, most effective measure to mitigate these stressors is proper, effective enforcement of laws and policies. An increased management presence, clear land demarcation and bi-national agreements that address trespassing into fragile areas, illegal poaching, and polluting, are necessary to securing the future of the massif (Walker and Walker 2009; FCD 2011).

Presently, the Wildlife Protection Act and the Protected Areas System Act provide for protection of biodiversity within protected areas. Violations result in a $BZD 500–1000 fine or six months in prison, hardly a significant sum to be an effective deterrent and stimulate change. Future legislation needs to increase fines and penalties for illegal resource extraction and incursions into protected areas. At the same time, the governments of Belize and Guatemala must recognize that because poverty and landlessness among residents in the border region are largely driven by money laundering by Guatemalan *narcotrafficantes*, deterrents to participating in illegal incursions and extractions alone will not provide a sustainable solution (Walker *et al.* 2008). While tourism and carbon trading both hold potential to stimulate effective conservation, we also encourage bi-national efforts (despite inherent difficulties) to address the root causes of stressors affecting the ecological integrity of the CM3.

Ecological linkages (hypotheses) between stressors and attributes of the massif, highlighted by this conceptual ecological model, provide a foundation for the development of a Research, Modeling and Monitoring (RMM) Plan to help direct research priorities (available at http://crocdoc.ifas.ufl.edu/projects/mayamountains/). The research community continues to develop in Belize, and progress calls for a collaborative endeavor to strengthen relationships among government, stakeholders, and researchers. Toward a collaborative effort, baseline data from biodiversity surveys and distribution mapping should focus on species of concern and help to guide conservation and management efforts. Data sharing among scientists can stimulate progress at all levels, including among managers and within government departments that help to instill legislation and policy key to continued conservation strategies. Given the necessary recognition and support, a valuable RMM program will help to ensure that the CM3 maintains its status as a biodiversity hotspot and its valuable ecosystem services for the health and interest of present and future generations.

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