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Long-term ecological legacies in western Amazonia

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Abstract

1. Modifications of Amazonian forests by pre-Columbian peoples are thought to have left ecological legacies that have persisted to the modern day. Most Amazonian palaeoecological records do not, however, provide the required temporal resolution to document the nuanced changes of pre-Columbian disturbance or post-disturbance succession and recovery, making it difficult to detect any direct, or indirect, ecological legacies on tree species.

2. Here, we investigate the fossil pollen, phytolith and charcoal history of Lake Kumpak, Ecuador, during the last 2,415 years in c. 3–50 year time intervals to assess ecological legacies resulting from pre-Columbian forest modification, disturbance, cultivation and fire usage.

3. Two cycles of pre-Columbian cultivation (one including slash-and-burn cultivation, the other including slash-and-mulch cultivation) were documented in the record around 2150–1430 cal. year BP and 1250–680 cal. year BP, with following post-disturbance succession dynamics. Modern disturbance was documented after c. 10 cal. year BP. The modern disturbance produced a plant composition unlike those of the two past disturbances, as fire frequencies reached their peak in the 2,415-year record. The disturbance periods varied in intensity and duration, while the overturn of taxa following a disturbance lasted for hundreds of years. The recovery periods following pre-Columbian disturbance shared some similar patterns of early succession, but the longer-term recovery patterns differed.

4. Synthesis. The trajectories of change after a cessation of cultivation can be anticipated to differ depending on the intensity, scale, duration and manner of the past disturbance. In the Kumpak⁴ record, no evidence of persistent enrichment or depletion of intentionally altered taxa (i.e. direct legacy effects) was found but indirect legacy effects, however, were documented and have persisted to the modern day. These findings highlight the strengths of using empirical data to reconstruct past change rather than relying solely on modern plant populations to infer past human management and ecological legacies, and challenge some of the current hypotheses involving the persistence of pre-Columbian legacies on modern plant populations.
1 | INTRODUCTION

Amazonia is one of the most biodiverse regions on Earth (Olson et al., 2001). This biodiversity has been shaped by an array of processes operating on a large range of temporal and spatial scales, including long-term tectonism (Hoorn et al., 2010), climate change (Liu & Colinvaux, 1985), riverine dynamics (Pupim et al., 2019), stochastic processes (Hubbell, 2001), biotic interactions (Schemske, Mittelbach, Cornell, Sobel, & Roy, 2009) and canopy-gap dynamics (Mittelbach et al., 2007). Humans have also been implicated in shaping the species richness and relative abundances of species in Amazonia. In particular, it has been suggested that pre-Columbian peoples, or the indigenous inhabitants of the forest prior to European arrival, modified forest composition and left ecological legacies that persist at least until the modern day (Balée, 1989; Denevan, 2006; Erickson, 2006; Levis et al., 2017; Maezumi et al., 2018). People have lived within Amazonia for at least 13,000 years (Roosevelt, 2013), and modified their environment through hunting (Antunes et al., 2016; Redford, 1992), the use of fire (Barlow & Peres, 2006; Bush et al., 2015), deforestation (Laurance, Albernaz, Fearnside, Vasconcelos, & Ferreira, 2004), cultivation (Brugger et al., 2016; Bush, Piperno, & Colinvaux, 1989), soil modification (Glaser & Birk, 2012; Neves, Petersen, Bartone, & Heckenberger, 2004), enrichment of forest with useful species (Balée, 1989; Balée & Erickson, 2006; Levis et al., 2017) and the construction of earthworks (Pärrsinen, Schaan, & Ranzi, 2009; Roosevelt, 1991; Watling et al., 2017).

Considerable disagreement exists regarding the scale of these transformations both in space and time (Bush et al., 2015; Clement et al., 2015; Ferreira, Levis, Iriarte, & Clement, 2019; Levis et al., 2017; Maezumi et al., 2018; McMichael & Bush, 2019; McMichael, Feeley, Dick, Piperno, & Bush, 2017; Piperno, McMichael, & Bush, 2019; Stahl, 2015). But regardless of the spatial and temporal scale of these modifications, the arrival of Europeans brought enslavement, malnutrition and novel diseases to a susceptible population. This arrival is suggested to have caused premature mortality of 90%–95% of the indigenous population in the 1600s (Black, 1992; Dobyns, 1983), with a concomitant abandonment of occupied lands (Smith, 1999). This rapid shift in land use is suggested to have caused a surge in carbon uptake (Dull et al., 2010; Koch, Brierley, Maslin, & Lewis, 2019; Nevele, Bird, Ruddiman, & Dull, 2011) and to have contributed to the hyperdominance of some plant species (Levis et al., 2012; ter Steege et al., 2013).

The ecological legacies left by pre-modern human activities can either be direct, that is, the intended product of manipulation of the environment, or indirect, that is, the unintended product of manipulation (Figure 1). Direct legacies would include the intentional enrichment of preferred species, or the intentional removal of non-preferred species (Clement et al., 2015). The direct enrichments or depletions caused by past human activities can affect the successional trajectory, or ecological legacy, in two ways. One possibility is that the populations that were enriched or depleted quickly rebound to pre-disturbance abundances (non-persistent enrichment/depletion, Figure 1). The other possibility is that enriched or depleted abundances of species persist through time, where enriched species establish reproductive populations that continue to the present day and depleted species do not recover to pre-disturbance abundances (Figure 1a). For example, palms with fruits eaten by people, such as peach palm *Bactris gasipaes* (Clement, 1988; Clement, Rival, & Cole, 2009; Hernández-Ugalde, Mora-Urpi, & Rocha, 2011), and Moriche *Mauritia flexuosa* (Rull & Montoya, 2014), along with Brazil nut *Bertholletia excelsa* (Levis et al., 2012; Scoles & Gribel, 2011;
Pre-Columbian people in Amazonia may have also depleted the relative abundances of some species (Clark, Clark, Sandoval, & Castro, 1995; Ferreira et al., 2019; Figure 1b). The depletions are likely to be among species that were cut to provide timber for construction or where consumption was a one-time disturbance, for example, harvesting for heart of palm (Haynes & McLaughlin, 2000). In Costa Rica, the absence of *Iriartea deltoidea* from forests near rivers in La Selva Biological Reserve was identified as a legacy effect of colonial era logging (Clark et al., 1995). In Amazonia, pollen percentages of *I. deltoidea* and phytolith percentages of taxa including *Iriartea* were lower when direct indicators of human activity (i.e. charcoal or crop pollen) were at their highest (Bush & McMichael, 2016; Heijink et al., 2020). Depletions, like enrichments, can be persistent, non-persistent or indirect (Figure 1b). The intensity, manner, scale and duration of past disturbance all influence post-abandonment successional trajectories (Bodin, Molino, Odone, & Bremond, 2020). In some areas, the land use was a polyculture featuring mixed crop field systems and orchards (Denevan, 2001). If abandoned, succession would have quickly displaced crop plants and disturbed-ground weeds with fast growing, light-loving trees, as a stage before a dense forest established (Bush & McMichael, 2016; McMichael Correa-Metrio & Bush, 2012; McMichael, Piperno, et al., 2012; Whitney et al., 2019). Addressing questions of past forest disturbance and recovery is best accomplished through a multiproxy approach that capitalises on the different strengths of the evidentiary lines. For example, though phytoliths cannot distinguish many of the tree taxa that can be identified with pollen, pairing the two proxies: (a) increases certainty in identifying cultivation and forest opening and (b) provides a more comprehensive view of the change in taxa associated with disturbance and recovery processes. Unlike pollen, phytoliths can also distinguish grasses to sub-family or sometimes even genera, making them particularly useful for disentangling grasses typical of disturbed or open settings, grasses that grow under the forest canopy, and aquatic grasses (Morcote-Rios, Bernal, & Raz, 2016; Piperno, 2006b). Palms are also abundant producers of phytoliths and many phytolith morphotypes can be identified to genus (Piperno, 2006b).

The study of past disturbance in lowland rainforests also has to be conducted at an appropriate temporal scale. Most palaeoecological records are temporally coarse-grained, generally offering centennial resolution, and cannot assess the nuanced changes of pre-Columbian disturbance, post-disturbance recovery and various types of ecological legacies of tree species. Here, we provide an almost unprecedented temporal resolution for a multiproxy Amazonian palaeoecological record. Using fossil pollen, phytolith, and charcoal from the 2,415-year Lake Kumpak* record, Ecuador, at 3–50 year time intervals, we assess the types, duration and variation of ecological legacies resulting from pre-Columbian fire, agriculture and forest disturbance.

### 2 | STUDY AREA

Lake Kumpak* (2°50′11″S, 77°57′41″W; 333 m elevation) is located in lowland Amazonia, Ecuador (Figure 2a). The lake has a diameter of 420 m, a maximum water depth of 19.5 m and is thought to be volcanic in origin (Colinvaux, Millerf, & Liu, 1985; Figure 2b). Lake Kumpak* is permanent and has no riverine influence, making it a rarity in Amazonian systems. The region receives approximately 2,000–3,000 mm of precipitation per year and lacks a defined dry season (https://www.climate-data.org; Liu & Colinvaux, 1988). Mean annual temperature is 24°C. Small streams deliver sediment-rich water to all sides of the mesotrophic lake (Figure 2b). A lack of outlets suggests that water level changes in response to precipitation. We found the lake to be anoxic below 2 m water depth (measured in 2014).

The lake was first cored in 1983 by Paul Colinvaux’s team and a low-resolution, 5,860-year history of its pollen and sediment stratigraphy was published (Liu & Colinvaux, 1988; Figure 2c,d). That study revealed a largely stable rainforest system, with more apparent ecological changes in the last 1,500 years than in the earlier portion of the record. The possibility that there was a human history was largely ignored in this initial study.

Following establishment of a Salesian mission station in the 1960s, most of the modern landscape surrounding Lake Kumpak* has been modified for small-scale agriculture and grazing. Today, a small community of the Shuar nation inhabits the areas around the lake. In 2014, patches of secondary forest and pastures formed a fragmented landscape around the lake where pastures were dominated by introduced grasses, especially the African grass species *Brachiaria* (Figure 2e,f). Common secondary forest taxa were *Didymopanax*, *Piptocoma*, *Cordia*, *Terminalia*, *Caryodendron*, *Croton* and *Inga*. A range of crop taxa were farmed in the area, including *B. gasipaes* (peach palm), *Carludovica palmata* (native Panama-hat plant), *Manihot esculenta* (native Amazonian manioc), *Degelia utilis* (barbasco plant), *Musa x paradisiaca* (banana), *M. sapientum* (plantain), *Ananas comosus*
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(pineapple), Carica papaya (papaya) and Zea mays (maize). The vegetation closest to the lake shore was dominated by remnant forest taxa with a closed canopy, including Mauritia, Wettinia, Symphonia, Sapium, Deguelia, Erythrina, Ficus, Virola, Hieronyma, Triplaris and Homalium. Undisturbed primary forest existed on slopes and ridges further north and west of the basin. Aerial photography from the early 1980s (Liu & Colinvaux, 1988) compared with 2014 show similar trends in openness, suggesting that the area has been consistently kept open for almost 30 years (Figure 2c–f), but this does not imply no change in the tree composition within the forest.

3 | MATERIALS AND METHODS

In July 2014, an 18.0-m sediment core was retrieved from 19.5 m water depth. The core was wrapped in the field in sections of 1 m, transported to Florida Institute of Technology and stored at 4°C. The sediment core represents the limit of coring ability as bedrock was not reached. Terrestrial macrofossil remains (n = 15) were isolated and radiocarbon dated to establish the Kumpak chronology (Supporting Information: Methods; Blauw & Christen, 2011; R Development Core Team, 2019; Reimer et al., 2013).

Subsamples were taken for pollen and phytoliths at every 5 cm from 0 to 530 cm core depth and at every 10–20 cm for the intervals from 530 to 760 cm. Charcoal was subsampled at 1–5 cm resolution throughout the 760 cm section. Pollen samples (n = 126) were treated according to standard methodology (Supporting Information: Methods; Fægri, Kaland, & Krzywinski, 1989; Stockmarr, 1971) and a minimum of 300 pollen grains was counted in each sample. Identification of pollen grains was made using appropriate keys (Colinvaux, De Oliveira, & Moreno, 1999; Roubik & Moreno, 1991), the Neotropical Pollen Database (Bush & Weng, 2007) and the reference collection at Florida Institute of Technology. Extended maize counts were performed on all subsamples. Phytolith samples (n = 131) were prepared according to standard methodology (Piperno, 2006b) and a minimum of 200 phytoliths were counted in each sample (Piperno, 2006b; Supporting Information: Methods). Phytolith keys (Morcote-Ríos et al., 2016; Pearsall, 1978; Piperno, 2006b) and the reference collection at University of Amsterdam were used for identification. Pollen and phytolith samples were analysed using Zeiss
Axioskop photomicroscopes with magnifications of 400x, 630x and 1,000x. Pollen and phytolith types were grouped into ecological assemblages to aid interpretation (Tables S1 and S2; Gentry, 1996). Each identified pollen or phytolith was assigned to one of four vegetation types: (a) grasses, (b) herbs, (c) arboreal and (d) palms.

Charcoal samples ($n = 515$) were prepared according to standard methodology (McMichael, Correa-Metrio, et al., 2012; McMichael, Piperno, et al., 2012; Whitlock & Larse, 2001; Supporting Information: Methods) and examined under an Olympus stereoscope at 7–70x magnification. ImageJ software (Rasband, 1997–2018) was used to calculate the volume ($mm^3/cm^3$; Weng, 2005) of all charcoal particles within each sample. Fossil percentage diagrams were constructed using C2 (Juggins, 2007).

Detrended correspondence analysis (DCA) was performed using R (R Development Core Team, 2019) and the vegan package (Oksanen et al., 2013) on the pollen and phytolith data, separately, to quantify trends in (dis)similarity between samples (slices of time within the stratigraphic sequence), and to determine which taxa within pollen or phytolith assemblages were most responsible for driving those differences (also see Supporting Information: Methods). We also used the DCA results to determine whether successional trajectories or ecological legacies could be seen in the data.

4 | RESULTS

The 18.0-m core spans the last 5,400 years, and all 15 radiocarbon ages were accepted to provide the chronology (Table S3; Figure S1). This paper focused on the last 2,415 years (760 cm), where sediment accumulation rate averaged 3.24 years per centimetre and remained consistent almost throughout the entire core (Figure S1). This 760 cm of sediment was dominated by alternating pale and dark organic clay laminations of very thin thickness ($<1$ mm) interspersed with medium (2–5 mm) to very thick (>10 mm) laminations (Supporting Information: Results; Figure S2).

The temporal resolution of sampling provides a c. 3- to 15-year resolution for charcoal occurrence and a c. 15- to 50-year periodicity for pollen and phytolith data. Old-growth arboreal pollen and phytoliths were prominent features throughout the Kumpak core record, Ecuador, with values fluctuating between 30% and 90% for pollen and 35%–95% for phytoliths (Figure 3). In the pollen record, decreases in old-growth arboreal forest and palm elements (e.g. Moraceae, Urticaceae, Iriartea, Alchornea, Didymopanax, Celtis, Mimosa and Mauritia-Mauritiella) were due to a replacement in the assemblage by grasses (Poaceae and Z. mays), herbs (e.g. Acalypha, Piperaceae and Asteraceae) and arboreal secondary forest elements (e.g. Cecropia; Figure 3a). The phytolith record followed similar trends as the pollen record (Figure 3b). Rugose spheres, which are mainly produced by arboreal old-growth forest taxa (e.g. Piperno, 2006b), are present in high percentages throughout most of the record (Figure 3b). Oblong echinate and globular echinate phytoliths, which represent palm genera such as Euterpe, Hyospathe and Attalea (Huisman, Racza, & McMichael, 2018; Morcote-Ríos et al., 2016), and conical palm phytoliths representing taxa such as Bactris, Iriartea, Wettinia, Alpinhaes and Socratea (Huisman et al., 2018; Morcote-Ríos et al., 2016), all increased at the expense of the rugose spheres. The increased abundances of palm phytoliths did not occur, however, in samples with the highest abundances of weedy taxa, grasses, Heliconia phytoliths or maize phytoliths (Figures 3b and 4).

The changes in abundances of conical palm phytoliths, which represent genera such as Iriartea, Wettinia and Bactris, were similar, but not exact, to those seen in the Iriartea pollen record (Figure 3). Botanical inventory surveys conducted by David Neill in 2014 observed Wettinia, a genus common to the ever-wet forests of the Andean piedmont (Kahn & De Granville, 2012), in abundance around the lake edge of Kumpak². Small stands of peach palm B. gasipaes were also observed in the adjacent farmlands, but no individuals of Iriartea were observed in the vicinity of the lake, supporting the modern decline of Iriartea observed in the pollen record (Figure 3). As conical phytoliths were present in the modern phytolith assemblages, and were common around the lake edge, we interpret changes in conical phytoliths as representing changes in Wettinia and Iriartea populations through time. Wettinia has most likely always been present to some degree around the lake, and when the populations of Iriartea declined over the last 150 years, Wettinia populations have persisted (Figure 3).

The globular echinate phytoliths, which represent genera such as Mauritia, Euterpe, Attalea and Hyospathe (Huisman et al., 2018; Morcote-Ríos et al., 2016), varied primarily between 1% and 10%, with occasional samples containing up to 20% (Figure 3). Abundant adult M. flexuosa individuals were observed around the lake edges during the vegetation surveys. The persistence of Mauritia pollen and the globular echinate phytoliths through time revealed that these stands have been present in similar abundances for most of the last 2,400 years (Figure 3).

These changes in forest and palm composition happened primarily in the absence of fire. Despite searching for charcoal in over 500 samples, fire was only detected in 13 samples, and only in extremely low quantities until the modern clearing of the landscape that occurred in the AD 1960s (Figure 3). The presence of charcoal and maize pollen or phytoliths provided the temporal brackets of human disturbance periods, which allowed us to assess trajectories of ecological change in the subsequent recovery periods.

4.1 | Disturbance and recovery at Lake Kumpak²

An increase in secondary forest elements at c. 2250 cal. year BP occurs before the onset of a disturbance phase, lasting from c. 2100 to 1430 cal. year BP (Figures 3 and 4; Figure S3). During the disturbance, a few pinhead-sized charcoal fragments (c. 0.06 mm³/cm³) were found at c. 2120 cal. year BP and 1770 cal. year BP. Maize pollen and/or phytoliths, however, were found in 12 of 17 samples (71%), with the highest frequency of maize findings between c. 1820 and 1450 cal. year BP (Figure 3). Grass pollen increased to 5% and grass phytoliths reached values up to 18% (Figure 3). Herbs also increased during the disturbance, including Piperaceae (15%),
**Figure 3** Percentage diagrams for (a) fossil pollen and (b) phytoliths and charcoal (mm$^3$/cm$^3$) plotted against time (cal. year BP) showing the most abundant taxa from Lake Kumpak, Ecuador. Maize pollen and phytoliths are shown as presence (orange circles) and grey bars indicate times of most intense disturbance during the two pre-modern disturbance phases. Asterisks indicate minute quantities of charcoal and plus signs indicate charcoal sample effort. Comb. indicates the family Combretaceae, Mela. indicates the family Melastomataceae, Mora. indicates the family Moraceae and Urti. indicates the family Urticaceae. P-D = pre-disturbance, R = recovery, D = disturbance and MD = modern disturbance. Colour available in online version.

**Acalypha** (11%), Asteraceae (3.5%) and Solanaceae (2.5%). After c. 1600 cal. year BP, grasses and herbs started to decline due to increased abundances of arboreal secondary forest and palm taxa including *Cecropia*, Combretaceae, Melastomataceae, *Iriartea* and other palms with oblong echinate phytoliths such as *Euterpe* and *Attalea* (Figure 3). Arboreal pollen and phytoliths continued to have high values over the next c. 350 years (maxima of 80% and 90%, respectively), with, that is, *Iriartea* pollen reaching values up to 20%.

Renewed disturbance and maize cultivation re-appeared in the record after c. 1250 cal. year BP until c. 680 cal. year BP (Figure 3),...
coinciding with decreased abundances of arboreal types (including *Iriartea*, Moraceae, Urticaceae, conical palm phytoliths, *Didymopanax*, *Stigmaphyllon*, Myrtaceae and *Mimosa*). Grasses and herbs increased, with grass pollen (12%) and grass phytoliths (14.5%) reaching maxima between c. 1070 and 680 cal. year BP (Figures 3 and 4). Compared with the previous disturbance, this phase appears to have been more intense and longer lasting, with maize pollen and/or phytoliths found in 19 of 37 samples (51%). Increases in herbs such as *Acalypha* (22.5%), Asteraceae (8%), *Iresine* (2%), Piperaceae (20%) and Solanaceae (2.5%) were evident as Cecropia pollen fluctuated (c. 3%–50%). Fire was very rare during this disturbance period (Figure 3).

With the decline of grasses and herbs after c. 680 cal. year BP, arboreal secondary taxa (*Cecropia*, *Ficus* and *Guazuma*) increased slightly for c. 50–300 years while other arboreal old-growth forest pollen and phytolith types increased steadily up to c. 80% and 80%, respectively (Figure 3). The highest increases in *Iriartea* pollen (35%) have occurred over the last 600 years, though populations have declined over last 100 years. *Iriartea* had near absence values (<1%) after c. 10 cal. year BP, coinciding with modern-day disturbance (Figure 3) when grass pollen and phytoliths increased in abundances to 4% and 5%, respectively, and maize phytoliths were found in 5 of 11 samples. Arboreal old-growth forest pollen and phytoliths declined (both with 50%) and *Cecropia* reached values above 40%. A small fire event is suggested by the presence of charcoal fragments at c. 480 cal. year BP (Figure 3).

The highest fire frequency in the Lake Kumpak* record occurred in the modern era. Fire frequency was higher during the last 80 years compared with any other portion of the record, with charcoal fragments identified between c. –15 cal. year BP and –30 cal. year BP (Figure 3). Two of the seven samples containing charcoal in the modern disturbance period also contained evidence of maize cultivation. Even with the fires during this period at Lake Kumpak*, the vegetation was less impacted than in the past. Percentages of modern maize and grasses were lower in the modern disturbance period than those found at c. 2150–1430 cal. year BP and c. 1250–680 cal. year BP (Figure 3).

The Detrended Correspondence Analyses (DCA) for pollen and phytoliths highlighted the successional trajectories following disturbance (Figure 4). The modern samples in the pollen spectra lay towards the negative ends of Axes 1 and 2, whereas the modern phytoliths were positioned in the middle of the plot. Samples from the most intense disturbance and subsequent recovery period (1250–680 cal. year BP) had values at the extreme ends of DCA Axis 1. The modern mid- to late successional taxa found in the recovery periods of both the pollen and phytolith data can then be seen to move towards 0 on DCA Axis 1 (Figure 4a,c). Samples containing crop pollen and phytoliths were on the negative end of DCA Axis 1, and the herb elements in the recovery periods of both the pollen and phytolith data can then be located on the positive end of DCA Axis 1 of both the pollen and phytolith data. The disturbance and succession trajectories seen in the DCA are all in the context of the arboreal old-growth forest taxa located in the middle of the biplot (Figure 4b,d).

### 5 Discussion

The Lake Kumpak* record is a rarity in Amazonian systems as it comes from a permanent lake without riverine influence, offering the potential for an unusually detailed palaeoclimatology. The high deposition rate allowed us to reconstruct charcoal at an almost
continuous resolution of 3.24 years, confirming the true rarity of fire in this system, and pollen and phytoliths at a c. 15- to 50-year resolution. The laminated sediments and $^{13}$C ages provided reassurance that there has been little post-depositional disturbance, allowing an almost linear age model to be constructed (Figure S1). Our study broadly supported the original pollen reconstruction from Lake Kumpak, which had samples every 100–300 years, but had no corresponding charcoal or phytolith analysis (Liu & Colinvaux, 1988). Our study, however, documented the ability of multi-proxy palaeoecological datasets analysed on decadal time scales to address questions regarding the long-term disturbance and recovery patterns of Amazonian forests.

5.1 | The intensity of past disturbances at Lake Kumpak

Based on our aerial imagery, the modern landscape around Lake Kumpak, consisting of a village of around 60–100 people and of a mosaic of farmland and regrowth, appears to have been more or less stable for the last 30 years (Figure 2c–f). Though all the forest around the lake is disturbed, there is about 80% forest cover. The corresponding pollen assemblages during this recent period of 80% forest cover contain about 93% forest pollen, of which <5% were from palms (Figures 3 and 5). The arboreal elements found in the pollen assemblages included: Moraceae, Urticaceae, Combretaceae, Melastomataceae, Alchornea, Didymopanax, Celtis and Cecropia (Figure 3).

In the modern botanical inventory surveys, species of Didymopanax, Moraceae, Combretaceae and Melastomataceae were observed in remnant forest around the lake today, primarily Wettinia, Mauritia and Bactris, were more strongly represented in phytolith than pollen sequences. Maize was also being grown around the lake when it was cored in 2014, which was detected in the phytolith samples (Figure 3). These values of forest cover, grass and maize derived from the pollen and phytolith samples, combined with the arealimagery and field surveys (Figure 2), provide a benchmark with which past clearance and disturbance can be compared.

Driven by increased abundances of grasses, herbs and the arboresial secondary taxa Cecropia, the modern pollen samples plot near the negative extremes of Axes 1 and 2. The DCA suggest that the modern pollen samples reflect substantial disturbance, though not as extreme as some samples from either of the two earlier periods of cultivation (c. 2150–1430 cal. year BP and 1070–680 cal. year BP; Figure 4a,b). The phytoliths clearly show the modern disturbance to be quite different to that of earlier episodes as modern samples cluster with those from the earlier recovery periods (Figure 4c). DCA Axis 1 of the phytolith record was largely driven by the increased

**FIGURE 5** Fossil percentage summary diagrams for pollen and phytoliths plotted against time (cal. year BP) from Lake Kumpak, Ecuador, showing taxa separated in four vegetation groups, including grasses (orange), herbs (pink), arboreal (green) and palms (blue). Maize pollen and phytolith presence (orange circles) and the charcoal volume (mm$^3$/cm$^3$) are shown. Black asterisks for charcoal indicate minute quantities and plus signs indicate charcoal sample effort. Dashed lines show the delineation of disturbance and recovery periods, and grey bars denote the times of most intense disturbance during the two pre-modern disturbance phases. Colour is available in the online version.
abundances of palm phytoliths over the period of 550 cal. BP to the modern period (Figure 4d). Phytoliths are not as sensitive as pollen to the changes in the non-palm arboreal vegetation and the placement of the modern disturbance samples is driven by the palm phytolith type *Iriartea-Wettinia*. *Iriartea* and *Wettinia* are currently indistinguishable, but the differing patterns of change in the pollen and phytoliths can be used to differentiate these taxa. *Iriartea* pollen declines sharply in the modern disturbance, but the *Iriartea-Wettinia* phytoliths do not. *Iriartea* was not recorded in the modern flora at the lake, but *Wettinia* was observed on the shoreline. As a result, the modern phytolith samples were statistically similar to those of the forest regrowth periods in the DCA, even though ecologically they were not.

The period from c. 1070 to 680 cal. year BP was probably the most intensely disturbed of the entire record (Figures 3–5), based on the amounts of *Cecropia*, *Poaceae*, *Z. mays*, and herb taxa in the pollen and phytolith data. In disturbed Amazonian forests, as much as 50% of the pollen signal comes from *Cecropia*, a pioneer secondary forest species that produces enormous quantities of pollen (Bush & Rivera, 1998). Percentages of *Cecropia* are similar between the modern system and the period from c. 1070 to 680 cal. year BP, though the amount of landscape opening may have varied. Palm abundances in both the pollen and phytolith record are low during this period compared with recovery periods and the modern period (Figures 3–5). The decline in arboreal elements was also significantly larger from 1070 to 680 cal. year BP than during the modern disturbance period (Figures 3–5). The reduction in forest pollen percentage is probably not linearly related to the area of forest clearing (Whitney et al., 2019), but it may provide a guide to estimating the extent of disturbance. Arboreal elements comprise 90% of the modern pollen assemblages of the last 30 years, where land clearance is known to affect 20% of the landscape (Figure 2c–f). When arboreal percentages decrease to 75% of the pollen assemblage, it suggests land clearance may have increased a similar amount, or up to 35% of the area around the lake. While this is a very speculative number, it is safe to say that the combined pollen and phytolith data suggest that the peak of clearance at c. 950 cal. year BP was substantially larger than that of today, and palms were likely disproportionately removed (Figures 3 and 5).

Herbaceous and grasses in the pollen and phytolith record suggest the landscape around Lake Kumpak was in the earlier period of disturbance from 2150 to 1430 cal. year BP. Charcoal abundances at Lake Kumpak were orders of magnitude less than in other Amazonian lakes containing similar evidence of maize cultivation, for example, Lakes Ayauch, Sauce and Gentry (Supporting Information: Discussion; Bush et al., 2016; Bush, Silman, & Listopad, 2007; McMichael, Bush, et al., 2012; McMichael, Correa-Metrio, et al., 2012). Lake Ayauch, just 25 km away from Kumpak, was occupied for over 6,000 years with maize cultivation and long-term fire use, suggesting that slash-and-burn agriculture was used to manage the landscape (Bush & Colinvaux, 1988; McMichael, Bush, et al., 2012; McMichael, Correa-Metrio, et al., 2012; Piperno, 1990). Natural fires are almost non-existent in western Amazonia, as the wet conditions of the forests limit the spread of fire, and findings of charcoal fragments in palaeoecological records have repeatedly been linked with human land use (Aragao et al., 2008; Bush et al., 2007, 2016; Cochrane, 2009; Cochrane & Schulze, 1999; Kelly et al., 2018; McMichael, Correa-Metrio, et al., 2012; Nepstad et al., 2004; Urrego et al., 2013).

Fire may not have been an important management tool at Lake Kumpak. Charcoal was almost uniquely associated with maize (Figures 3 and 5), but the paucity of samples containing charcoal, and the low amounts of charcoal found in those samples, suggest that the cultivation around Lake Kumpak was not reliant on fire. One possibility was that rather than using slash-and-burn cultivation, the inhabitants of Kumpak may have been using slash-and-mulch (Joslin et al., 2011). This technique helps to retain nutrients volatilised during burning, and limits soil compaction, which reduces erosion from a denuded forest surface (Hölscher, Möller, Denich, & Fölster, 1996; Jordan, 1985). Mulching reduces weed growth while providing a slower, more sustained nutrient release than burning, and runs less risk of carbon ignition and soil degradation than slash-and-burn (Arroyo-Kalin, 2012; Joslin et al., 2011; van Vliet, Adams, Vieira, & Mertz, 2013). The fertility of the soils around the lake is not known, but if the origin of the lake is a volcanic maar, the soils may be more fertile than typical of Amazonia (Rostain, 2012). The Lake Kumpak data appear to be the first empirical evidence for the pre-Hispanic use of slash and mulch in western Amazonia.

5.2 Disturbance and recovery

The composition of pollen from the modern disturbance period falls within the variability of past disturbances, and shares characteristics with both the disturbance ending at 1430 cal. year BP and 680 cal. year BP (Figure 5). Our pollen and phytolith data, however, suggest that modern human disturbance between 10 and −10 cal. year BP (AD 1940–1960), and the subsequent modern occupation, created ecologically different conditions from those that occurred in the past (Figures 4 and 5). As with past cultivation periods, *Iriartea* and most other arboreal forest elements decline abruptly while disturbance taxa such as *Cecropia*, *Trema*, *Solanaceae* and *Poaceae* increase in abundance. During the modern disturbance, however, none of the herb taxa (e.g. *Asteraceae*, *Piperaceae* and *Acalypha*) increased in
percentages as they did during and after past disturbances. The differences between the modern disturbance period and past disturbances are probably caused by the increased reliance on fire in modern times compared with the past (Figures 3 and 4), and are consistent with expectations of slash-and-burn agriculture (Arroyo-Kalin, 2012; van Vliet et al., 2013).

Though some of the patterns of early succession are similar between the two past disturbance events, there are differences in the longer-term recovery patterns. For example, within 100 years of the cessation of maize cultivation, Ficus, a longer-lived pioneer genus, increased in abundance following the more intense disturbance ending at 680 cal. year BP, but not the one ending at 1430 cal. year BP (Figure 3; Figure S4). Myrtaceae increase within 100 years after disturbance ending at 680 cal. year BP (Figures 3, 5 and 6).

The total duration of the recovery period is much shorter for the two disturbance events is likely related to the differing disturbance intensities. The duration of the recovery period is much shorter with the disturbance ending at 1430 cal. year BP compared with the disturbance ending at 680 cal. year BP (Figures 3, 5 and 6).

5.3 | Ecological legacies

The predominant idea among archaeologists regarding ecological legacies is that useful species were deliberately enriched or depleted in the pre-Columbian era, and that those altered abundances have persisted until the modern era (Ferreira et al., 2019; Levis et al., 2012, 2017; Figure 1). Under this scenario, useful or domesticated species in the Lake Kumpak sediment record should have flourished during the peak of maize cultivation and show persistently elevated abundances even after the cessation of cultivation (direct and persistent enrichment; Figure 1a). Our record does not support this contention as no useful taxa (i.e. Lecythidaceae, Theobroma, Mauritia, etc.) showed such a permanent pattern of enrichment. We also saw no evidence of persistent depletion, as the taxa with depleted populations, that is, Iriartea, recovered (Figure 6). Instead, our data show that while pre-Columbian activities can alter recovery trajectories for hundreds of years following the cessation of a disturbance, the trajectories do not include evidence of persistent enrichment or depletion (Figure 6).

Though many taxa are either too rare for a pattern to be reliably detected or simply show no significant response to land use change (e.g. Mauritia), we identify 14 taxa as showing a positive population response to the phases of disturbance and recovery. Taxa with the highest abundances during maize cultivation were as follows: Acalypha, Asteraceae, Cecropia, Combretaceae, Iresine, Lonchocarpus, Malvaceae, Piperaceae, Poaceae, Saurauia, Solanaceae, Tontelea, Trema and Zea (Clement et al., 2015) could be useful species and therefore the product of direct enrichment, whereas the others are most likely to have been indirect enrichments. Some of these are known to be early successional taxa (e.g. Cecropia, Trema, Acalypha, Asteraceae, Piperaceae) that are non-persistent and decrease shortly after cultivation ends (Figures 3 and 6). Ficus and some mid-successional
taxa showed post-occupation increases, followed by declines about 100 years into the succession (Figures 3 and 6; Figure S4). Here, we classify these as indirect, non-persistent ecological legacies (Figures 1a and 6; Figure S4).

*Iriartea deltoidea* is one of the commonest trees of western Amazonia (ter Steege et al., 2013, 2020), and has consistently shown a negative response to human activity in palaeoecological records (Figure 4; Bush & McMichael, 2016; Heijink et al., 2020). At Lake Kumpak, the periods of maize cultivation coincided with the loss of *Iriartea*, which is to be expected, as it would have been harvested for timber (Supporting Information: Discussion; Bernal et al., 2011; Clark et al., 1995; Zambrana et al., 2007). A century or more after the depletions of *Iriartea* populations ended, they recovered at Lake Kumpak. The populations also recovered to levels that exceeded those in the pre-cultivation period (Figures 3 and 6) and its abundance prior of the last 5,200 years (Liu & Colinaux, 1988). We classify this population expansion as an indirect persistent enrichment that terminates with another direct depletion in near-modern times.

Our observations fit with the known autecology of *Iriartea* in that it is known to be a mid-successional species that can grow at high stem densities in floodplain forests subject to long-term disturbance by rivers (Balslev, Luteyn, Ollgaard, & Holm-Nielsen, 1987; Pitman et al., 2001). It seems unlikely that the increases seen in the Lake Kumpak record resulted from *Iriartea* being cultivated for remote usage, as transporting trunks the 3 km to the nearest river would have been problematic. Far more likely is that *Iriartea* regrew naturally as an early-mid successional species, and that its surge in abundance c. 200 years after cultivation ended was the synergistic effect of regional increased precipitation levels (van Breukelen, Vonhof, Hellstrom, Wester, & Kroon, 2008) and the release from human exploitation. These surges in abundance may have also been facilitated by changes in the soil, drainage or soil erosion caused by occasional fire and cultivation. *Iriartea* maintained high populations for >500 years after abandonment, that is, several tree generations (Pinard, 1993).

It is evident that generational time, individual longevity and tree size must be taken into account in estimating direct and indirect legacy effects. For example, a large, long-lived, tree such as *Bertholletia excelsior* (Brazil nut) or a clonal individual such as *B. gasipaes* (peach palm) could exhibit direct legacy effects, as it could be the same individual that was tended prior to European arrival. Conversely, short-lived species such as *Theobroma cacao* (cocoa), *Tontelea* (edible fruits) or *Inga edulis* (ice-cream bean) will re-sort their abundances through multiple generations, and without human intervention are likely to revert to lower abundances (Figures 4–6; Whitney et al., 2014). Consequently, short-lived species or earlier successional species are far less likely to show a direct linkage to pre-Columbian forest than late succession, long-lived species, and any apparent enrichment in those taxa is more likely to reflect subsequent disturbances, such as those that occurred during the Amazonian rubber boom of c. 1850–1920 (McMichael, Feeley, et al., 2017; McMichael, Matthews-Bird, Farfan-Rios, & Feeley, 2017).

The successional dynamics and lack of persistent ecological legacies at Lake Kumpak show that modern abundances of useful species should not be used to infer past human activity. High abundances of useful species are found in forests that contain no evidence of past human impact (Bodin et al., 2020). Natural floodplain and gap succession are all that are required to account for the great majority of *Iriartea* occurrences (Pitman et al., 2001). The ability of seeds to disperse also plays a large role in the relative abundances of many tropical forest plants. For example, local palm abundances may decrease if seed dispersers are lost, but increase if, despite poor seed dispersal, seed predators are also lost (Wright et al., 2000). Hunting and deforestation that occurred from the time of the early Jesuit missions in the 1600s, through the Amazonian rubber boom of AD 1850–1920, to the modern era, are all likely to have shaped the relative abundances of many Amazonian plants. Indeed, these more recent activities are more likely to have legacy effects on the forest than those occurring before European arrival.

6 | CONCLUSIONS

We were able to document successional dynamics and potential for ecological legacies for hundreds of years following the cessation of a disturbance from Lake Kumpak in lowland Amazonian Ecuador, at time intervals of 5–50 years. Our data contained three different disturbance periods over the last 2,415 years, including the period of modern disturbance (Figure 1c–f). The disturbances all varied in intensities and durations. The modern disturbance period, which contained the highest fire frequency, was compositionally different from the two past disturbance periods, which contained little to no fire. The Lake Kumpak record suggests that the intensity of disturbance, the duration of the disturbance and the presence or absence of fire in the disturbance regime affect the subsequent successional trajectories and potential ecological legacies.

We found evidence of non-persistent enrichment and depletions of taxa, but those legacies were not present in the modern-day forest. It takes hundreds of years for a complex tropical forest to regain its pre-disturbance composition, in which time early and mid-successional species become rarer. Many taxa considered to be useful species are best suited to early successional settings and would be outcompeted during succession. We found no evidence of persistent enrichment or depletion of taxa (i.e., direct legacy effects) in a setting that contained pre-Columbian cultivation until c. 680 cal. BP. These findings underscore the inaccuracy and uncertainty of using modern plant population densities to infer past human management and ecological legacies without corresponding direct empirical data. Our data also reinforce the potential power of drawing upon highly resolved multiproxy data palaeoecological datasets to address important questions in neoecology.

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AUTHORS’ CONTRIBUTIONS
C.M.Å., M.F.R., S.N.H., M.P., Jo.V., D.N. and Ja.V. performed the research; C.M.Å., C.N.H.M. and M.B.B. analysed the data; C.M.Å., C.N.H.M. and M.B.B. wrote the paper, with input from all authors; M.B.B. and C.N.H.M. designed the research project; C.M.Å., C.N.H.M., D.N. and M.B.B. conducted the field work.

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DATA AVAILABILITY STATEMENT
The datasets generated from this study are available through the Dryad Digital Repository https://doi.org/10.5061/dryad.xksn02vd8 (Åkesson et al., 2020) and through the NEOTOMA Paleoecological Database (https://neotomadb.org/).

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REFERENCES
Åkesson, C. M., McMichael, C. N. H., Racza, M. F., Huismans, S. N., Palmeira, M., Vogel, J., ... Bush, M. B. (2020). Data from: Long-term ecological legacies in western Amazonia. Dryad Digital Repository, https://doi.org/10.5061/dryad.xksn02vd8
Antunes, A. P., Fewster, R. M., Ventincquie, E. M., Peres, C. A., Levi, T., Rohe, F., & Shepard, G. H. (2016). Empty forest or empty rivers? A century of commercial hunting in Amazonia. Science Advances, 2, e1600936. https://doi.org/10.1126/sciadv.1600936
Aragao, L. E. O. C., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L., & Saatchi, S. (2008). Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. Philosophical Transactions of the Royal Society B: Biological Sciences, 363, 1779–1785. https://doi.org/10.1098/rstb.2007.0026
Arroyo-Kalin, M. (2012). Slash-burn-and-churn: Landscape history and crop cultivation in pre-Columbian Amazonia. Quaternary International, 249, 4–18. https://doi.org/10.1016/j.quaint.2011.08.004
Balée, W. (1989). The culture of Amazonian forests. In D. A. Posey & W. Balée (Eds.), Resource management in Amazonia: Indigenous and folk strategies (pp. 1–21). New York, NY: New York Botanical Garden.
Balée, W., & Erickson, C. L. (2006). Time, complexity, and historical ecology. New York, NY: Columbia University Press.
Balslev, H., Luteyn, J., Olgaard, B., ... Holm-Nielsen, L. B. (1987). Composition and structure of adjacent unshaded and flooded forest in Amazonian Ecuador. Opera Botanica, 92, 37–57.
Barlow, J., & Peres, C. (2006). Effects of single and recurrent wildfires on fruit production and large vertebrate abundance in a Central Amazonian Forest. Biodiversity & Conservation, 15, 985–1012. https://doi.org/10.1007/s10531-004-3952-1
Bernal, R., Torres, C., García, N., Isaza, C., Navarro, J., Vallejo, M. I., ... Balslev, H. (2011). Palm management in South America. The Botanical Review, 77, 607–646. https://doi.org/10.1007/s10229-011-9088-6
Blauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis, 6, 457–474.
Black, F. M. (1992). Why did they die? Science, 258, 1739–1740.
Bodin, S. C., Molino, J.-F., Odonne, G., & Bremond, L. (2020). Unraveling pre-Columbian occupation patterns in the tropical forests of French Guiana using an anthropological approach. Vegetation History and Archaeobotany, 29(5), 567–580. https://doi.org/10.1007/s00362-019-00767-w
Brugger, S. O., Gobet, E., van Leeuwen, J. F., Ledru, M.-P., Colombaroli, D., van der Knaap, W. O., ... Tinner, W. (2016). Long-term human–environment interactions in the Bolivian Amazon: 8000 years of vegetation dynamics. Quaternary Science Reviews, 132, 114–128. https://doi.org/10.1016/j.quascirev.2015.11.001
Bush, M. B. (2002). On the interpretation of fossil Poaceae pollen in the humid lowland neotropics. Palaeogeography, Palaeoclimatology, Palaeoecology, 177, 5–17.
Bush, M. B., & Colinvaux, P. A. (1988). A 7000-year pollen record from the Amazon lowlands, Ecuador. Vegetatio, 76, 141–154.
Bush, M. B., & Colinvaux, P. A. (1994). Tropical forest disturbance: Paleoecological records from Darien, Panama. Ecology, 75, 1761–1768. https://doi.org/10.2307/1939635
Bush, M., Correa-Metrio, A., McMichael, C., Sully, S., Shadik, C., Valencia, B., ... Overpeck, J. (2016). A 6900-year history of landscape modification by humans in lowland Amazonia. Quaternary Science Reviews, 141, 52–64. https://doi.org/10.1016/j.quascirev.2016.03.022
Bush, M. B., & McMichael, C. N. (2016). Holocene variability of an Amazonian hyperdominant. Journal of Ecology, 104, 1370–1378. https://doi.org/10.1111/1365-2745.12600
Bush, M. B., McMichael, C. H., Piperno, D. R., Silman, M. R., Barlow, J., Peres, C. A., ... Palace, M. W. (2015). Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. Journal of Biogeography, 42, 2277–2288. https://doi.org/10.1111/jbi.12638
Bush, M. B., Piperno, D. R., & Colinvaux, P. A. (1989). A 6000 year history of Amazonian maize cultivation. Nature, 340, 303–305. https://doi.org/10.1038/340303a0
Bush, M. B., & Rivera, R. (1998). Pollen dispersal and representation in a neotropical rain forest. Global Ecology and Biogeography Letters, 7, 379–392. https://doi.org/10.2307/2997685
Bush, M., Silman, M., & Listopad, C. (2007). A regional study of Holocene climate change and human occupation in Peruvian Amazonia. Journal of Biogeography, 34, 1342–1356. https://doi.org/10.1111/j.1365-2699.2007.01704.x
Bush, M. B., & Weng, C. (2007). Introducing a new (freeware) tool for palynology. Journal of Biogeography, 34, 377–380. https://doi.org/10.1111/j.1365-2699.2006.01645.x
Clark, D. A., Clark, D. B., Sandoval, R. M., & Castro, M. V. C. (1995). Edaphic and human effects on landscape-scale distributions of...
the Amazonian tree flora. Science, 342, 1243092. https://doi.org/10.1126/science.1243092

ter Steege, H., Prado, P. I., Lima, R. A. F. D., Pos, E., de Souza Coelho, L., de Andrade Lima Filho, D., … Pickavance, G. (2020). Biased-corrected richness estimates for the Amazonian tree flora. Scientific Reports, 10, 1-13. https://doi.org/10.1038/s41598-020-66686-3

Uhl, C., Clark, H., Clark, K., & Maquirino, P. (1982). Successional patterns associated with slash-and-burn agriculture in the upper Rio Negro region of the Amazon basin. Biotropica, 14, 249-254. https://doi.org/10.2307/2388082

Urrego, D. H., Bush, M. B., Silman, M. R., Niccum, B. A., La Rosa, P., McMichael, C. H., … Palace, M. (2013). Holocene fires, forest stability and human occupation in south-western Amazonia. Journal of Biogeography, 40, 521-533. https://doi.org/10.1111/jbi.12016

van Breukelen, M., Vonhof, H., Hellstrom, J., Wester, W., & Kroon, D. (2008). Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in Amazonia. Earth and Planetary Science Letters, 275, 54–60. https://doi.org/10.1016/j.epsl.2008.07.060

van Vliet, N., Adams, C., Vieira, I. C. G., & Mertz, O. (2013). ‘Slash and burn’ and ‘shifting’ cultivation systems in forest agriculture frontiers from the Brazilian Amazon. Society & Natural Resources, 26, 1454-1467.

Watling, J., Iriarte, J., Mayle, F. E., Schaan, D., Pessenda, L. C., Loader, N. J., … Ranzi, A. (2017). Impact of pre-Columbian ‘geoglyph’ builders on Amazonian forests. Proceedings of the National Academy of Sciences of the United States of America, 114, 1868-1873. https://doi.org/10.1073/pnas.161439114

Weng, C. (2005). An improved method for quantifying sedimentary charcoal via a volume proxy. The Holocene, 15, 298-301. https://doi.org/10.1191/0959683605hl795rr

Whitlock, C., & Larse, C. (2001). Charcoal as a fire proxy. In J. P. Smol, H. J. B. Birks, & W. M. Last (Eds.), Tracking environmental change using lake sediments. Terrestrial, algal, and siliceous indicators. Dordrecht, The Netherlands: Kluwer.

Whitney, B. S., Dickau, R., Mayle, F. E., Walker, J. H., Soto, J. D., & Iriarte, J. (2014). Pre-Columbian raised-field agriculture and land use in the Bolivian Amazon. The Holocene, 24, 231-241. https://doi.org/10.1177/0959683613517401

Whitney, B. S., Smallman, T. L., Mitchard, E. T., Carson, J. F., Mayle, F. E., & Bunting, M. J. (2019). Constraining pollen-based estimates of forest cover in the Amazon: A simulation approach. The Holocene, 29, 262-270. https://doi.org/10.1177/0959683618810394

Wright, S. J., Zeballos, H., Domínguez, I., Gallardo, M. M., Moreno, M. C., & Ibáñez, R. (2000). Poachers alter mammal abundance, seed dispersal, and seed predation in a Neotropical forest. Conservation Biology, 14, 227-239. https://doi.org/10.1046/j.1523-1739.2000.98333.x

Zambrana, N. Y. P., Byg, A., Svenning, J.-C., Moraes, M., Grande, C., & Balslev, H. (2007). Diversity of palm uses in the western Amazon. Biodiversity and Conservation, 16, 2771-2787. https://doi.org/10.1007/s10531-007-9218-y

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.