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Remote sensing of ancient Maya land use features at Caracol, Belize related to tropical rainforest structure

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Abstract

To understand the social, political, economic, and ecological implications of historic land use patterns of Caracol, one of the largest (~200 sq km) Maya archaeological sites, we are conducting a regional survey using satellite and airborne sensors. About one-fifth of this polity has been mapped with traditional ground-based methods. In this NASA-funded project, we acquired Landsat TM/ETM, IKONOS, and small-footprint LiDAR data to detect archaeological features and measure rainforest properties based on canopy spectral signatures, three-dimensional canopy structure, and below-canopy topography. Using pattern analysis techniques, we will delineate causeways, agricultural terraces, reservoirs, plazas, and buildings to determine the extent and spatial organization of the urban and suburban settlements around Caracol.
Although the Maya typically clearcut ~75% of the land they inhabited, the vegetation rebounded to yield the most vast natural reforestation event in recent history (*c.* 1000 BP). From the imagery and point-cloud data, we will derive aboveground biomass and habitat structure (e.g., canopy top height, canopy openness, crown diameter of dominant trees, canopy texture) and assess forest recovery patterns. Thus, this study will link ancient land use legacies to current ecological condition and represents the most ambitious application of LiDAR for below-canopy archaeological prospecting to date.

Keywords Below-canopy, LiDAR, Maya, MesoAmerica, Rainforest, Settlement patterns.

1 Introduction

The social, political, and economic interpretation of ancient Maya settlement patterns requires broad-scale, regional surveys that extend beyond the urban epicenter (Chase and Chase 2003). Traditional ground-based survey methods are time-consuming and labor intensive. Recent advances in remote sensing and digital image processing show tremendous promise to assist with this process.

Here, we describe an effort, funded by NASA's Space Archaeology program that combines passive and active hyperspatial data to simultaneously record three-dimensional forest structural and below-canopy archaeological features from a largely unexcavated Maya site in Belize. This will permit the identification of previously unknown historic formations while determining the relationships between millennial-old land use practices and contemporary forest composition and structure.

2 Project Objectives

1) Use satellite remote sensing to detect Maya archaeological features at Caracol based on spectral signatures of the rainforest vegetation. The spatial extent and distribution of structures that comprise the urban metropolis, suburban hamlets, and trade routes will be determined.

2) Use airborne light detection and ranging (LiDAR) to map below-canopy topography in areas encompassed by known and detected Maya archaeological features. New causeways, reservoirs, agricultural terraces, plazas, and buildings around Caracol will be identified.

3) Relate contemporary rainforest canopy structure to historic Maya land use patterns. From satellite imagery and airborne LiDAR, we will derive forest biomass and habitat quality estimates (i.e., from measures of canopy top height, vertical distribution of return, degree of canopy openness, crown diameter of dominant trees) at Caracol.

3 Study Area

Caracol is the largest Maya archaeological site in Belize. Located near the Guatemala border on the Vaca Plateau of the Cayo District (Figure 1), it encompasses roughly 180km^2. At its cultural peak (c. AD 750), the metropolitan population is estimated to be ~150,000, which makes it one of the most populous cities in the Pre-Columbian world (Chase and Chase 1996). Caracol was, in essence, the capital city that maintained control of a 12,000 sq km region for several centuries (Chase and Chase 2003). It differs from other Maya lowland city states in terms of its large population size (e.g., it was nearly twice the size of the competing Maya city-states of Tikal and Calakmul) and its high population density (e.g., suburbs 6-8km outside of the Caracol urban center consisted of 1000 inhabitants per sq km). Because of the size and density of archaeological features found at Caracol, its outer limits have not been clearly demarcated.

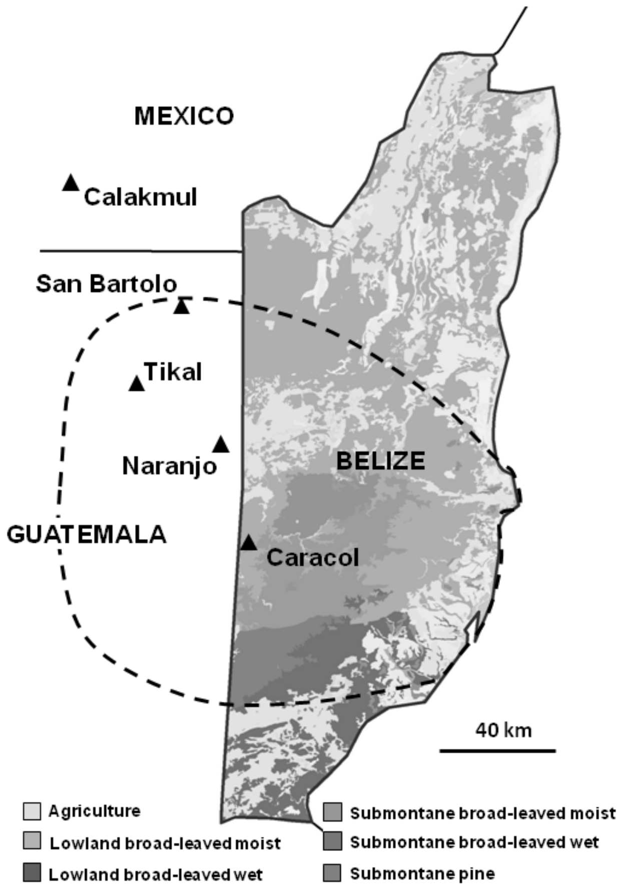

Fig. 1. Vegetation map of Belize (Meerman 2006) depicting location of mentioned Maya sites. The dashed line indicates the region controlled by Caracol, *c.* AD 750 (Chase and Chase 1996).

Unlike other Maya sites, the physical organization of Caracol is laid out in a radial plan like Washington, DC or Paris (Chase and Chase 1996). At its hub is the administrative and ceremonial plaza that contains the Caana pyramid monument. The 42m Caana is the tallest building in ancient as well as modern-day Belize. An estimated 75km of intra-site roads extend outward to surrounding hamlets that were absorbed into the city-state and to new residential settlements that arose as the prominence of Caracol increased (Chase and Chase 2001). The areal extent of metropolitan Caracol is estimated from the distribution of the termini of the causeways. These consist of a series of suburban complexes which are thought to have served as secondary administrative plazas, pre-existing centers, and large residential clusters. The termini form two rings around Caracol. The inner ring is approximately 3km from the urban epicenter and is comprised of low lying non-residential buildings. The second ring, located 4.6 to 9.6km way from the epicenter, is comprised of hamlets that were annexed. Portions of inter-site causeways totaling more than 75km have been detected in Landsat imagery (Figure 2). These extend ~40km northwest of Caracol towards another annexed Maya city-state, Naranjo, and ~24km to the south and southeast. However, these inter-site roads have not been verified at ground level.

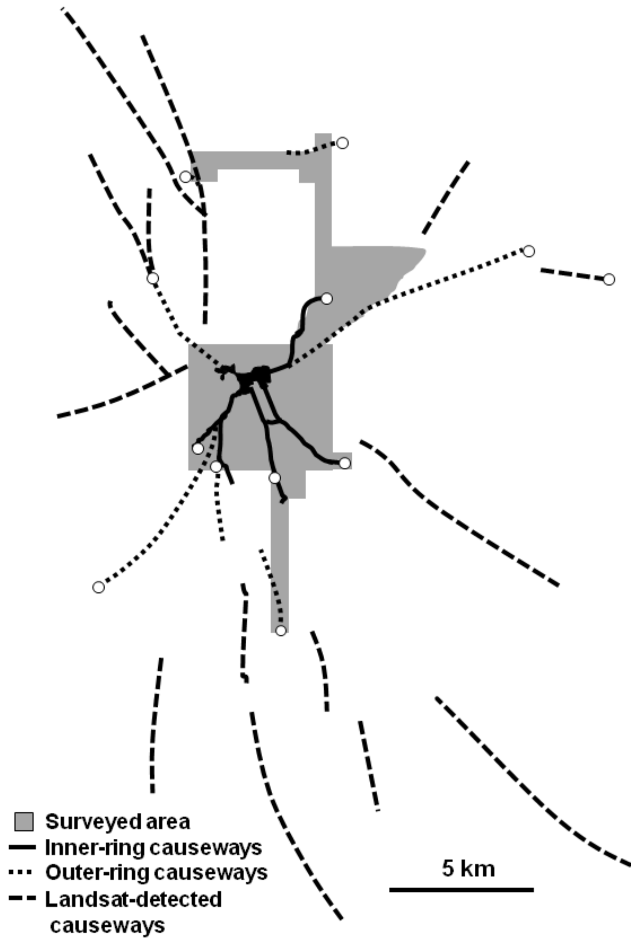

Fig. 2. Causeway map of Caracol (www.caracol.org). The inner blackened polygon corresponds to the urban epicenter from which the forest has been cleared. White circles designate termini.

Though discovered by archaeologist A. H. Anderson in 1938, only about a twelfth (~22 sq km) of this important site, i.e., the epicenter, has been intensively surveyed (Figure 3). Most of Caracol remains hidden below the canopy of lowland broad-leaved moist forest, designated by UNESCO as tropical evergreen seasonal broad-leaved lowland hill forest located on steep karstic terrain (Meerman 2006). As of 1998, the locations and dimensions of over 106 plaza groups of 4400 building structures have been mapped. Thus, if the density across the landscape remains constant, thousands of structures (on the order of 30,000; Chase and Chase 1998) and perhaps new termini plazas await discovery.

4 Remotely Sensed Data Acquisition and Analysis

In support of Objective 1

We have acquired hyperspatial IKONOS imagery (1m resolution panchromatic and four, 4m resolution multispectral bands) to explore the 200 sq km area immediately surrounding the Caracol urban epicenter and coarser scale Landsat TM (30m resolution) to examine a broader (2000 sq km) region.

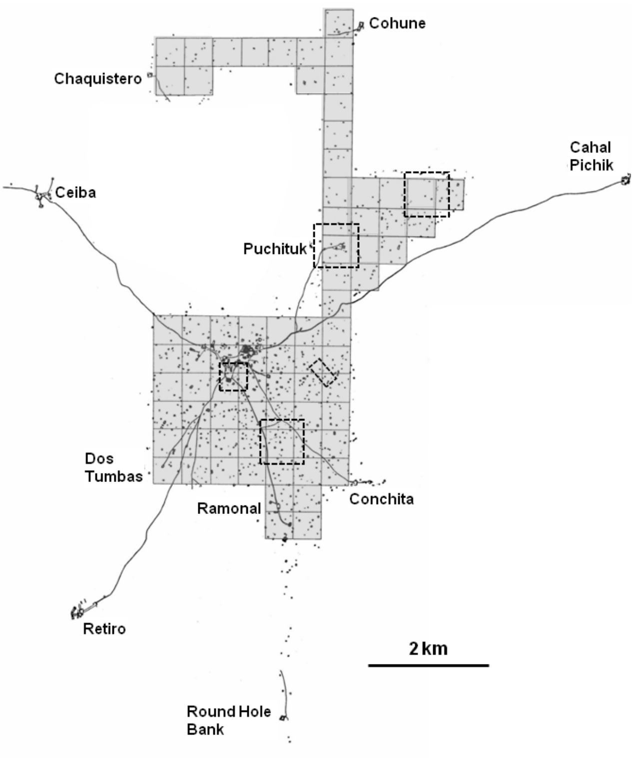

Fig.3. Settlement map of ~21 km^2 of Caracol (Chase and Chase 2001). Additional areas have since been mapped. Names correspond to causeway termini. Black specks represent plaza groups of buildings that have been mapped. Dashed rectangles are mapped terraced areas (Chase and Chase 1998).

Though hyperspatial imagery has been used to observe Maya archaeological features readily in the absence of forest canopy (e.g., Figure 4), only recently have methodologies been developed to reliably detect subcanopy features. To map the presence of archaeological structures in Caracol, we will employ the spectral signature analysis techniques that proved successful in identifying the presence of Maya structures below the forest canopy in the Petén in Guatemala (Sever and Parry 2006).

This methodology has not been shown to identify Maya archaeological features consistently, and may depend on vegetation type and/or phonological state (see Garrison *et al.,* 2008). The IKONOS and TM imagery were acquired from both wet and dry seasons and will be used to evaluate the robustness of these procedures in the broad-leaved moist forests around Caracol, as compared to the semi-deciduous moist forests, savannas, and wetlands in the Petén. We will use automated feature extraction techniques to identify forest patches that exhibit unique spectral signatures associated with underlying Maya structures. Through these procedures, we should be able to generate a more accurate measure of the extent of the greater metropolitan Caracol area and its regional influences.

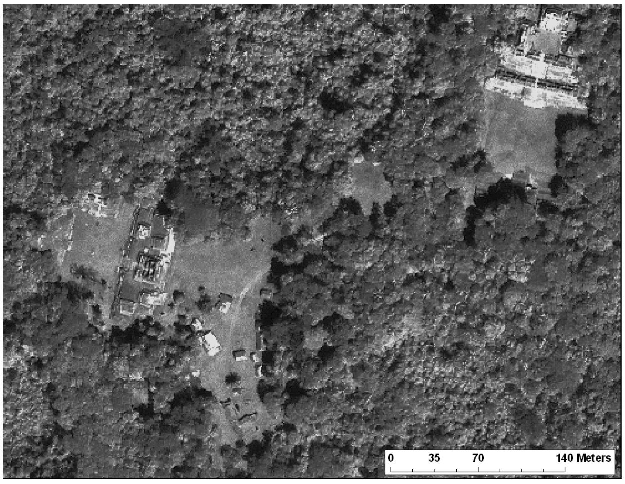

Fig. 4. A panchromatic IKONOS image of the excavated epicenter of Caracol surrounded by rainforest canopy. The Caana pyramid is located in the upper right-hand corner. The Temple of the Wooden Lintel (A group) is on the left.

In support of Objective 2

Passive satellite sensors (e.g., IKONOS, Landsat) have been used to locate historic Maya features (Chase and Chase 2001); however, they generally only discern archaeological structures that: (1) extend above the canopy; (2) are found in areas devoid of vegetation; or (3) disrupt existing vegetation patterns in some way such as altering the spectral signature. Alternatively, an active microwave sensor, STAR-3i, was used to map canopy topography in the Petén (Saturno *et al.,* 2007). Elevated canopy heights corresponded to the presence of underlying Maya structures which tended to be situated on higher, drier ground.

Using the first laser return from the upper portions of the trees LiDAR, like STAR-3i, can be used to measure canopy topography (Weishampel *et al.,* 2000). As light penetrates the forest canopy and is reflected back, it records information about the three-dimensional distribution (x,y,z) of reflective surfaces. Because canopies are porous, some photons penetrate into the lower canopy and some reach the ground. Returned signals simultaneously provide measures of forest architecture and ground elevation (Figure 5). The horizontal and vertical resolution of these surface height measures are on the order of centimeters yielding very accurate topographic maps. Thus, LiDAR sensors can penetrate the forest canopy to measure obscured archaeological features.

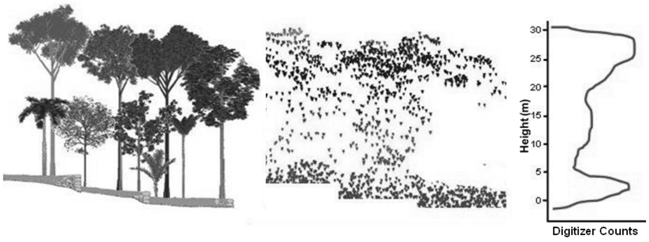

Fig. 5. LiDAR point cloud data for a theoretical forest profile on a relic agricultural terrace. Returns would be filtered out to identify ground returns versus those from understory vegetation. From the point clouds, digital surface (DSM) and digital terrain (DTM) models, would be produced. The right panel represents a pseudo-waveform created by summing the returns across vertical bins.

Though results from early applications of single-track, profiling LiDAR sensors were not especially encouraging (McKee and Sever 1994; P. Sheets, pers. comm.), recent applications of significantly more advanced airborne laser swath mapping system (ALSM) technology shows considerable promise for archaeological prospecting (see Devereux *et al.,* 2005; Risbøl *et al.,* 2006; Sittler and Schellberg 2006). A pilot study, directly related to our proposed research, showed the remarkable accuracy of LiDAR for detecting below-canopy Maya ruins in Copán, Honduras when compared to a total station survey (Gibeaut *et al.,* 2003).

LiDAR sensors have been shown to provide accurate, detailed digital elevation models (DEMs) below dense, closed-canopy wet tropical rainforests at La Selva, Costa Rica (Hofton *et al.,* 2002) of sufficient quality to map hydrologic features (i.e., drainage patterns), which provide insight into human settlement patterns, water management, and storage capability (Saturno *et al.,* 2007). The rainforests at Caracol are seasonal and more open than those in Costa Rica, which should provide ample ground returns especially when flown at the end of the dry season, (i.e., March to May). Within a ~200 sq km region defined by the known causeway termini, state-of-the-art airborne LiDAR data were acquired in April 2009. Detailed topographic maps will be produced from these data, revealing natural (e.g., ground terrain) and anthropogenic (e.g., buildings, roads, terraces) features.

Previous and ongoing field investigations/excavations will provide comparisons of surface topography, allowing correlation of the digital topographic map with height measures of decomposed human made features. These GIS and hand-drawn maps include >22 sq km of Caracol roadways, public buildings, and residential groups, as well as approximately 4 sq km of Caracol's dense agricultural terracing (Chase and Chase 1998; 2001). It is expected that previously unmapped features will be detected by extrapolating linear ground features across the landscape and by using pattern recognition algorithms and image enhancement techniques such as edge detection and textural analysis (Lee *et al.,* 2005). The LiDAR data will also be used to delineate the intra-site network of causeways. Since they facilitated transportation and communication, these causeways can be thought of as political and economic statements that provided administration and integration of this Maya metropolis.

Caracol is known as the 'Garden City' because its dense settlements were embedded in a complex matrix of agricultural terraces (Chase and Chase 1998). However, there is no naturally running water for crop irrigation near the urban center. To adapt sufficiently to these conditions, the Maya constructed a network of thousands of kilometers of stone terraces considered to be the most elaborate in the Maya lowlands (Dunning 1996) and hundreds of reservoirs (Healy *et al.,* 1983).

We will map the 3-dimensional surface topography (i.e., representing Maya buildings, landuse patterns, and forest canopies) using the remote sensing/data processing facilities available through the National Center for Airborne Laser Mapping (NCALM; Carter *et al.,* 2001). The NCALM system records four returns per pulse as it scans across a ~0.5km swath. When a pulse is transmitted, part of the pulse reflects off an object close to the aircraft (e.g., the canopy top), while the remainder of the pulse continues through the trees and reflects off the hard surface (e.g., the ground or a building). At a nominal above-ground altitude of 600-1000m, the system yields 10-15 laser returns per square meter with a height accuracy of 5-10cm and a horizontal accuracy of 25-40cm. This system also records the relative intensity of each return. By crisscrossing flight lines over the central Caracol area, a higher density of photons and more accurate DEM will be obtained. A comprehensive set of the ALSM elevation and intensity features will be used to characterize the canopy and to identify and segment anthropogenic structures. A robust probabilistic method to isolate the optimal ALSM feature set for building segmentation features (Luzum *et al.,* 2005) as well as information-theoretic filters for separating vegetation structure from bare surface topography will be used (Kampa and Slatton 2004). These have been applied to detect small walking trails (Lee *et al.,* 2005) underneath forest canopies.

In support of Objective 3

The idea that ecology needs archaeology and vice versa focuses on human causes of environmental change and how, in turn, environmental change affects human society (Briggs *et al.,* 2006; Foster *et al.,* 2003). Because present-day rainforests (and other "wild" areas) bear the fingerprints of historic human disturbance (Heckenberger *et al.,* 2003; Willis *et al.,* 2004), archaeologists are necessary to provide ecologists with a view of past human land use. Such environmental impacts may require several centuries for the disturbed system to return to its pre-human-disturbed state, if, indeed, it does recover as most systems are in a state of continual disturbance. The system, once disturbed, may undergo an entirely different successional trajectory. Recovery of forest composition and structure tends to be relatively rapid when the disturbance primarily impacts the forest canopy and considerably slower when soils (e.g., fertility and texture) are also heavily impacted (Chazdon 2003). For example, secondary, 400 year-old central Amazon forests growing on pre-Columbian archaeological landscapes detected with remote sensing have not returned to "high" forest and still exhibit signs of acute alteration (Heckenberger *et al.,* 2003).

The collapse of the Maya civilization (*c.* AD 950) is the most recent example of a vast naturally reforested landscape (Sterpa 2005). Evidence consistently supports the hypothesis that there was a massive transformation of the central Maya lowlands from seasonally dry tropical forests to an open, cultivated landscape (Figure 6). The contribution that environmental degradation (e.g., deforestation and/or soil erosion) played in this collapse is subject to debate (Abrams *et al.,* 1996; Turner *et al.,* 2003). The ancient Maya landscape between the ceremonial centers and dense rural/agricultural settlements typically consisted of less-managed forests, complex agroforestry systems, and abandoned agricultural lands with secondary growth. Nearly 75% of the Maya environment was anthropogenically cleared for settlement and agriculture at its peak; thus, much of the present 'old-growth' or 'virgin' Central American rainforests are 600-1000 years old and have grown on what was a largely human-dominated, agrarian landscape (Redman 1999). As such, this example affords insights to other regions that are presently undergoing reforestation or woody encroachment (Chazdon 2003; Gómez-Pompa and Kaus 1999).

Caracol is located in the Chiquibul Forest Reserve, which is one of the largest remaining continuous tracts of tropical rainforest in Central America. Some of the forest stands surrounding Caracol were virtually undisturbed by humans over the last millennium. Studies of post-agricultural recovery of tropical forests show that the recovery of forest structure, soil nutrients, and species richness is far more rapid than recovery of species composition (Chazdon 2003). However, some ecological processes in tropical rainforests (e.g., plant growth rates) rebound more quickly than certain measures of ecosystem structure (e.g., vertical canopy structure) after a disturbance. The recovery of species composition is dependent on the landscape matrix surrounding the disturbance, (e.g., the presence of seed sources). Thus, the land use patterns around an abandoned field may dramatically influence recovery. Moreover, species abundance patterns may also reflect past Maya land use practices in at least two ways. First, the presence of agriculturally/economically important tree species may reflect the presence of Maya orchard-gardens (called *pet kotoob*; Gómez-Pompa *et al.,* 1987) and other forestry practices or second, the Maya-disturbed, often limestone-rich soils may promote tree species, such as the ramón (*Brosimum alicastrum*), that are adapted to these conditions or are exhibiting stress due to them (Foster and Turner 2004; Lambert and Arnason 1982; Turner *et al.,* 2001). These latter micro-environmental conditions may explain the differences in spectral signatures from canopies above the archaeological ruins (Saturno *et al.,* 2007). As noted by Healy *et al.* (1983), the tree species composition on the agricultural terraces, which were designed to reduce soil erosion, does not match the composition found on ruins in the plazas. Because species composition influences canopy structure, structural differences may exist, reflecting past land use legacies (Weishampel *et al.,* 2007). However, the physiognomy of *pet kotoob* sites has been reported as similar to other tropical forest stands in the vicinity (Gómez-Pompa *et al.,* 1987).

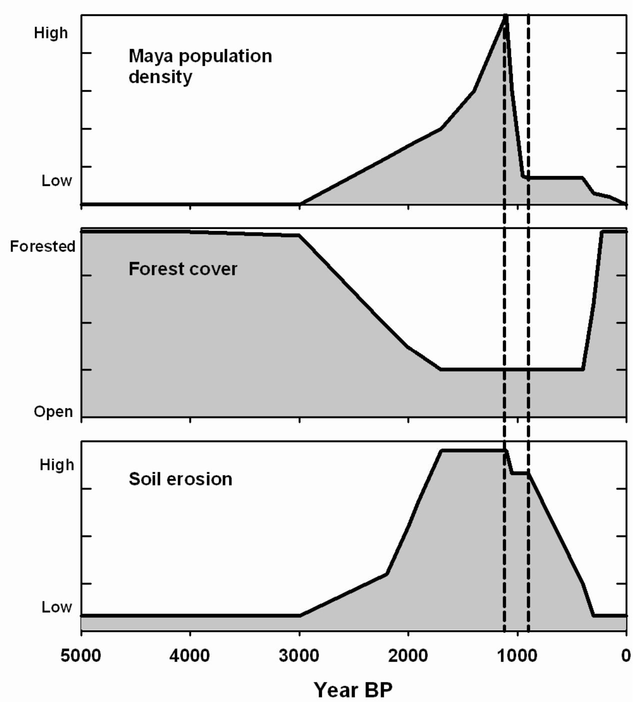

Fig. 6. impacts to tropical forests in the southern Yucatán adapted from Binford *et al.* (1987). The first and second dashed lines correspond respectively to the last date recorded on a Caracol stela and when the site was totally abandoned.

Canopy structure largely dictates the biophysical environment of a forest. Its organization influences tree physiology, atmospheric exchange, and arboreal and understory habitats. Discrete LiDAR and hyperspatial imagery are well-suited to characterize canopy architecture (Lim *et al.,* 2003; Clark *et al.,* 2004a). Tropical forests, such as those engulfing the Maya city of Caracol, contain large stores of labile carbon (i.e., wood) that are not easily quantified by passive remote sensing (e.g., Landsat) methods. The estimation of forest canopy height (or digital canopy models, DCMs) using small-footprint LiDAR is accomplished by subtracting the digital surface model (DSM, the canopy topography) from the digital terrain model

(DTM) and has been shown to be very accurate in tropical rainforest environments (Clark *et al.,* 2004b). In addition to height, small-footprint LiDAR DCMs permit the detection and segmentation of individual, canopy dominant tree crowns (Popescu and Zhao 2008). Measurements of crown area of trees in closed-canopy tropical rainforests with IKONOS imagery has shown mixed results (Asner *et al.,* 2002; Clark *et al.,* 2004a). Given height and crown area, Brown *et al.* (2005) developed allometric relationships for functional groups of Belizean tree species and were able to discern aboveground carbon stocks (biomass) in forests with a high degree of accuracy.

Analysis of LiDAR waveforms from a closed-canopy, tropical forest in Costa Rica revealed the three-dimensional structure of the forest (Weishampel *et al.,* 2000) and the relationship between the waveforms properties and aboveground biomass (Drake *et al.,* 2002). The robustness of these LiDAR/biomass relationships will be determined in conjunction with previous flights over tropical rainforest sites in Costa Rica. These relationships will be extrapolated to Caracol to produce maps of tropical forest structure that includes data on height, biomass, and internal canopy organization across this previously intensively occupied landscape. The hyperspatial imagery coupled with LiDAR will readily permit the segmentation of emergent trees which often account for the majority of biomass in rainforests (Clark and Clark 1996). Using existing and newly generated maps of prehistoric agricultural and other land use features (Chase and Chase 1998; 2001; 2003), contemporary forest structure will be compared with the past constructed landscape to examine possible correlations with Maya land use and calculated ages since abandonment. Patterns of forest recovery on causeways, agricultural terraces, urban plazas, and other land use classes will be identified and quantified.

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