Early maize (*Zea mays* L.) cultivation in Mexico: Dating sedimentary pollen records and its implications

Andrew Sluyter*† and Gabriela Dominguez‡

*Department of Geography and Anthropology, Louisiana State University, 227 Howe-Russell Geoscience Complex, Baton Rouge, LA 70803; and ‡Department of Geography and the Environment, University of Texas, Austin, TX 78712

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A sedimentary pollen sequence from the coastal plain of Veracruz, Mexico, demonstrates maize cultivation by 5,000 years ago, refining understanding of the geography of early maize cultivation. Methodological issues related to bioturbation involved in dating that record combine with its similarity to a pollen sequence from the coastal plain of Tabasco, Mexico, to suggest that the inception of maize cultivation in that record occurred as much as 1,000–2,000 years more recently than the previously accepted 7,000 years ago. Our analysis thereby has substantive, theoretical, and methodological implications for understanding the complex process of maize domestication. Substantively, it demonstrates that the earliest securely dated evidence of maize comes from macrofossils excavated near Oaxaca and Tehuacán, Mexico, and not from the coastal plain along the southern Gulf of Mexico. Theoretically, that evidence best supports the hypothesis that people in the Southern Highlands domesticated this important crop plant. Methodologically, sedimentary pollen and other microfossil sequences can make valuable contributions to reconstructing the geography of early maize cultivation, but we must acknowledge the limits to precision that bioturbation in coastal lagoons imposes on the dating of such records.

Mesoamerica | Tabasco | Veracruz

Although maize (*Zea mays* L.) is one of the world's most important crops, theories about its domestication remain controversial (1, 2). Most researchers agree on three broad issues: (*i*) a grass called teosinte (*Zea* spp.) is the wild ancestor of maize; (*ii*) people living in what is now Mexico domesticated it; and (*iii*) they did so 5,000–10,000 years ago. But much disagreement remains concerning the mechanism, location, and timing of the domestication process and, therefore, its relationship to Mesoamerican social and environmental processes, such as the inception of sedentism and deforestation. The two main hypotheses pit a domestication hearth in the Southern Highlands around Tehuacán and Oaxaca, at an elevation of 1,200–2,000 m, against domestication at lower elevations, in the Balsas Depression that bounds the Southern Highlands on the north (3) (Fig. 1).

This report contributes a sedimentary pollen sequence from the coastal plain of the state of Veracruz (Fig. 1) that demonstrates maize cultivation there by 5,000 years ago, and this finding refines the understanding of the geography of early maize cultivation and its relationship to social and environmental change. More pointedly, the methodological issues involved in dating that record combine with its similarity to a pollen sequence from the coastal plain of the state of Tabasco (Fig. 1), lately reported as "the earliest record of maize cultivation in Mexico" (1), to demonstrate that maize cultivation in the Tabasco lowlands might actually have begun as much as 1,000–2,000 years more recently than the previously claimed 7,000 years ago. If so, the earliest securely dated evidence of maize cultivation in Mexico actually comes from the Southern Highlands (4) and best supports the hypothesis that domestication occurred there rather than the Balsas Depression.

Support for a domestication hearth in the Southern Highlands, with subsequent diffusion to the Gulf Coast Lowlands and Balsas Depression, originally came from excavations during the 1960s of rock shelters near Tehuacán (Fig. 1) that recovered maize macrofossils that radiocarbon assays on associated charcoal suggested were at least 7,000 years old (5). The significance of those macrofossils became controversial after direct dating during the 1980s by accelerator mass spectrometry (AMS) seemed to revise their age to no more than 5,500 years ago (6, 7). Nonetheless, recent AMS assays on similar cobs from a rock shelter at an almost 2,000-m elevation near Oaxaca (Fig. 1) date to 6,200 years ago and reinvigorate support for a model in which groups living in the Southern Highlands had already domesticated maize by 6,000–7,000 years ago and later diffused its cultivation to groups living at lower elevations in the valley of the Balsas River and coastal lowlands (4). Less convincingly but nonetheless of relevance, plant breeding experiments have lately shown that *Zea diploperennis*, a highland species of teosinte, can hybridize with a widespread wild grass called gamagrass (*Tripsacum dactyloides*) to produce offspring that are morphologically similar to the earliest maize macrofossils from Tehuacán (2).

Evidence to support a domestication hearth in the Balsas Depression, with subsequent diffusion to both the Gulf Coast Lowlands and the Southern Highlands, emerged just as AMS dating was raising doubts about the antiquity of the Tehuacán macrofossils. Molecular analysis now shows that maize is most closely related to *Z. mays* ssp. *parviglumis*, a teosinte that at present occurs only in the Balsas Depression (8, 9). Yet before the recent report of 7,000-year-old maize pollen from Tabasco, the direct evidence for maize cultivation outside of the Southern Highlands was more recent than the macrofossils from Tehuacán, even assuming they might be only 5,500 years old (1, 7). The Tabasco pollen record reported in 2001 (1) has thus provided key support for a domestication hearth outside of the Southern Highlands because it contributed the first direct evidence for maize cultivation elsewhere that was at least contemporaneous with and possibly much older than that from Tehuacán. The Tabasco record thereby seemed to support the molecular evidence that pointed to a domestication hearth in the Balsas Depression, from which maize subsequently diffused to both the Southern Highlands and the Gulf Coast Lowlands.

Results and Discussion

This report presents a long record of maize cultivation from the Veracruz coastal plain that is similar in terms of sedimentary sequence to the key Tabasco record, corroborating some of its

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Abbreviations: AMS, accelerator mass spectrometry; B.P., before present.

†To whom correspondence should be addressed. E-mail: asluyter@lsu.edu.

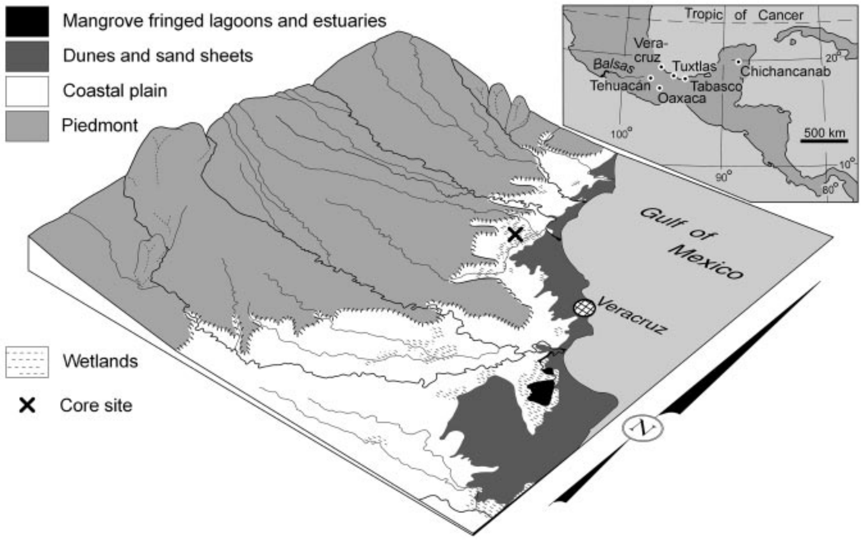

Fig. 1. The core locality in regional and local context, with places referred to in the text: the Veracruz, Tabasco, and Tuxtlas pollen cores; Tehuacán and Oaxaca; Lake Chichancanab; and the Balsas River and Depression. Scale of block diagram varies because of perspective; core locality is 24 km northwest of Veracruz.

attributes but forcing the conclusion that no evidence exists for maize cultivation as early as 7,000 years ago from the Gulf Coast Lowlands. The pollen sequence (Fig. 2) derives from an 8.5-m sedimentary core recovered with a Livingston-type corer from a small freshwater lake at the lowest point in an extensive belt of wetlands that covers the coastal plain between the dunes and the piedmont, some 24 km northwest of the port of Veracruz. Seven AMS radiocarbon assays provide the chronology (Table 1).

Like the Tabasco core, the Veracruz core comes from within 15 km of the current shoreline, records the Holocene sequence of depositional environments characteristic of the coastal plain of the southern Gulf Coast, and reveals how people modified

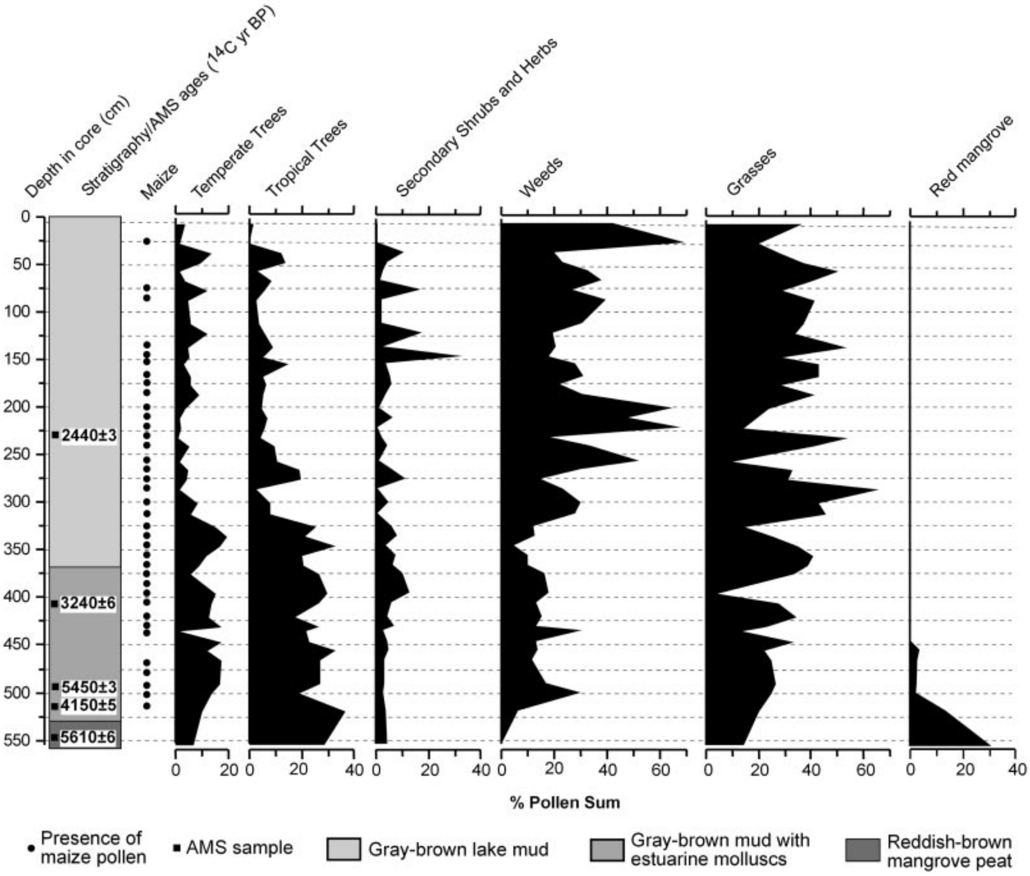

Fig. 2. Summary pollen diagram showing sedimentary sequence, pollen spectra, presence of maize pollen, and AMS assays.

Table 1. Radiocarbon samples, ages, and dates

AMS laboratory no.	Depth, cm	Material	$\delta^{13}C_{PDB}$, ‰	Corrected age/ conventional age, ^{14}C yr B.P. ± 1 σ	Calibrated date max. 1 σ range, calendar yr B.P.	Calibrated date max. 2 σ range, calendar yr B.P.	Calibration curve
OS-1339	229	Wood charcoal layer	−22.36	2,440 ± 35	2,362–2,680	2,355–2,702	Northern hemisphere terrestrial
OS-1332	407	Hardwood	−28.54	3,240 ± 65	3,389–3,556	3,356–3,630	Northern hemisphere terrestrial
OS-2528	487	*N. reclivata*	−3.92	5,450 ± 35	5,777–5,882	5,727–5,907	Northern hemisphere marine
Beta-130582	513	Pollen fraction	−28.50	4,150 ± 50	4,587–4,820	4,530–4,830	Northern hemisphere terrestrial
OS-3190	548	*R. mangle* peat	−27.80	5,610 ± 60	6,317–6,437	6,287–6,527	Northern hemisphere terrestrial
OS-1334	678	*R. mangle* peat	−27.80	6,290 ± 50	7,170–7,261	7,025–7,321	Northern hemisphere terrestrial
OS-3176	713	*R. mangle* peat	−28.32	6,470 ± 85	7,293–7,458	7,184–7,564	Northern hemisphere terrestrial

that environment over the last 5,000 years (Fig. 1). As sea level rose during the early Holocene, marine lagoons fringed by mangrove forests formed behind barrier islands (1, 10, 11). Sedimentation subsequently aggraded those lagoons: by the mid-Holocene, they had become brackish estuaries; by late Holocene they had become a coastal plain marked by freshwater lakes surrounded by wetlands, crossed by streams with flanking levees, and edged along only the seaward margin with lagoons, estuaries, and mangrove forests.

Previous research has shown that levees and the fringing Tertiary piedmont and Pleistocene dunes have for millennia provided settlement sites above the floodwaters with which the strongly seasonal precipitation regime inundates the coastal plain (12). During the estuarine conditions of the mid-Holocene, people fished, gathered clams such as *Rangia cuneata* and *Polymesoda caroliniana*, and cultivated maize (11). As brackish estuaries gave way to freshwater lakes and wetlands, people ditched them and mounded the spoil into planting platforms for maize cultivation. That form of intensive wetland agriculture lengthened the cropping period by facilitating drainage at the end of the wet season and splash irrigation through the dry season (13). Excavations of planting platforms demonstrate, on the basis of the presence of ceramics characteristic of the Late Preclassic and Early Classic periods [500 years before Christ (B.C.) to *anno Domini* (A.D.) 500], that people used those fields from 2,500–1,500 years ago (14). Vestiges of sloping-field terraces mark the piedmont west of the coastal plain; their precise chronology remains unknown, but Postclassic (A.D. 900-1519) peoples probably used them for cotton and maize cropping (15).

Maize pollen occurs in the Veracruz core beginning at a depth of 515 cm, with 14 grains with diameters of 59–94 μm (mean, 77 μm) (Fig. 2). That diameter range is diagnostic for Mexican landraces, and the spinule density of 6–7 per μm^2 also conforms to that of maize (16) (Fig. 3). Further confirming the inception of maize cultivation at that level, the pollen spectrum displays indicators of forest clearance and cultivation: a decrease in tropical trees and parallel increases in weeds and grasses (Fig. 2). The bulk of the grass pollen count belongs to a population of grains with diameters of <51 μm that represent many indeterminable species. That population of small grass pollen is distinct from the population of maize pollen, with an absolute gap in the diameter frequency distribution at 51–58 μm. Because teosinte produces pollen with a diameter range of 46–87 μm, that gap in the frequency distribution at 51–58 μm provides some evidence that teosinte was not present in the vicinity.

Similar maize pollen occurs in a total of 37 levels between depths of 25 and 515 cm (Fig. 2). Counts range from 1 to 40 grains per level, and the average is 11. Diameters range from 58 to 95 μm (mean, 69–84 μm), except for four anomalously large grains from the 185-cm level that have diameters of 101–109 μm. In addition, each level displays a similar absolute gap in the diameter frequency distribution at 51–58 μm that separates a population of small pollen grains belonging to wild grasses and another of large pollen grains belonging to maize. The small samples of maize pollen, compared with the 125 million pollen grains a single tassel produces (16), recovered from each level do not permit significant conclusions about the possibility of a trend toward larger pollen diameters with progressive selection for varieties with longer ears. Yet that the earliest maize pollen in the core is so similar in diameter to the reference statistics for extant Mexican landraces is suggestive of domestication having taken place considerably earlier and elsewhere, with subsequent diffusion to the Gulf Coast Lowlands.

The upper, lacustrine segment of the pollen sequence, from 0 to 350 cm deep, conforms to but elaborates on what previous research has already revealed about regional land use and climate change (Fig. 2). Similar to other pollen records from the Gulf Coast lowlands, including the one from Tabasco, the Veracruz sequence confirms that only after 3,500 years ago did maize farmers begin to clear large areas of forest (1, 17). Then, around 2,500 years ago, as marked by the AMS-dated layer of wood charcoal at a 229-cm depth, people began to clear trees from seasonal wetlands and construct complexes of fields; that timing for the inception of intensive wetland agriculture confirms the chronology inferred from the ceramics excavated from the planting platforms themselves (14). The move into the wetlands corresponds to the beginning of the dry period from 475 to 250 B.C. revealed in the sequence of gypsum deposition at Lake Chichancanab, some 800 km to the east (18) (Fig. 1). A slight reexpansion of tropical forest, perhaps also signaling the contraction of intensive wetland agriculture, marks the return of more humid conditions after A.D. 1025, also corresponding to the Lake Chichancanab paleoclimate sequence (18). The sudden increases in the pollen of tropical trees and invasive, secondary shrubs and herbs ≈500 years ago reflect the extreme depopulation of the colonial period (from a regional population of ≈500,000 when the conquistadors arrived in A.D. 1519 to a mere 5,000 or so a century later) and the consequent old-field succession of former agricultural fields (19). The Spaniards introduced cattle to take advantage of the resulting matrix of grassland with patches of low deciduous woodland, but grass pollen production actually decreased as grazing negatively impacted flowering (20). The most recent land-use phase, beginning in the middle of the 20th century, involved the conversion of forest and grassland to irrigated sugar cane, the pollen of which together with that of other grasses and weeds dominates the top 25 cm of core (Fig. 2).

Despite being generally confident that the dates on each AMS sample are accurate, the date on the *Neritina reclivata* (OS-2528) macrofossil at a depth of 487 cm ultimately must be rejected because the date on the pollen fraction (Beta-130582) at 513 cm indicates that bioturbation by burrowing clams, such as *R. cuneata*, significantly disrupted the association between such macrofossils and the pollen record in the estuarine sedimentary unit (Fig. 4). The *N. reclivata* macrofossil is about 1,500 years older than the pollen fraction at the same depth. A local

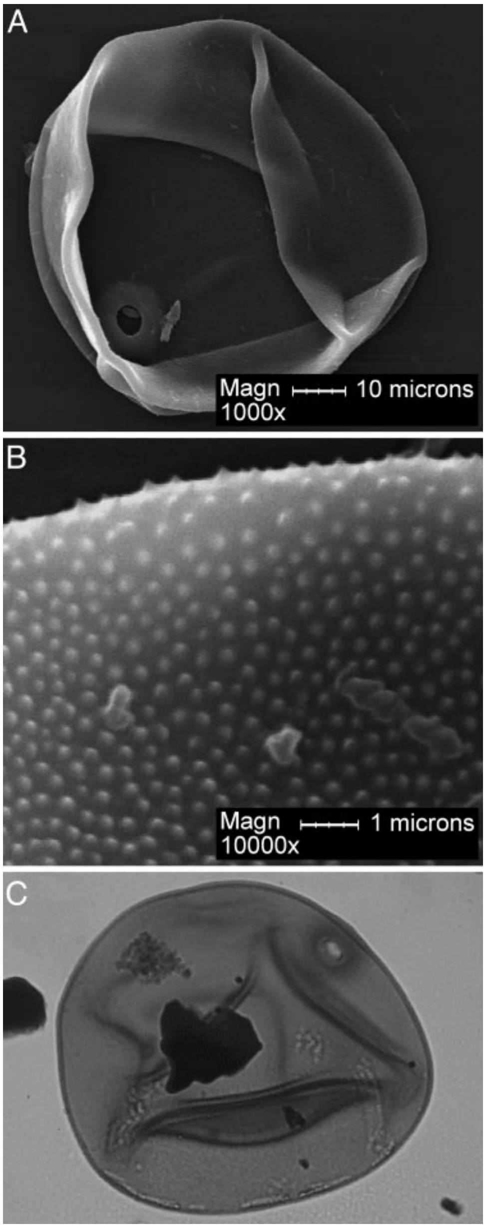

Fig. 3. Maize pollen grains from core. (*A*) Maize pollen grain from the 515-cm level taken by scanning electron microscopy at ×1,000 magnification. (*B*) Top edge of grain shown in *A* at ×10,000 magnification. (*C*) Maize pollen grain from the 505-cm level from light microscope at ×400 magnification.

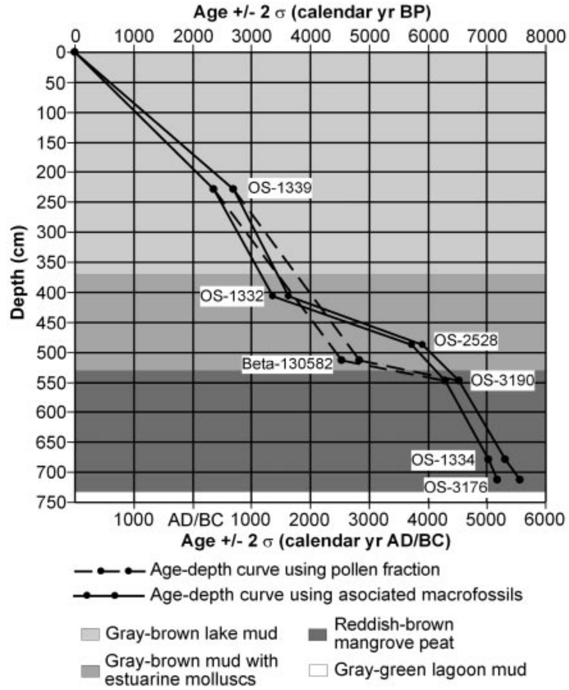

Fig. 4. Age/depth relationships of AMS dates showing calibrated 2-σ envelopes.

reservoir effect that differs from the correction built into the northern hemisphere marine curve of CALIB 5.0.1 might possibly explain some 10% of that difference but no more than that (21). By the same criteria, the wood macrofossil might also indicate an erroneous date for its depth and was therefore also rejected. This lack of association between macrofossils and the pollen fraction occurs because bioturbation affects the fine fraction, which includes microfossils such as pollen, differently than the coarse fraction, which includes macrofossils such as shells and wood fragments. Whatever the complex, unknown dynamics of that process in any particular core, the pollen fraction presumably is uniformly affected because of its relatively homogenous size and density. In the case of such bioturbated estuarine sediments, the pollen sequence itself provides a reasonable proxy for regional vegetation change. The standard paleoecological assumption that macrofossils and pollen at the same depth are the same age, however, is inappropriate when the research question requires temporal precision that can resolve the domestication of maize in one area of Mesoamerica and its diffusion to other areas over the course of, perhaps, only 1,000 years.

The direct AMS date on the pollen fraction therefore provides the basis for concluding that in the Veracruz lowlands maize cultivation began at most some 4,500 years ago, the 2-σ calibrated range being 4,530–4,830 years ago (Fig. 4 and Table 1). Such a relatively conservative conclusion recognizes that even a homogenized pollen fraction contains some pollen and other organic material (such as inclusions of charcoal, which is particularly resistant to oxidation and can therefore have a long postmortem residence time in a watershed) that might have been eroded and redeposited at the core locality, yielding an older-than-actual AMS date for that level in the core. An AMS date on a pure maize pollen fraction might well provide a more precise age estimate for the local inception of maize cultivation but would require a mass equal to some 20,000 maize pollen grains, compared with the 14 recovered from the 515-cm level. In contrast, acceptance of the standard assumption that macrofossils and pollen at the same depth are the same age would result in reliance on the macrofossil dates and the erroneous conclusion, as previously reported, that maize cultivation in the Veracruz lowlands began ≈6,000 years ago (11).

Yet exactly that problematic assumption underlies the report of 7,000-year-old maize pollen from Tabasco (1) and therefore forces the conclusion that that estimate is too old by as much as 1,000–2,000 years. The chronology for that record relies on AMS assays on macrofossils associated with pollen and not on the pollen fraction itself. However, just as in the Veracruz record, the earliest Tabasco maize pollen occurs in sediments bioturbated by burrowing bivalves such as *R. cuneata*, first in a lagoon and then in an estuary that persisted until some 4,000 years ago. In the Veracruz case, reliance on dates on associated macrofossils would have resulted in a date for the inception of maize cultivation that was some 1,500 years too old. Given the similar sedimentary context, failing direct AMS dating of the Tabasco pollen, and given the now demonstrated difficulty of dating pollen records in such bioturbated sediments even with direct AMS dating of the pollen fraction, it is difficult to accept the claim that maize cultivation in the Tabasco lowlands began 7,000 years ago. The evidence from the Veracruz core suggests a date some 1,500 years more recent, as does a pollen record from the Tuxtlas area of the Gulf Coast Lowlands (17).

Conclusions

Our findings mean that the earliest securely dated remains of maize in Mexico are macrofossils from the Southern Highlands that date to at least 6,200 years ago. Those cobs indicate already protracted selection for larger ears, suggesting that they number among the increasingly productive and diverse landraces that developed with diffusion throughout the varied environments of the Neotropics. Further macro- and microfossil evidence is necessary to elaborate the dynamic geography of maize's domestication and diffusion. Such evidence might well eventually demonstrate maize cultivation in the Gulf Coast Lowlands 7,000 or more years ago, as recently claimed (1). But if sedimentary pollen records are to contribute to the effort to reconstruct the process through which maize diffused throughout Mesoamerica from a domestication hearth, researchers will need to acknowledge that bioturbation in coastal lagoons imposes critical precision limits on dating those records. On the basis of the existing evidence, diffusion from a maize domestication hearth throughout the Neotropics might have occurred over the course of a period equal to the limits on dating precision that our analysis demonstrates for sedimentary pollen records from coastal lagoons, decisively limiting their utility in the reconstruction of that process.

Methods

In addition to standard methods of pollen analysis, all 10 slides prepared for each level were scanned for the large grass pollen characteristic of maize and its close relatives; the major diameters of all grains >39 μm were measured and recorded (22). The pollen grains of early maize must be indistinguishable from those of the teosinte (or, possibly, a teosinte–*Tripsacum* hybrid) from which it diverged, all such *Zea*-type pollen being subspherical, monoporate, annulate, essentially psilate to scabrate under light microscopy, with relatively evenly distributed spinules under scanning electron microscopy and with a major diameter of 46–87 μm (16, 22). But with selection for longer ears, the pollen of maize became substantially larger than that of its wild relatives and thereby became identifiable in the pollen record on the basis of having a diameter, for Mexican landraces, of 58–99 μm (mean, 77 μm) (22). This diameter range overlaps with the teosinte range, but any *Zea*-type pollen with a major diameter >90 μm is conservatively diagnostic of maize cultivation. Moreover, in particular reference to pollen records from the Veracruz and Tabasco coastal plains, *Tripsacum* does occur there but teosinte does not do so now, although it might once have (23). In both the Veracruz and Tabasco cores, therefore, all of the *Zea*-type pollen probably indicates maize cultivation, assuming teosinte never occurred there; in addition, even if teosinte did occur there in the past, *Zea*-type pollen grains with major diameters >90 μm certainly indicate maize cultivation.

The $\delta^{13}C_{PDB}$ values for the seven AMS assays fall within the expected ranges for the measured materials and allow correction for fractionation effects to yield conventional ages in radiocarbon years before present (^{14}C yr B.P.) (24). The hard-water effect, which could potentially cause older-than-actual ages, does not pertain because OS-1339, OS-1332, and Beta-130582 are terrestrial and therefore equilibrated with atmospheric radiocarbon; OS-2528 is marine; and OS-1334, OS-3176, and OS-3190 are red mangrove (*Rhizophora mangle*), an emergent hydrophyte that equilibrates with atmospheric radiocarbon. Calibration to calendar years for OS-1339, OS-1332, OS-1334, OS-3176, and OS-3190 is therefore based on the northern hemisphere terrestrial curve of CALIB 5.0.1 (24). Chemical and mechanical concentration techniques produced the homogenized pollen fraction for the Beta-130582 assay, also calibrated with the CALIB 5.0.1 northern hemisphere terrestrial curve (24–26). OS-2528 is an entire *N. reclivata* shell with intact periostracum and vibrant pigmentation, indicating that postmortem transport was minimal and that its aragonite did not inverted to calcite, which would have resulted in a younger-than-actual age; calibration used the CALIB 5.0.1 northern hemisphere marine curve to correct for the reservoir effect that otherwise results in older-than-actual ages for marine materials (21).

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