Human arrival and landscape dynamics in the northern Bahamas

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The first Caribbean settlers were Amerindians from South America. Great Abaco and Grand Bahama, the final islands colonized in the northernmost Bahamas, were inhabited by the Lucayans when Europeans arrived. The timing of Lucayan arrival in the northern Bahamas has been uncertain because direct archaeological evidence is limited. We document Lucayan arrival on Great Abaco Island through a detailed record of vegetation, fire, and landscape dynamics based on proxy data from Blackwood Sinkhole. From about 3,000 to 1,000 y ago, forests dominated by hardwoods and palms were resilient to the effects of hurricanes and cooling sea surface temperatures. The arrival of Lucayans by about 830 CE (2σ range: 720 to 920 CE) is demarcated by increased burning and followed by landscape disturbance and a time-transgressive shift from hardwoods and palms to the modern pine forest. Considering that Lucayan settlements in the southern Bahamian archipelago are dated to about 750 CE (2σ range: 600 to 900 CE), these results demonstrate that Lucayans spread rapidly through the archipelago in less than 100 y. Although precontact landscapes would have been influenced by storms and climatic trends, the most pronounced changes follow more directly from landscape burning and ecosystem shifts after Lucayan arrival. The pine forests of Abaco declined substantially between 1500 and 1670 CE, a period of increased regional hurricane activity, coupled with fires on an already human-impacted landscape. Any future intensification of hurricane activity in the tropical North Atlantic Ocean threatens the sustainability of modern pine forests in the northern Bahamas.

anthropogenic burning | Lucayan | Caribbean | pollen | vegetation change

The first explorers and settlers in the Caribbean islands were Amerindians from South America, who migrated north through the Lesser Antilles and eventually into the Bahamian archipelago. At European contact, the inhabitants of The Bahamas were the Lucayans, an Arawakan-speaking Taíno people, whose name translates as "island men" in the native Arawakan language (1). It has been debated whether Lucayans originated from Cuba or Hispaniola (2–4), but recent analysis of Lucayan skull morphology suggests they migrated into the Bahamian archipelago from Hispaniola and Jamaica by 800 CE (5) (Fig. 1). The earliest known Lucayan settlements in The Bahamas are the Three Dog Site on San Salvador, which was occupied from 600 to 900 CE (2σ range) (6), and the Coralie Site on Grand Turk, occupied 650 to 885 CE (2σ range) (7). Lucayan populations at the time of Columbus's arrival in 1492 CE on San Salvador (called *Guanahani* by native Taíno people) most likely numbered in the tens of thousands (8), with lower population densities in the drier southernmost islands (2, 7). Within 30 y, the population of The Bahamas had been greatly reduced by disease and Spanish enslavement to provide labor on Hispaniola and Cuba (9). Thus, the history of human colonization and ecological impact in The Bahamas depends on archaeology and evidence of landscape disturbance because Lucayan oral tradition is forever lost.

Few archaeological remains have been recovered from the northern Bahamian islands, which include Grand Bahama Island and Abaco Island. On Grand Bahama, Lucayan artifacts were discovered adjacent to a hearth that was dated 1390 to 1500 CE, just prior to Columbus's arrival (10). On Abaco Island, sinkholes preserved the remains of two Lucayan individuals. A human tibia from Sawmill Sink and a human epiphysis recovered from Great Cistern Sinkhole date to 1101 to 1290 CE (2σ range) and 1255 to 1340 CE (2σ range), respectively (11, 12). Independent of direct archaeological evidence, the arrival of people in new landscapes typically causes profound ecological change, involving fire, deforestation, local extinctions, and invasive plant and animal introductions. Initial human settlement on islands is often reflected by evidence of burning and vegetation changes preserved in pollen and charcoal records from lakes and wetlands (13–15). However, disentangling colonization impacts from synchronous natural environmental perturbations, such as climate or sea level change, can be challenging. In The Bahamas, Lucayan arrival has been inferred previously from increased charcoal deposition and more abundant *Pinus caribaea* about 1200 to 1250 CE at West Pond, Abaco (median age 1175 CE) (16) and at Church's Bluehole, Andros (median age 1265 CE) (17).

Here, we present a high-resolution record of fire and vegetation history in the northern Bahamas over the last 3,000 y that

Significance

The oral history for Amerindian migration through The Bahamas was lost after Columbus's arrival in 1492 CE and Lucayan enslavement in the early sixteenth century. The Lucayans encountered unique prehuman reptile-dominated terrestrial food webs (i.e., tortoise and crocodile), with palm and hardwood forests that were resilient to regional oceanographic cooling and hurricane perturbations. New evidence indicates that Lucayans arrived in the northern Bahamas by about 830 CE after expanding rapidly throughout The Bahamas in less than 100 y. Following subsequent burning, reptiles were extirpated, and pyrogenic pine forests took over Great Abaco Island. Compounded perturbations, including forecasts of future hurricane intensification, may continue to alter Bahamian ecosystems, particularly pine forests, which are less resilient than precontact tropical hardwood ecosystems.

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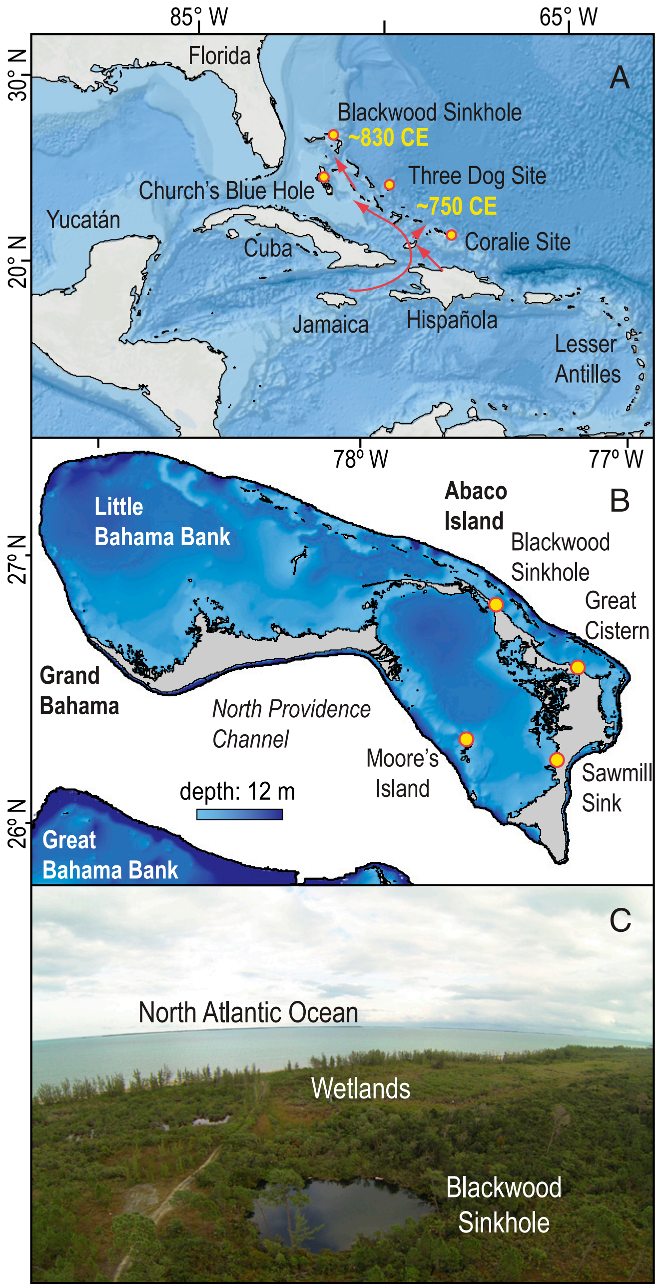

Fig. 1. (*A*) Blackwood Sinkhole and key localities for inferring Lucayan migration patterns through The Bahamas. Church's Bluehole provides pollen and charcoal evidence of late Holocene vegetation change. Archaeological evidence from the Coralie Site (Grand Turk) and Three Dog Site (San Salvador) documents human arrival in the southern Bahamas by about 750 CE. Red arrows highlight Lucayan migration in less than 100 y (5). (*B*) Blackwood Sinkhole and key sites providing evidence for Lucayan occupation on Great Abaco Island. (*C*) Aerial photo of Blackwood Sinkhole showing proximity to the nearby wetlands (site of core BLWD-MC1) and the Atlantic Ocean.

documents prehuman terrestrial vegetation, evidence for Lucayan arrival through landscape burning, and ongoing landscape modification from colonial activities into the 20th century. Our results provide the highest-resolution record (both in chronological and vegetation detail) of pollen and charcoal currently available for the northern Caribbean region. The evidence reported here indicates Lucayan arrival in the northern Bahamas (Abaco Island) by about 830 CE and elucidates the impacts of humans and climate on northern Bahamian landscape dynamics. Furthermore, the record illustrates the resilience of Bahamian vegetation to climate variability (e.g., regional sea surface temperatures, hurricanes) prior to human contact, in stark contrast to the sensitivity of the modern pine-dominated landscape to ongoing fires and hurricane activity.

Study Site

The Little Bahama Bank is the northernmost carbonate platform in the Bahamian archipelago, with Great Abaco Island and Grand Bahama Island in the eastern and western margins of the platform, respectively. The local carbonate geology has formed a mature karst landscape with abundant caves and sinkholes. During late Pleistocene sea level lowstands, marine carbonate particles were transported by wind into dunes, which created shoreline-parallel and curvilinear features that characterize the modern topography (*SI Appendix*, Fig. S1). Modern wetlands often form in the swales between these lithified Pleistocene dunes.

Blackwood Sinkhole (32 m diameter, about 38 m deep in the main sinkhole) is positioned about 220 m inland from the coastline on a modern topographic high (<10 m above sea level) on the windward margin of northern Great Abaco Island (see Fig. 1; 26.79°N, 77.42°W). The sinkhole is groundwater fed with no inflowing or outflowing streams, and the groundwater level varies tidally and is co-positioned with sea level (*SI Appendix*, Fig. S2). Blackwood Sinkhole is surrounded currently by stands of *Pinus caribaea* var. *bahamensis,* similar to other northern Bahamian islands (Great Abaco, Grand Bahama, New Providence, and Andros). *Pinus caribaea* is limited in the southern Bahamas to scattered stands on North and Middle Caicos and Pine Cay (18). During heavy rainfall events, low-elevation landscape features within 1 km of Blackwood Sinkhole preferentially flood, including a large trough (about 6 km long) lying about 300 m west of the site. A small wetland about 100 m to the east of the site presently contains salt-tolerant taxa, including *Conocarpus erectus* (buttonwood or button mangrove) and *Typha* (cattail). Radiocarbon dating of peat at the underlying limestone contact indicates the emplacement of this wetland by 560 to 595 CE (2σ range) (19).

The Sediment Record and Pollen Preservation

Anoxic bottom water has preserved an exceptionally high-quality stratigraphic record in Blackwood Sinkhole (19, 20) (*SI Appendix*, Fig. S3). Radiocarbon dating of Blackwood Sinkhole Core 2 (BLWD-C2, collected and sampled in May 2011) indicates the topmost 110 cm of sediment was deposited during the last 3,000 y (20). Internal stratigraphic architecture is characterized by laminated authigenic carbonate and algal sapropel, with varying quantities of coarse-grained detrital carbonate particles and terrestrial plant remains. Carbonate particles are most likely derived from terrestrial and wetland habitats or through disintegration of the porous vertical limestone walls of the sinkhole from groundwater dissolution. Deposition of these particles provides a record of intense hurricane strikes, and resultant landscape flooding, on the eastern margin of Abaco over the last 3,000 y (19). Increased inputs of organic matter into Blackwood Sinkhole over the last 850 y are consistent with the establishment of this wetland by about 580 CE (21), after concomitant sea level and groundwater level rise promoted wetland colonization in adjacent topographic lows (20). The exceptional pollen preservation and laminated stratigraphy in BLWD-C2 preserve ecologically significant spikes (and declines) for individual pollen percentages (*SI Appendix*, Fig. S4) and for aquatic pollen and spore percentages, pollen concentrations for the main taxa and taxon groups, and microscopic charcoal and sand concentrations (*SI Appendix*, Fig. S5).

Discussion

The Prehuman Landscape. The Blackwood Sinkhole pollen record documents prehuman vegetation dynamics on Abaco Island from 1000 BCE to about 830 CE. The oldest Lucayan sites farther south on San Salvador and Grand Turk were first occupied in the 8th century (Fig. 1) (6, 7). As such, any prior vegetation changes on Abaco Island at Blackwood Sinkhole would have been caused by natural environmental factors. In general, terrestrial vegetation in Pollen Zone A is dominated by a diverse forest of palms (Arecaceae) and tropical hardwoods, which include Myrtaceae (*Eugenia* spp.), Anacardiaceae (*Metopium toxiferum*), *Bursera simaruba*, Fabaceae, and Solanaceae (*Solanum* spp.) (Fig. 2). Very low microscopic charcoal deposition in Zone A indicates little fire activity on the natural landscape prior to the last millennium. Previous work on Abaco Island and Puerto Rico indicates that the western tropical North Atlantic margin experienced heightened intense hurricane activity from about 600 BCE to 1000 CE (19, 22), which is perhaps linked to a more northerly position of the Intertropical Convergence Zone (19). It appears that dominant forest taxa were minimally impacted during this interval of increased hurricane activity, as palms and tropical hardwoods must have recovered relatively quickly following any storm damage and remained dominant on the landscape. It is possible that hurricanes may have provided opportunities for increased secondary terrestrial taxa by opening up the forest canopy, as suggested by an expansion of ferns after about 600 CE. Overall, however, the precontact forest was resistant to repeated hurricane-induced disturbance. A variety of historical studies demonstrate the ability of hardwood forests to regenerate following hurricane damage (23–26).

The pollen data also suggest that terrestrial vegetation in the northern Bahamas appears to have been resistant to about 1 to 2 °C cooling events in the tropical and subtropical North Atlantic Ocean between about 1000 BCE and 1000 CE (blue shading in Fig. 3). For example, forest structure changed negligibly during centennial-scale cooling events off the coast of West Africa (27) and in the nearby Sargasso Sea (28) or during cooling around 850 BCE that has been associated with a slowdown of the oceanic conveyor from reduced North Atlantic Deep Water formation (29). These observations are significant because regional cooling and inferred Caribbean aridity during the Little Ice Age (LIA, 1300 CE to 1850 CE) (30) have been hypothesized as promoting *Pinus* expansion in the northern Bahamas. Indeed, biogeographical analysis of human-impacted vegetation across the tropical North Atlantic indicates that lower mean annual temperatures contribute to latitudinal variability in Caribbean forest structure (31). However, if the prehuman Abaco vegetation had been sensitive to regional sea surface temperature (SST) decreases, the temporal resolution of the Blackwood Sinkhole pollen record is sufficiently detailed to have shown a landscape response. In contrast, the observed landscape stability on Abaco from about 1000 BCE to about 1000 CE demonstrates that any SST decrease during the LIA probably was not the primary driver of Bahamian landscape change during the last millennium.

Alternately, hydroclimate change (e.g., seasonality or mean annual rainfall) may have influenced the abundance of less dominant taxa during the precontact period. Current precipitation in the northern Bahamas averages about 1,400 mm/y, but moisture delivery is seasonal, with 75% of mean annual rainfall occurring during boreal summer (May through October) (32). Summer rainfall is strongly modulated by geographic displacement of the North Atlantic Subtropical High, whereas winter rainfall is linked to El Niño/Southern Oscillation (ENSO) dynamics.

Hydroclimate patterns and their atmospheric-oceanic forcing in the tropical North Atlantic are highly regional. There are limited hydroclimate reconstructions spanning the CE for the northern Caribbean, including reconstructed δ^2H from plant wax archived in Blackwood Sinkhole (21). Evidence from two speleothems in western Cuba is somewhat equivocal. For example, an abrupt increase in mean annual rainfall proposed at about 1000 CE (33) in one speleothem is not documented in the other (34). One factor contributing to this uncertainty may be that rainfall seasonality has not been constant over the last 3,000 y, perhaps because of long-term changes in the North Atlantic Oscillation or ENSO. Thus, abrupt increases in *Lemna* (duckweed, a floating freshwater macrophyte) between 300 and 1000 CE in Blackwood Sinkhole may suggest intermittently fresher surface water than found in its modern oligohaline setting. The pollen record from Church's Blue Hole on Andros Island has been interpreted previously as providing evidence for local hydroclimate change during the late Holocene (17). However, it is highly likely that the Andros pollen record is also significantly overprinted by human-mediated landscape change over the last 1,000 y. In sum, prior to human arrival, the tropical hardwood and palm forests of Abaco were sustainable when subject only to natural climate variability (e.g., hurricanes and hydrologic fluctuations).

Lucayan Arrival and Occupation. Increased microscopic charcoal deposition by nearly an order of magnitude from an average of 2,380 pieces/cm^3 to about 20,000 pieces/cm^3 at 830 CE (2σ range: 720 to 920 CE) suggests anthropogenic burning associated with Lucayan arrival on Abaco. This evidence is interpreted to indicate increased local fires because it is accompanied by dramatic vegetation changes around Blackwood Sinkhole. An increase in the relative abundance of weeds and herbs includes the native disturbance indicator *Ambrosia*-type pollen. An arrival date of about 830 CE is earlier than the age range for the Gilpin Point peat deposit in Abaco, where a Lucayan bead was discovered (35), and earlier than the age of human remains recovered from Abaco blue holes (Sawmill Sink, Great Cistern) (*SI Appendix*, Table S1). Given the mid-8th century age for the southern Lucayan occupation sites on San Salvador (Three Dog Site) and Grand Turk (Coralie Site), the evidence of landscape burning on Abaco by the mid-9th century suggests rapid expansion of the Lucayan culture through the Bahamian archipelago in less than 100 y. This is a much faster rate of Lucayan cultural expansion than has been considered previously (11, 35, 36).

The most significant change in terrestrial forest structure at Blackwood Sinkhole occurs at 970 CE (2σ range: 875 to 1090 CE) as the abundance of palms and tropical hardwoods decreases (Zone A), and the vegetation begins shifting to the modern pine-dominated landscape (Zone B). The forest clearing and burning for agriculture and wood harvesting triggered by Lucayan arrival on Abaco caused a cascade of ecological changes spanning several centuries (Zone B1, Early Lucayan Period). Trees in the Myrtaceae family (*Eugenia* spp.) and *Bursera simaruba* declined immediately and precipitously, while some forest taxa, including *Metopium toxiferum*, Solanaceae, and Fabaceae, persisted before declining sharply. Palms (Arecaceae) were nearly eliminated by about 1055 CE. Forest turnover is seen with increased successional tree species *Myrica cerifera* and *Trema lamarckianum* and a rise in *Acacia* spp. As pollen from hardwoods and palms diminished, a more open landscape is signaled by increased ferns and herbaceous taxa (e.g., Asteraceae and *Ambrosia*-type pollen), which colonized newly burnt terrain. The Lucayans actively cultivated manioc (cassava) as their primary food staple and apparently harvested wood (e.g., *Erythroxylon*, *Conocarpus*, *Guaiacum*, and *Croton*) from the landscape for cooking fuel (10).

After 970 CE, pollen percentages for *Pinus* and mangroves increase substantially (Zone B1). *Pinus caribaea* var. *bahamensis* forests grew on higher elevations around the sinkhole, while *Conocarpus erectus*, *Laguncularia racemosa*, ferns, and *Typha angustifolia*-type (including *Typha domingensis*) expanded in wetlands in adjacent topographic lows. The onset of increased landscape burning at about 830 CE on Abaco led to the establishment of the modern pyrogenic pine forests by about 1200 CE (2σ range: 1100 to 1320 CE; Zone B2, Late Lucayan Period) at Blackwood Sinkhole and elsewhere on Abaco (16, 37). At Church's Blue Hole on Andros Island, the pollen record shows a shift from dry shrub vegetation to mesic hardwoods about 520 CE and a more dramatic vegetation change to pinewoods about 1260 CE (17). Regionally, *Pinus* forests dominate wetter environments in the greater Caribbean (e.g., southern Florida and larger islands such as Cuba and Hispaniola). In Florida's subtropical longleaf pine forests (*Pinus palustris*), landscape burning at higher temperatures benefits pine over competitors such as hardwood trees (38). An increase in Cupressaceae pollen at about 1400 CE suggests the expansion of *Juniperus barbadensis* on the landscape around Blackwood Sinkhole at the expense of *Pinus caribaea* between about 1400 and 1500 CE.

Pollen grains from the four common New World mangrove species (*Rhizophora mangle*, *Avicennia germinans*, *Conocarpus erectus*, and *Laguncularia racemosa*) are found in Blackwood Sinkhole (*SI Appendix*, Table S2). *Rhizophora mangle* is an abundant pollen producer, so the small amounts of this pollen type likely reflect dispersal from elsewhere on Abaco. The minimal amounts of *Avicennia germinans* pollen indicate it was never a major component of the local vegetation in the last 3,000 y. In contrast, the percentages of pollen from *Conocarpus* and *Laguncularia* increase dramatically after about 970 CE, suggesting widespread expansion of a wetland mangrove community in the topographic lows around Blackwood Sinkhole during Zone B. This inference also accords with a rapidly increased influx of mangrove-derived organic matter at about 1100 CE (20). Sea-level rise, as seen elsewhere in the Caribbean (39), would have inundated adjacent depressions and expanded nearby wetlands in keeping with the Blackwood mangrove evidence. Decreased hurricane activity at about 1000 CE may have further enabled wetland development on the windward coastline of Abaco Island (20).

At about 830 CE, Lucayans would have arrived on a landscape that provided habitats for the unique reptile-dominated ecosystems that existed on Abaco prior to human contact (40), including the largest terrestrial herbivore and carnivore: Albury's tortoise (*Chelonoidis alburyorum*) and the Cuban crocodile (*Crocodylus rhombifer*). Radiocarbon dated fossil remains indicate that Albury's tortoise was present on Abaco from at least 2450 BCE until it vanished abruptly about 1000 CE (40), following human arrival and loss of palms and tropical hardwood forests. Excavations on Grand Turk (Coralie Site) and San Salvador (Three Dog Site) show that sea turtle also was an important dietary resource for Lucayans (7, 10). The evidence from Blackwood Sinkhole is consistent with the hypothesis that Lucayans played a role in the extinction of large reptiles on Abaco (40). Evidence from archaeological sites and sinkholes indicates that tortoises were extirpated on most Bahamian islands within 1 to 2 centuries following the initial arrival of people, with the exception of the Coralie Site where tortoises persisted for about 300 y (41). Further human-induced ecological changes are evidenced by increases in charcoal concentrations and disturbance pollen taxa (e.g., *Myrica*, *Trema*, Asteraceae, *Ambrosia*-type, and *Acacia*) in Zone B1 between 970 and 1330 CE, which reflect continued burning and land clearance for agriculture. Corn, cotton, and tobacco were cultivated during the Meillican expansion, which extended from Turks and Caicos to Abaco by the late 12th

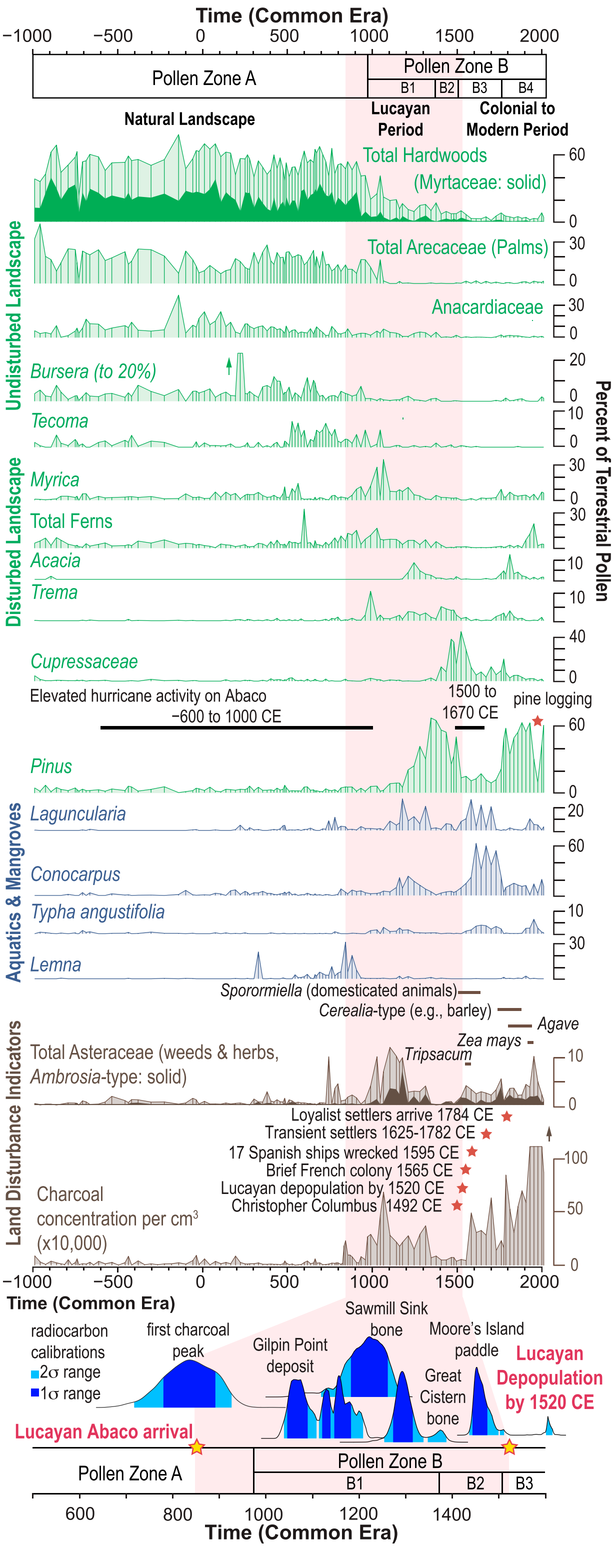

Fig. 2. Salient aspects of vegetation and landscape change on Abaco Island over the last 3,000 y as indicated by Blackwood Sinkhole pollen and charcoal evidence, local hurricane records, archaeological remains, and historic sources. (*Upper*; 1000 BCE–2000 CE) Palms and hardwoods, for example, Myrtaceae, Anacardiaceae, *Bursera*, and *Tecoma*, characterized the landscape prior to human contact and burning. Increased charcoal deposition signals human arrival about 830 CE. Arrows for charcoal and *Bursera* indicate peaks well in excess of the *y*-axis scales. Increased *Myrica*, ferns, *Acacia*, *Trema*, Cupressaceae, and Asteraceae, plus the aquatics *Typha angustifolia* and *Lemna*, reflect a disturbed landscape following human settlement, leading to the establishment of *Pinus* forests by about 1200 CE. Periodic increases in mangroves (*Laguncularia* and *Conocarpus*) and pine indicate a more hurricane-susceptible ecosystem during the last millennium coeval with regional landscape inundation through relative sea level rise. Palms and hardwoods persisted during elevated hurricane activity from 600 BCE to 1000 CE (indicated by black line), whereas increased hurricane activity from 1500 to 1670 CE (indicated by black line) and modern pine logging (star) diminished the pine forest. (*Lower*) Detailed lower *x*-axis time scale (500–1600 CE) applies to directly dated archaeological evidence from Abaco and the first charcoal peak at Blackwood Sinkhole about 830 CE, including 1σ and 2σ CIs for radiocarbon age calibrations. Stars mark important dates ranging from Lucayan arrival through European influences.

century CE (42). Following human arrival, the landscape of Abaco was subject to multiple perturbations (i.e., burning, landscape clearance, extirpation of native fauna, and introduction of cultigens), along with further climate fluctuations, which resulted in the dramatic alteration of the island's ecosystems.

Columbian Impacts and Lucayan Enslavement. Several hundred years after Lucayan arrival and removal of the largest herbivore and top carnivore, the vegetation on Abaco settled into a new dynamic in response to the impacts of forest clearance, agricultural intensification, and the development of a pyrogenic ecosystem. After the establishment of *Pinus caribaea* and *Juniperus barbadensis* stands on Abaco, *Pinus* and *Juniperus* diminished around Blackwood Sinkhole. *Pinus* declined significantly from 1510 to 1765 CE, as documented by decreased pollen percentages from a mean of 50% in Zone B2 to 15% in Zone B3, accompanied by diminishing *Pinus* pollen concentrations (*SI Appendix*, Fig. S5). Similarly, Cupressaceae pollen dropped from a maximum of 45% to a minimum of 5% at about 1575 CE. Decreased *Pinus* and Cupressaceae pollen also coincided with maximum values for mangrove pollen in Zone B3 from *Conocarpus* (mean: 35.9%) and *Laguncularia* (mean: 13.6%) and a modest expansion of *Typha* (cattail) in the adjacent wetlands. The wind- and salt-tolerant mangroves *Conocarpus* and *Laguncularia* would have covered most local topographic depressions around Blackwood Sinkhole, while *Pinus* woodlands remained as persistent upland vegetation on Abaco (16, 37) and elsewhere in the northern Bahamas (17).

These vegetation changes unfolded during a period of complex influences from climate, fire, and human history. New herbivores (e.g., horses, pigs, and cattle) and mammalian carnivores (domestic dogs and cats) arrived with the first transient Europeans. In BLWD-C2, the introduction of horses and pigs by Spanish explorers is reflected by fungal spores from *Sporormiella* spp., which appear at about 1495 CE and reach their maximum abundance of 2.4% at about 1610 CE. *Sporormiella* is an obligate coprophilous spore found on the dung of wild and domestic herbivores. Given the lack of large natural mammalian herbivores on Abaco, *Sporormiella* likely indicates the arrival of horses (and other introduced animals). By royal decree in 1493 CE, Spanish explorers were required to carry two brood mares on every ship sailing for the New World. Columbus's second voyage in 1493 brought the first horses to the Americas, followed by further introductions from the expeditions of Amerigo Vespucci in 1499 to 1500 CE and Ponce de Leon in 1513 CE. By the 1520s, horses could be found on all island groups in the Caribbean. Horses from a Spanish fleet of 17 ships that wrecked off Abaco in 1595 CE (9) most likely provided the ancestors of the Abaco barb, wild horses found historically on this island but now extirpated, who had close genetic ties to the Spanish barb.

Most Lucayans were enslaved by 1520 CE, and an estimated 40,000 slaves were taken to Hispaniola, while the sparse

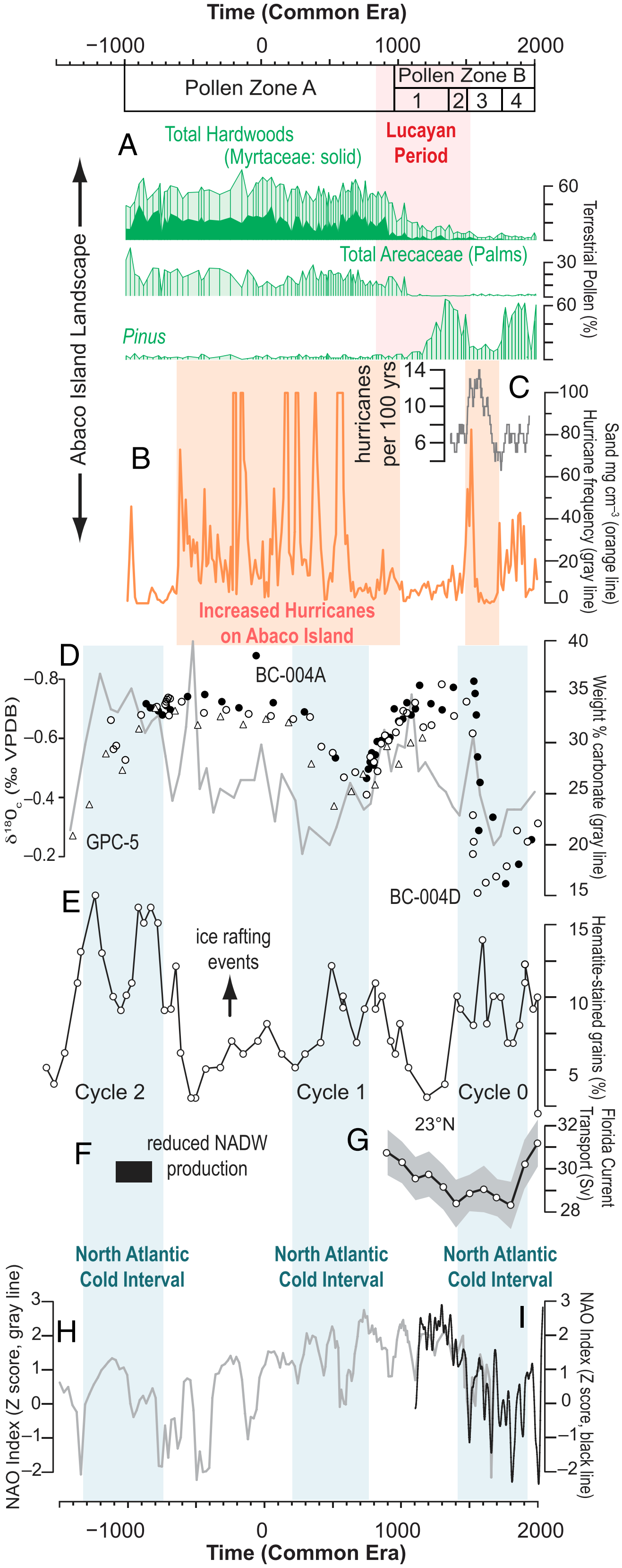

Fig. 3. (*A*) Percentages of dominant terrestrial pollen taxa from Blackwood Sinkhole that document resilient prehuman vegetation and the pronounced shift to pyrogenic pine forests following human arrival and the introduction of fire as an ecological factor. (*B*) $CaCO_3$ sand concentrations at Blackwood Sinkhole (orange line) showing increased hurricane activity prior to and after the Lucayan Period (19). (*C*) Hurricane frequency based on 100-y moving windows of sand concentrations at Thatchpoint Blue Hole (gray line) (44). (*D*) Weight percent carbonate in sediment (gray line) and oxygen isotopic ratios ($\delta^{18}O_c$) on planktonic foraminifera in Bermuda Rise sediment cores (28). (*E*) North Atlantic ice rafted debris from higher-latitude sediment cores and noted Bond Cycle cooling events (51). (*F*) Prominent interval of reduced North Atlantic Deep Water formation (29). (*G*) Florida Current transport reduction during the Little Ice Age, with 95% CI in gray (52). (*H*) NAO (North Atlantic Oscillation) index reconstruction based on redox chemistry in a Greenland lake (gray line) (53). (*I*) NAO index reconstruction based on a Scottish speleothem and Moroccan tree rings (black line) (54). Blue shading denotes intervals for which decreased sea surface temperature has been inferred for the tropical and subtropical North Atlantic Ocean.

indigenous population that remained in The Bahamas continued to trade salt, fish, and cotton with transient European seafarers (43). The period between about 1500 and 1670 CE also experienced a statistically significant increase in intense hurricane strikes (about 13 events/century) than during the last 200 y (about seven events/century), as suggested by a near-annual reconstruction of hurricane passage on Abaco Island (44; see Fig. 3*C*). Thus, one possible driver of ecosystem dynamics on Abaco is that intensified hurricane activity damaged *Pinus* (*SI Appendix*, Fig. S6) and possibly *Juniperus* stands and allowed expansion of low-lying mangrove wetlands. Emerging ecospace created by the loss of these evergreen trees, along with increased Asteraceae, indicate a more open upland landscape. The passage of Hurricanes Frances and Jeanne in 2004 provide recent examples that destroyed *Pinus* forests on Grand Bahama, where hurricane winds severed trunks from canopies and overland surge salinized fresh groundwater sources. The forest damage was still clearly evident 10 y later (*SI Appendix*, Fig. S7) despite groundwater modeling that indicates groundwater resources on low-lying carbonate islands can recover within 3 y (45). Disturbances from forest clearing, the introduction of new domestic plants and animals, hurricane destruction of trees, saltwater intrusion due to storm surges, and renewed intensity of fires may have interacted to produce complex ecological impacts in the coastal northern Bahamas. High-resolution records and modern studies from Gulf of Mexico coastal environments show that catastrophic hurricanes were followed by major fires within a few years to decades (46–48). Although the ecological responses on low-lying carbonate islands in The Bahamas are not comparable to those on siliciclastic landscapes because of differences in groundwater dynamics, the record from Blackwood Sinkhole also shows an increase in fires from 1510 to 1760 CE following heightened hurricane activity, which led to ecological responses over multiple decades to hundreds of years. More abundant *Pinus* deadwood would have provided additional fuel for both natural and human-induced fires. Thus, the compounded disturbances of heightened hurricane activity followed by increased burning, on a landscape already impacted by land clearance and the introduction of domestic animals, would have jointly produced the ecological changes apparent in Zone B3. As a consequence, the postcontact *Pinus* forests in the northern Bahamas may be less resilient to disturbance than the natural (i.e., prehuman) palm and tropical hardwood ecosystem. This phenomenon accords with a variety of studies demonstrating resilient responses of tropical hardwood forests to hurricane damage (23, 24). Similarly, historical studies show that hurricanes in the 1800s and 1900s in New England caused selective damage to pine trees compared to hardwood species and document the greater ability of hardwoods to revegetate and to shift forest dominance from pines to hardwoods (25). As a case in point, after Hurricane Joan struck the southeastern coast of Nicaragua in 1988, seedlings reappeared abundantly in rain forests but were nearly absent in pine forests, suggesting that forests with tropical hardwood species have fundamentally different ecological responses to catastrophic disturbance than pine forests (26).

Modern Period. Abaco Island was colonized after the American Revolution by British Loyalists who emigrated from New York and Florida in late 1783 and early 1784 CE. At that stage, renewed burning to clear land for agriculture caused an exponential increase in charcoal deposition in Blackwood Sinkhole Zone B4 and a resurgence of pyrogenic *Pinus caribaea* var. *bahamensis* forests in the modern era. Small amounts of *Cerealia*-type (cereal) pollen are found between 1835 and 1975 CE. *Cerealia*-type pollen is produced by some wild grass species as well as by Eurasian cultigens, most likely *Hordeum* spp. (barley) and *Triticum* spp. (wheat), both presumably brought to The Bahamas by European settlers. *Zea mays* (corn) pollen is found in two sediment samples deposited about 1905 and 1930 CE, indicating local corn cultivation because *Zea mays* produces large pollen grains with limited transport potential. *Agave sisalana* (Agavaceae) pollen is found in three samples in the uppermost 5 cm of the core (1905 to 1975 CE). The large *Agave* pollen grain also has little potential for wind dispersal. The inhabitants of Abaco Island produced sisal from 1889 to the early 1900s CE, involving plantations exceeding 2,000 acres and sisal production adjacent to Blackwood Sinkhole itself (known historically as Cocoa Plum Creek) (*SI Appendix*, Fig. S8). The pronounced spike in *Agave* pollen, which is situated decades after the collapse of the local sisal industry, may have resulted from nearby naturalized *Agave sisalana* plants. Sediment deposited since 1860 CE includes very limited pollen from the nonnative, invasive tree *Casuarina equisetifolia*, which grows throughout the islands. When Europeans arrived, *Juniperus barbadensis* was more plentiful on the landscape. The decline in *Juniperus barbadensis* around Blackwood Sinkhole during the past 300 y may be a consequence of harvesting, as exemplified in Bermuda where Europeans preferentially removed cedar (*Juniperus bermudiana*) for housing and ship building (49). Finally, significantly decreased *Pinus* pollen percentages and concentrations late in Zone B4 correlate with 20th century logging and deforestation on Abaco (*SI Appendix*, Fig. S9). Additional European impacts (e.g., introduction of new herbivores, renewed burning, plantation agriculture, and logging) exacerbated the cascade of ecological impacts initiated by human arrival and anthropogenic burning, making these ecosystems even more susceptible to future disturbances. Blackwood Sinkhole illustrates how compounded perturbations, especially when they involved intensified human intervention, may lead to fundamental and long-term ecosystem change (46).

Conclusions

This study presents the highest-resolution pollen and charcoal record from The Bahamas, providing the clearest perspective on natural island landscape dynamics, and subsequent changes related to human arrival and land use after 830 CE. Precontact vegetation on Abaco between about 1000 BCE and 830 CE had a forest structure dominated by hardwoods and palms that was resilient to increased hurricane activity and climatic fluctuations. Once anthropogenic burning began around 830 CE, coincident with the arrival of Lucayan people in the northern Bahamas, the forest changed and was never again dominated by palms and hardwoods. Pollen and charcoal deposition after 830 CE documents a transition from hardwoods and palms to the establishment of the modern pine forest dominated by *Pinus caribaea* var. *bahamensis* by about 1200 CE. The combined impact of fire and forest disturbance, coupled with possible hydrological changes beginning about 970 CE, resulted in a new postcontact dominance of pine forests, alternating with mangrove stands, mainly *Conocarpus*, on centennial time scales. Increased hurricane activity after about 1500 CE appears to have contributed to a subsequent decline in pine forests and increased mangroves into the 18th century CE. Further impacts accompanied the arrival of Europeans, including the introduction of domestic animals in the 15th and 16th centuries. Agricultural intensification is indicated by the cultivation of *Zea mays* and other cereals, *Agave sisalana* plantations of the late 1800s, and possible harvesting of *Juniperus barbadensis*. The vegetation on Abaco Island in The Bahamas was resilient to periodic hurricane perturbations from 1000 BCE to 970 CE. Once humans introduced fire and agriculture, and overhunted native fauna, the postcontact vegetation settled into a new state in which *Pinus caribaea* var. *bahamensis* forests dominated the uplands, while mangrove dynamics reflect hydrologic variability in topographic depressions. Given medium to high confidence that intense hurricane activity will increase in the coming decades in response to 2 °C global warming (50), the resilience and sustainability of Bahamian ecosystems may again be at risk due to human actions.

Materials and Methods

Advanced technical scuba diving procedures were used to extract sediment push cores from Blackwood Sinkhole. BLWD-C2 was imaged and processed for sediment analysis and Accelerator Mass Spectrometry ages; pollen and charcoal were extracted using standard palynological methods (*SI Appendix, SI Materials and Methods*).

Data Availability. All data discussed in this paper are available in cited references and in the National Centers for Environmental Information's Paleoclimatology Database (https://www.ncdc.noaa.gov/paleo-search/study/32972).

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