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A 6900-year history of landscape modification by humans in lowland Amazonia

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ABSTRACT

A sedimentary record from the Peruvian Amazon provided evidence of climate and vegetation change for the last 6900 years. Piston cores collected from the center of Lake Sauce, a 20 m deep lake at 600 m elevation, were 19.7 m in length. The fossil pollen record showed a continuously forested catchment within the period of the record, although substantial changes in forest composition were apparent. Fossil charcoal, found throughout the record, was probably associated with humans setting fires. Two fires, at c. 6700 cal BP and 4270 cal BP, appear to have been stand-replacing events possibly associated with megadroughts. The fire event at 4270 cal BP followed a drought that caused lowered lake levels for several centuries. The successional trajectories of forest recovery following these large fires were prolonged by smaller fire events. Fossil pollen of *Zea mays* (cultivated maize) provided evidence of agricultural activity at the site since c. 6320 cal BP. About 5150 years ago, the lake deepened and started to deposit laminated sediments. Maize agriculture reached a peak of intensity between c. 3380 and 700 cal BP. Fossil diatom data provided a proxy for lake nutrient status and productivity, both of which peaked during the period of maize cultivation. A marked change in land use was evident after c. 700 cal BP when maize agriculture was apparently abandoned at this site. *Iriartea*, a hyperdominant of riparian settings in western Amazonia, increased in abundance within the last 1100 years, but declined markedly at c. 1070 cal BP and again between c. 80 and −10 cal BP.

1. Introduction

Climate change and human activity have had profound influences on forests in many regions of Amazonia. The early- to mid-Holocene was drier than the modern Amazonian climate (Mayle et al., 2000). Since the mid-Holocene, however, there has been an overall tendency toward wetter environments and an increase in the spatial extensiveness and temporal frequency of human disturbance (Mayle et al., 2000; Mayle and Power, 2008; Neves and Petersen, 2006). The arrival of Europeans and their diseases in the 1500s led to a >90% reduction in Amazonian populations (Denevan, 2003; Dobyns, 1966; Newson, 1996), though there is little agreement on pre-European population estimates (e.g. Bush et al., 2015a; Bush and Silman, 2007; Clement et al., 2015) After the population collapse, a new wave of settlers arrived in Amazonia during the Rubber Boom from 1850 to 1920 A.D. (e.g.Weinstein, 1983). Over the last century, transmigration policies have further increased environmental impacts (Hecht and Cockburn, 1989).

At finer spatial and temporal scales, the development of ancient Amazonian cultures has been seen to be heterogeneous, as have the impacts of climate change. It has been suggested that indigenous cultures were influenced by a c. 200-year periodicity of climatic events (Meggers, 1994; Schimmelmann et al., 2003). Regardless of whether such a periodicity exists, the potential for unusually large climatic events to occur is evident by two ‘droughts of the century’

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(2005 and 2010) that occurred within a decade (e.g. Aragão et al., 2007; Marengo et al., 2011). It is also apparent from those events that the influence of large climatic pulses may also be heterogeneous in their effect across the Amazon Basin. The full ecological impact of such large climate events is poorly understood. It is clear, however, that tree mortality in fragmented habitats is greater than in intact ones (Asner and Alencar, 2010; Laurance and Williamson, 2001; Nepstad et al., 2007), and that if fire results, it induces long-lasting changes that reverberate through the ecosystem far longer than the duration of the event itself (Barlow and Peres, 2008; Cochrane and Laurance, 2002).

The successional recovery post-disturbance depends on the magnitude of the disturbance and also the conditions under which recovery is taking place. Successional chronosequences from new succession, e.g. regrowth along newly accreted river shorelines appear to take c. 200–300 years to reach maturity (Foster, 1990). All forests experience natural disturbance, such that a mosaic of regrowth stages exists within an old growth terra firme forest (Chambers et al., 2013; Richards, 1996). Most of the loss of above ground biomass comes in small disturbances, e.g. >20 m^2 canopy gaps, with very little occurring as a result of large disturbance events, e.g. 5 – >30 ha blow downs (Espírito-Santo et al., 2014). These smallest gaps do not allow enough light to reach the forest floor to start a new succession (Hubbell et al., 1999), hence it is the rarer larger gaps that could influence the composition of a forest. Succession in such large gaps or following fire would be expected to follow the classic sequence of pioneers and light-demanding species progressively giving way to shade-tolerant competitors.

1.1. Amazonian climatic variability and human activity in the mid- and late-Holocene

Human colonization of the Andes and Amazonia approximately coincided with the onset of the Holocene (Dillehay et al., 2008; Roosevelt et al., 1996). Across the span of the Holocene, Amazonian and Andean climates were strongly influenced by precessional forcing (Baker et al., 2001; Bush et al., 2002), such that, on a millennial scale, at the nadir of wet season insolation lake levels tended to be low (Baker et al., 2001; Bird et al., 2011). For the tropical southern hemispheric Andes and western Amazonia, a drought-prone period began c. 9000 cal BP, peaked at c. 5500 cal BP, and ended c. 4000 cal BP (Abbott et al., 1997; Ekdahl et al., 2008). A complex series of droughts formed what has become known as the 'Mid-Holocene dry event'. In Bolivia and Peru, lake levels began rising c. 4000 cal BP, and continued to rise until c. 3300 cal BP or 2500 cal BP, according to location (Abbott et al., 1997; Hillyer et al., 2009; Mosblech et al., 2012). This pattern was reproduced in the speleothem calcite record from the Tigre Perdido Cave (van Breukelen et al., 2008), which revealed the last 3000 years to have been considerably wetter than the mid-Holocene, with slight fluctuations at multi-centennial to millennial scales.

1.2. A basic trajectory of human occupation of western Amazonia

Humans have lived within lowland Amazonia for the entire Holocene (Roosevelt et al., 1996), although their role in shaping the forest is contentious (Bush et al., 2015a; Clement et al., 2015; Roosevelt, 2013). In western Amazonia, the earliest evidence of human occupation is the presence of shell middens at c. 10,000 cal BP in the Bolivian Llanos (Lombardo et al., 2013), while the earliest known agriculture is the occurrence of maize pollen in the sediments of the Llanos de Moxos at c. 6500 cal BP (Brugger et al., 2016) (Fig. 1). After that time, there is increasing evidence of people occupying western Amazonia, especially in riverine and lakeside settings (Bush et al., 2007a; Bush and Silman, 2007; Denevan, 1996; Urrego et al., 2013).

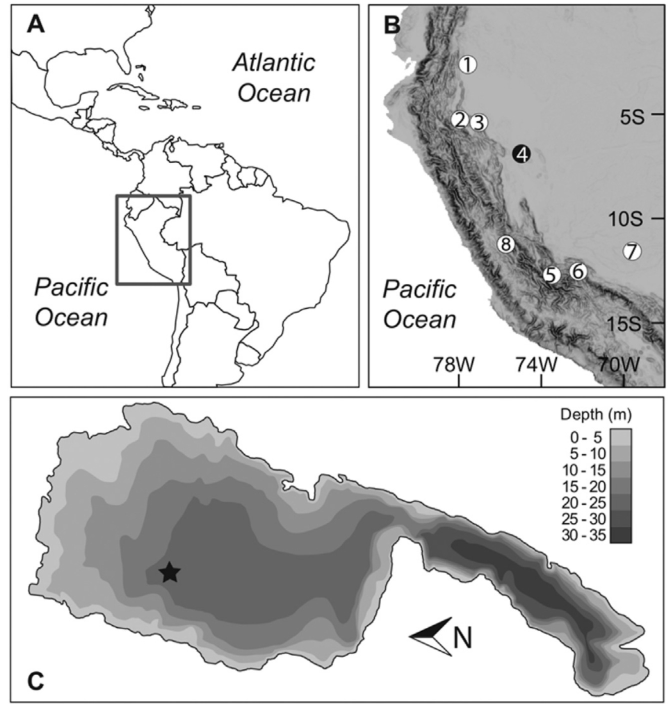

Fig. 1. Sketchmap showing the location and bathymetry of Lake Sauce, Peru. Coring location is marked with a star. Numbers refer to Peruvian and southern Ecuadorian locations mentioned in the text: 1 = Lakes Ayauch[i] and Kumpak[a], 2 = Caverna Tigre Perdido, 3 = Lake Pomacochas, 4 = Lake Sauce, 5 = Lake Pacucha, 6 = Lake Huaypo, 7 = Lake Gentry; 8 = Huagapo Cave.

Between 3000 and 2000 cal BP agricultural activity expanded in many parts of Amazonia (Piperno, 2006). This expansion was a manifestation of a longer-term shift from hunter-gatherer to increasingly settled communities. Intensified agricultural effort coincided with the formation of anthropogenic soils, known as *terras pretas* or Amazonian black earths, in central and eastern Amazonia (Glaser and Birk, 2012; Glaser and Woods, 2004; Neves et al., 2004), the development of complex societies in the upper Xingu and Marajó Island (Heckenberger et al., 2008; Roosevelt, 1991), geoglyph construction in southwestern Amazonia (Pärssinen et al., 2009; Schaan et al., 2012), and large-scale landscape transformation in the seasonal wetlands of Bolivian Amazonia (Erickson, 2000). Although the scale of human disturbance of Amazonian landscapes is actively debated (Balée, 2010; Bush et al., 2015a; Clement et al., 2015; McMichael et al., 2015), long-term human occupation and landscape modification was most likely to occur besides lakes and rivers (Denevan, 1996).

A lack of reliable historical accounts of Amazonian populations and landscape at the time of European contact has allowed a range of hypotheses to co-exist regarding the environmental impact of pre-Columbian populations. The extent to which these pre-Columbian populations influenced Amazonian ecology, particularly patterns of alpha and beta diversity, is contentious. Meggers (1954, 2007) argued that Amazonian peoples were environmentally determined, due to harsh climatic conditions and poor soil quality, to remain socially and technologically primitive. This view of small hunter-gatherer groups suggested that the pre-Columbian occupants of Amazonia had almost no impact on the forests. The discovery of complex village structures representing organized societies who engaged in agriculture (Heckenberger et al., 1999, 2008; Roosevelt, 1991), aquaculture (Erickson, 2000) and