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Regional, Holocene records of the human dimension of global change: sea-level and land-use change in prehistoric Mexico

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Abstract

Regional, Holocene records hold particular relevance for understanding the reciprocal nature of global environmental change and one of its major human dimensions: ‘sustainable agriculture’, i.e., food production strategies which entail fewer causes of and are less susceptible to environmental change. In an epoch of accelerating anthropogenic transformation, those records reveal the protracted regional causes and consequences of change (often agricultural) in the global system as well as informing models of prehistoric, intensive agriculture which, because of long tenures and high productivities, suggest strategies for sustainable agricultural in the present. This study employs physiographic analysis and the palynological, geochemical record from cores of basin fill to understand the reciprocal relation between environmental and land-use change in the Gulf of Mexico tropical lowland, focusing on a coastal basin sensitive to sea-level change and containing vestiges of prehistoric settlement and wetland agriculture. Fossil pollen reveals that the debut of maize cultivation in the Laguna Catarina watershed dates to ca. 4100 BC, predating the earliest evidence for that cultivar anywhere else in the lowlands of Middle America. Such an early date for a cultivar so central to Neotropical agroecology and environmental change, suggests the urgency of further research in the study region. Moreover, the longest period of continuous agriculture in the basin lasted nearly three millennia (ca. 2400 BC–AD 550) despite eustatic sea-level rise. Geochemical fluxes reveal the reciprocity between land-use and environmental change: slope destabilization, basin aggradation, and eutrophication. The consequent theoretical implications pertain to both applied and basic research. Redeploying ancient agroecologies in dynamic environments necessitates reconstructing the changing operational contexts of putative high productivity and sustainability. Adjusting land use in the face of global warming and eustatic sea-level rise necessitates understanding sediment influxes to coastal basins which, in turn, depend on vegetation, climate, and land use in watersheds.

Keywords: Mexico; Veracruz; Holocene; Paleoecology; Sea level; Land use; Agriculture

1. Introduction

In general terms, three classes of records have increased understanding of the reciprocity between human activity and change in regional environments as well as, more profoundly, change in linkages among elements of the global environmental system (Bradley and Eddy, 1991): (1) global, recent records,
e.g., meteorological; (2) global, Quaternary records, e.g., ice-cap isotopic; (3) regional, Holocene records, e.g., lacustrine palynological. The first class entails real-time, real-space observation of phenomena, has good spatial-temporal resolution and global coverage, but pertains to only the immediately-recent past. The second class entails reconstruction through proxy data, spans the Quaternary and the globe, but generally has poor spatial-temporal resolution. The third class also employs proxy data but achieves intermediate spatial-temporal resolution by focusing on regional, Holocene change rather than on the global, Quaternary change evident from the viewpoints of the polar ice caps and the oceanic basins.

The third class of records (e.g., Berglund, 1991) holds particular relevance for understanding the human dimension of global change and one of its major subsets: sustainable agriculture (Wilbanks, 1994). First, those regional, Holocene records pertain to the epoch of accelerating anthropogenic environmental transformation—both regional transformation and global, systemic transformation. Second, they record the protracted regional causes and consequences of change in the global system. Third, many of those causes and consequences relate to agriculture (Turner et al., 1990). For example, expansion of agriculture has long been comprised a primary cause of regional land-cover change; that land-cover change relates to climatic change; and that climatic change entails consequences for the sustainability of regional agriculture. Practical aspects of ‘‘the human dimension of global change’’ concept, therefore, intimately relate to the concept of ‘‘sustainable agriculture’’: agricultural practices which entail fewer causes of and are less susceptible to environmental change.

Because of long tenures and high productivity, some forms of prehistoric agriculture have become models for sustainable agricultural in the present (Browder, 1989); yet success remains equivocal, partially due to poor understanding of dynamic environmental contexts (Denevan, 1995). Although results clearly remain assessable only over the short term, some redeployments of ancient knowledge seem sustainable and productive (e.g., Erickson, 1992), others not so (e.g., Chapin, 1988), and still others provocative in their potential but untested (e.g., Beach and Dunning, 1995). Much of the difficulty in redeploying ancient agroecological knowledge stems from poor understanding of the dynamic cultural and environmental contexts of the agroecosystems being modeled. The present contexts of vestigial field systems do not necessarily reflect their ancient, probably dynamic, operational contexts; therefore, redeployment schemes cannot a priori project past productivity and sustainability into present contexts.

Sea-level change—through effects on hydrology, erosion, and deposition—has particularly profound implications for agriculture. For example, along the Hondo River of Belize, prehistoric wetland agriculture might have changed in form and function as relative sea level rose throughout the Holocene (Pohl et al., 1990). The ancient Chimu of Peru periodically modified and eventually abandoned their irrigation canals as relative sea level fell and resulted in stream down cutting and strand of canal intakes—a secular trend which El Niño cyclicality catastrophically exacerbated (Ortloff, 1988). Also along the Peruvian coast, the function of sunken-embanked fields might have changed from water-table access to runoff diversion as relative sea level fell and resulted in stream down cutting and a lower water table (Moseley and Feldman, 1984).

2. Study region and problem

Laguna Catarina, near the port of Veracruz, Mexico (Fig. 1), is the hydrological center of just such a dynamic coastal environment and agroecosystem: a basin sensitive to Holocene sea-level change and a focus of prehistoric settlement and wetland agriculture. Based on nonchronometric stratigraphic and microfossil data, Hebda et al. (1991) hypothesize that the basin changed from an open marine bay at mid Holocene to a freshwater wetland at present due to the prograding delta of the Antigua River and “shoreline bars”. Vestiges of intensive agriculture pattern the wetlands surrounding Laguna Catarina (Figs. 1–3; Siemens, 1983a). Some 1700 ha of relic fields occur in that basin alone, with more to the north and south in other wetlands of the Gulf of Mexico tropical lowland (Sluyter, 1994). On the basis of phytoliths and ceramics from excavations, Siemens et al. (1988) have tentatively established that maize (Zea mays mays) cultivation took place at the El Yagual and Mata de Chile field complexes.
Fig. 1. The environs of the port of Veracruz showing the locations of wetlands, most of which are patterned with the vestiges of Prehispanic, intensive wetland agriculture (data sources: INEGI, 1973, 1980, 1982, 1983-1984, 1985; SRH, 1973a,b,c; locations of prehistoric settlements: Casimir, 1950; locations of excavations: Siemens et al., 1988).

(Fig. 1) "by about A.D. 500 and perhaps earlier, before the time of Christ".

Much of the modeling of the function of such vestigial, intensive wetland agriculture derives from the major extant occurrence of that agroecosystem: the highly productive *chinampas* of the Basin of Mexico (Sluyter, 1994). Although multiple working hypotheses remain characteristic, the general function of intensive wetland agriculture seems to have involved regulation of soil moisture in the root zone of the fields and maintenance of a nutrient sump in the intervening canals. Construction techniques
would have included ditching into or mounding above the natural surface, possibly both. Environmental context would have included a water table at the surface for at least part of the year. In some cases, farmers may have accelerated drainage as the water table fell at the end of the wet season and then retained water in the canals for splash or subirrigation during the dry season. In other cases, farmers may have lowered a perennially high water table or raised the planting surface above the water surface. In all cases, they took advantage of wetlands by adjusting the elevation of the root zone relative to the water table in order to maintain an advantageous degree of soil moisture. The vestiges of such ancient labor and knowledge now occur as patterning of microtopography and vegetation in wetlands throughout the Americas (Denevan, 1970; Denevan and Turner, 1974; Sluyter, 1994).

The Veracruzan vestiges, however, display a distinctly different context and morphology than the Basin of Mexico chinampas, the basis of much of the functional modeling (Sluyter, 1994). On the Gulf Coast, small, typically curvilinear field vestiges occur in seasonal backswamps near the mouths of streams that head in the highlands to the west. In the Basin of Mexico, the large, distinctly rectilinear chinampas occur in perennial, closed-basin lakes. A functional model for the backswamp context involves careful regulation of drainage beginning at the end of the wet season to allow cropping as early as possible yet retain water for splash and subirrigation later in the dry season (Siemens, 1983b). Such a sensitive technology would have required a labyrinthine canal system interrupted by ephemeral dams, resulting in the curvilinear morphology. That morphology and function contrast with the rectilinear chinampas, where subirrigation rather than drainage predominates and, at one time, relied on permanent dams to control water levels and salinities in the interconnected lakes of the Basin on Mexico (Palerm, 1973).

This study interprets the relation between environmental context and the distinctive wetland fields of the Gulf of Mexico lowlands. The next section develops and tests an alternative hypothesis of basin genesis to the “shoreline bars” of Hebda et al. (1991) by employing previous research on the piedmont, nonchronometric data from coastal dunes, and chronometric data from cores of basin fill. The subsequent section focuses on the relationship between that dynamic environmental context and land-use change, particularly the nature and tenure of prehistoric wetland agriculture, by interpreting palynological and geochemical data from those same cores.

3. Basin genesis

Laguna Catarina and its surrounding wetlands form a basin in the narrow coastal plain between a fanglomerate piedmont and a spatially complex belt...
of eolian sand (Fig. 1). Explicating the genesis of the basin therefore requires understanding the piedmont to the west and the dunes to the east.

3.1. The piedmont

The geological map (INEGI, 1980; Fig. 4) suggests that the piedmont derives from Tertiary and Pleistocene erosion of coastal ranges and deposition of the detritus as marine fanglomerates. The Sierra Madre Oriental consist of folded and faulted Jurassic and Cretaceous limestones (Guzmán, 1952; INEGI, 1980). In the study region, Tertiary volcanism cut through and uplifted the parallel limestone ranges, building composite peaks of andesite and largely obscuring the Mesozoic materials with basalts and tuffs. Cenozoic erosion of those ranges formed a piedmont apron of fanglomerates to the east as turbidity currents and debris flows deposited sand and poorly sorted, subangular to well rounded limestone and igneous clasts in coalescing, submarine alluvial fans (Mossman and Viniergra, 1976; Helu et al., 1977). Quaternary volcanism further mantled the piedmont with basalts and tuffs. In response to Pleistocene regressions, the streams draining the humid slopes of the Sierra Madre Oriental deeply entrenched their meanders into the piedmont. The Antigua River, for example, flows some 100 m below the interfluvial surface only 30 km from the Gulf of Mexico.

3.2. The dunes

No such previous research exists for the complex belt of dunes, but nonchronometric analysis of distribution, morphology, and alignment suggests an early-to-mid Holocene origin. Vegetated longitudinal dunes form a nearly continuous landward belt characterized by linear and parabolic forms with crest elevations up to 120 m and lengths up to several kilometers (Fig. 1). Except for localized blowouts, these longitudinal dunes are stable. Unvegetated, active transverse dunes form a discontinuous gulfward belt, characterized by barchinoid ridges and discrete barchans with crest elevations up to 50 m. As Figs. 5 and 6 demonstrate, all four dune forms reflect the wind vector associated with winter fronts. Strong, periodic northers characterize the winter;
Fig. 5. A section of a vertical aerial photograph of the mouth of the Agua Fría River showing the alignment and spatial relationship of transverse and longitudinal dunes (INEGI, 1973; December 1973; see Fig. 1 for location).

moderate, steady northeast-to-east tradewinds characterize the summer. The northers rather than the trades are the effective winds because of the formers’ higher mean speed and their occurrence during the dry season, when reduced soil moisture promotes eolian processes.

Despite the lack of chronometric data, a working hypothesis of dune genesis derives from models of coastal eolian processes (Nordstrom et al., 1990; Pye and Tsoar, 1990). They suggest that all of the dune types formed under a wind regime similar to the present and that rather than deriving from climatic change, the morphological variety records changing deflational conditions, with more or less sand available for dune formation. The longitudinal dunes formed during the postglacial transgression, beginning ca. 19,000 yr B.P. (Pirazzoli, 1993). The full-glacial shoreline was ca. 125 m below (Fairbanks, 1989; Bard et al., 1990) and ca. 30 km farther east (NOAA and USDC, 1985) than at present. Rising sea level eroded the shoreline, creating sand beaches subject to deflation. Belts of successively larger longitudinal dunes formed under a wind regime similar to the present, each belt eroding with continued transgression and contributing sand to the next. As the transgression rate slowed ca. 7000 yr B.P. (Fairbanks, 1989), reduced erosion decreased the sand supply and promoted dune stability and vegetation. The narrow beaches which formed through continued erosion of the outermost longitudinal dunes supplied enough sand to form transverse dunes. Such dunes, however, could only form to leeward of beaches oriented normal to effective wind direction along the scalloped shoreline, thus resulting in a discontinuous distribution (Fig. 1). A group of emergent reefs (Freeland, 1971) affords protection from erosion to the E–W trending shoreline south of the port of Veracruz and may explain the absence of transverse dunes there.

Fig. 6. The (A) mean monthly precipitation and (B) mean wind speed and frequency for selected months for the eight cardinal and subcardinal directions, both for the port of Veracruz (data sources: García, 1970; Tejeda Martínez et al., 1989).
Alternatively, the longitudinal dunes might be older than early Holocene. Fossil pneumatophores, presumably of black mangrove (*Avicennia germiana*), occur among coastal dunes 25 km north of the Actopan River (Fig. 1) and might indicate msl (mean sea level) ca. 70 m above present at sometime after the dunes formed (Malpica-Cruz, 1988), probably during the Sangamonian interglacial. The eolian sand bodies inland from the longitudinal dunes almost certainly represent the vestiges of Pleistocene dune cordons. On the whole, however, fluvial dissection of the longitudinal dune belt itself is minimal and does not suggest exposure to the major regression and drop in base level associated with the Late Wisconsin glaciation. Streams typically follow narrow channels through the dunes (Fig. 1). Moreover, exposures in quarries and roadcuts among the longitudinal dunes display only minimal development of organic and calcic soil horizons, again suggesting a Holocene origin (Ward, 1973).

![Fig. 7. Looking east across Laguna Catarina from the embankment of a modern drainage canal during the dry season, the dunes on the horizon (January 1992; see Fig. 1 for location).](image)

3.3. Hypothesis

A hypothesis of basin genesis derives from consideration of the relationship among the fanglomerate piedmont, the coastal dunes, and sea-level change. The spatial and temporal relationship of the piedmont and the dunes defined the hydrological-depositional context for the genesis of the coastal plain and its wetland-fringed lakes, including Laguna Catarina. As sea-level rose to its current position over the course of the Holocene, lagoons formed between the piedmont and the stabilizing belt of longitudinal dunes. Streams adjusted to rising base level by depositing sediment in those lagoons, in deltas, and on floodplains along lower reaches. As lagoons aggraded, the deltas of the major inflowing streams prograded toward the dune belt and eventually sealed tidal inlets; marine influence ended. With continued basin aggradation, a narrow coastal plain emerged between the dunes and the mouths of the piedmont canyons. Laguna Catarina and its surrounding wetlands are a vestige of one of those lagoons, with open water now reduced to a shallow, limnetic lake which varies in extent with the flood regime of the flanking streams—from ca. 1000 ha in the wet season to less than 100 ha in the dry season (Fig. 7). The secular aggradation of the lagoon, catastrophically punctuated by the sealing of the tidal inlet, formed the dynamic context for prehistoric settlement and land use. Cores of basin fill serve to test the foregoing hypothesis.

3.4. Methods

In January 1993, a Livingston-type piston corer (University of Minnesota Limnological Research Center, 1 m × 5 cm barrel; Aaby and Digerfeldt, 1986) facilitated recovery of three parallel cores from Laguna Catarina: 93LC1, 93LC2, and 93LC3 (Fig. 1). Water level was low given the already advanced dry season, and a wood grating resting on the mat of water hyacinth (*Eichhornia crassipes*) at the lake margin provided a stable work platform. Limited people-power dictated the maximum coring depth of 8.5 m. On the basis of a 1 m contour-interval map (SRH, 1973a), its related benchmarks, and survey by dumpy level, the surface at the core site is 1.0 ± 0.5 m above msl. The horizontal interval between cores is 2 m, with 93LC2 providing the fossil and chronometric data, 93LC3 the sedimentological data, and 93LC1 remaining in reserve for future analysis. Cores 93LC2 and 93LC3 display closely parallel stratigraphy, with the minor (+2.5 cm) differences in 93LC3 normalized to 93LC2 on the basis of the relatively sharp stratigraphic boundaries (Fig. 8).

Laboratory analyses of subsamples followed established procedures after removal of the core's surface, description of moist sediments, extraction of
chronometric samples, and sampling at stratigraphically-modified, regular intervals (Fægri and Iversen, 1989, pp. 72–75; Munsell Color, 1992). Wet sieving samples at −1.00 φ removed molluscs and mollusc fragments > 2.00 mm; peat subsamples required visual removal of molluscs (ASTM, 1980, pp. 109–110, 340–343). Subsequent carbonate estimation was by Chittick apparatus (Machette, 1986), organic matter by loss-on-ignition (Davies, 1974). Particle size estimation was by hydrometer on the ≤ 2.00 mm fraction after pretreatments removed carbonates, salts, and organic matter with hydrochloric acid, water, and hydrogen peroxide (ASTM, 1980, pp. 111–121; Kunze and Dixon, 1986). Due to low minerogenic content, peat samples for particle size estimation represent ca. 70 cm of core length. Pollen preparation was by acetolysis after concentration with hydrochloric acid, hydrofluoric acid, and zinc chloride solution (Fægri and Iversen, 1989, pp. 77–83). Sieving the resulting residue removed charcoal and organic particles ≤ 10 μm and > 150 μm prior to staining with Safranin O (Kodak CI 50240), mounting on slides in acrylic resin (Du Pont Elvacite 2044), and comparison with the University of Texas Herbarium Pollen Collection by light microscopy at ×400 magnification.

3.5. Data and analysis

Fig. 8 illustrates the combined stratigraphy of cores 93LC2 (normal) and 93LC3 (normalized) on the basis of sedimentological and macrofossil criteria. Four units are evident: (1) lagoon/tidal flat mud; (2) mangrove peat; (3) estuarine mud; (4) lacustrine mud.

The basal unit is gray and dark greenish gray mud, containing indeterminable, well-rounded mollusc fragments and white mottling—characteristic of a lagoon or mudflat (Elliott, 1986). The organic matter concentration is ca. 6%. Several fragments of
monocotyledon leaves might be referable to turtle grass (*Thalassia testudinum*), a marine angiosperm which grows subaqueously at depths of up to 10 m (Den Hartog, 1970). The CaCO$_3$ concentration ranges from 18–30%. And the sand fraction is minimal, the subangular to subround, frosted grains indicating eolian transport from the dunes to the east (Butzer, 1971). Several subangular pumice lapilli up to 5.5 mm in length occur in association with charred wood fragments at ca. 7.75 m depth, dramatically depressing pH. An eruption of either Volcán San Martín, some 150 km to the southeast, or Volcán Pico de Orizaba, some 100 km to the west, might have produced those airfall pyroclasts. The former volcano is at the outer transport limit for lapilli of ca. −2 ø (Walker, 1971), but winds from the west are minimal (Figs. 4 and 6).

Overlying the lagoon/tidal flat unit is dark reddish brown and black peat containing in situ estuarine molluscs—characteristic of a red mangrove (*Rhizophora mangle*) forest fringing a lagoon tidal flat (Thom, 1967). On the basis of wood anatomy (CWAR, 1993), only red mangrove contributed to the peat; no black or white mangrove (*Laguncularia racemosa*) wood is present. The peat is in situ since it consists of heterogeneous detritus and roots, displays neither bedding nor sorting, and contains abundant *R. mangle* pollen (Cohen, 1970). Red mangrove typically occupies oligo- to hyperhaline intertidal environments on inactive mudflats and oyster reefs, along the margins of coastal lagoons and the lower reaches of streams, and around lakes and ponds in interdistributary basins—not as an obligate halophyte but because salinity eliminates competition from most other flora (Thom, 1967; Tomlinson, 1986; Britton and Morton, 1989). Black and white mangrove are equally halophytic but do not favor frequent immersion and waterlogged soil. Red mangrove typically lives between msl and mhw (mean high water), a narrow elevational range in the microtidal Gulf of Mexico (tidal range at the port of Veracruz equals 0.52 m, and would be further attenuated by a narrow tidal inlet [USDC et al., 1992]). The median elevation of living peat, therefore, closely approximates msl (Woodroffe, 1981). The organic matter concentration ranges from 39 to 78%, the CaCO$_3$ from 7 to 11%, and the sand fraction again is minimal and eolian. Pumice ash occurs at the top of the unit. The molluscs are common rangia (*Rangia cuneata*) and, since many are articulated and retain their pigment layer, in situ.

Overlying the mangrove forest unit is dark gray mud containing in situ estuarine molluscs—characteristic of an estuary (Elliott, 1986). The organic matter concentration ranges from 6 to 9%, the CaCO$_3$ from 12 to 21%, and the sand fraction, again, is minimal and eolian. Pumice ash occurs at the base of the unit. The majority of the molluscs are common rangia, far outnumbering the three individuals of Carolina marsh clam (*Polymesoda caroliniana*) and two of olive nerite (*Neritina reclinata*). Many of the molluscs remain articulated and retain their pigment layer, showing no evidence of transport. Common rangia and Carolina marsh clam are commonly occurring infaunal bivalves that favor upper estuarine environments with sufficient freshwater discharge to produce periodic limnetic to mesohaline conditions, mean water depths of 1–2 m, mud bottoms, and a microtidal range; they commonly occupy the substrate of red mangrove forest (Parker, 1960; Andrews, 1977). Olive nerite is a rarely occurring epifaunal gastropod that also favors upper estuarine environments with mean water depths of 1–2 m and typically lives among the beds of seagrass, such as turtle grass and manatee grass (*Syringodium filiforme*), which commonly grow just seaward of red mangrove (Parker, 1960; Britton and Morton, 1989).

The upper unit is very dark gray, brown, black and dark olive gray mud with white mottling—characteristic of a limnetic lake (Allen and Collinson, 1986). The organic matter concentration ranges from 6% to a high of 18% at the surface, the CaCO$_3$ from 8 to 26%. Generally, the sand fraction is minimal and, again, eolian. The dramatic influx of angular to subangular, unfrosted sand at ca. 1.5 m depth represents anthropic disturbance (discussed in the section on land use). Three discrete charcoal lamina, also anthropic, occur at ca. 2.25 m depth, each some 2 mm thick.

Table 1 presents the six AMS (Accelerator Mass Spectrometry) radiocarbon ages which allow chronometric analysis. The δ$^{13}$C$_{PDB}$ values fall within the expected ranges for the measured materials (Lerman, 1972) and provide corrections for fractionation effects. Hard-water effects do not obtain: OS-1339 and OS-1332 are terrestrial; OS-2528 is marine; and
Table 1
Radiocarbon samples, ages, and dates from core 93LC2

<table>
<thead>
<tr>
<th>Laboratory number</th>
<th>Median depth in core</th>
<th>Material</th>
<th>$\delta^{13}$C$_{PDB}$ (%o)</th>
<th>Corrected age from NOSAMS ($^{14}$C yr BP ± 1σ)</th>
<th>Calibrated date max. + 1σ (date(s))max. − 1σ (sidereal yr BC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-1339</td>
<td>229.5</td>
<td>wood charcoal</td>
<td>−22.36</td>
<td>2440 ± 35</td>
<td>755 [511, 435, 428] 408 BC</td>
</tr>
<tr>
<td>OS-1332</td>
<td>407</td>
<td>&quot;hardwood&quot;</td>
<td>−28.54</td>
<td>3240 ± 65</td>
<td>1594 [1513] 1426 BC</td>
</tr>
<tr>
<td>OS-2528</td>
<td>487</td>
<td>Neritina reclivata</td>
<td>−3.92</td>
<td>5450 ± 35</td>
<td>3929 [3899] 3805 BC</td>
</tr>
<tr>
<td>OS-3190</td>
<td>547.5</td>
<td>Rhizophora mangle peat</td>
<td>−27.80</td>
<td>5610 ± 60</td>
<td>4498 [4457] 4360 BC</td>
</tr>
<tr>
<td>OS-1334</td>
<td>677.5</td>
<td>Rhizophora mangle peat</td>
<td>−27.80</td>
<td>6290 ± 50</td>
<td>5270 [5253] 5149 BC</td>
</tr>
<tr>
<td>OS-3176</td>
<td>712.5</td>
<td>Rhizophora mangle peat</td>
<td>−28.32</td>
<td>6470 ± 85</td>
<td>5444 [5430, 5394, 5386] 5299 BC</td>
</tr>
</tbody>
</table>

OS-1334, OS-3176, and OS-3190 are an emergent hydrophyte that equilibrates with atmospheric radiocarbon (Deevey et al., 1954). Since these data represent the first nonspurious radiocarbon ages for the study region, they require calibration to sidereal years in order to correlate the basin fill with data on cultivation and settlement framed within the regional ceramic chronology. Calibration of OS-1339, OS-1332, OS-1334, OS-3176, and OS-3190 employs bidecadal tree-ring data (Stuiver and Reimer, 1993, dataset 1). Calibration of OS-2528 incorporates a time-dependent correction for global oceanic reservoir effect (Stuiver and Reimer, 1993, dataset 3) with no deduction for a regional oceanic reservoir effect (ΔR)—unknown for this locality but probably minimal (Stuiver and Braziunas, 1993). Fig. 8 presents sidereal dates interpolated between calibrated $^{14}$C ages and between the upper $^{14}$C age and the present surface.

The shallowest sample is one of the charcoal lamina. The clear definition of the lamina, the quantity of charcoal, and its $\delta^{13}$C$_{PDB}$ value suggest that deposition was contemporaneous with widespread burning of arboreal vegetation, wind transporting the charcoal to the lake surface (Patterson et al., 1987; Clark, 1988).

The second sample is a platy, 40 mg chip of indeterminable "hardwood" (CWAR, 1993) in horizontal position, suggesting minimal postdepositional disturbance. Since estuarine conditions prevailed at the time and since entry through the tidal inlet would have been unlikely, one of the inflowing streams probably introduced the wood from the watershed. Therefore, postmortem transport time would have been relatively brief and the $^{14}$C age refers to the substrate surface at the time of deposition.

The third sample is an entire shell of olive nerite. Since this gastropod species is epifaunal and this individual displays no evidence of postmortem transport, its stratigraphic position represents the surface of the substrate at death. The intact periostracum and still vibrant pigmentation indicate that contamination by more-modern $^{14}$C through inversion of aragonite to calcite has not occurred (Grant-Taylor, 1972; Mangerud, 1972; Goslar and Pazdur, 1985).

The three deepest samples are red mangrove peat. Measurements on thick accumulations of mangrove peat, despite small sigmas, can only yield nominal ages because its organic carbon occurs as an amorphous mass of fine roots (Tomlinson, 1986), thus ensuring continuous contamination with more-modern $^{14}$C as younger roots penetrate older peat. This characteristic limits sample homogenization to removal of the large prop roots which might have deeply penetrated the otherwise amorphous peat. Therefore, these three ages might be somewhat too recent vis-à-vis the samples’ stratigraphic positions.

3.6. Discussion of basin genesis

The gross change from lagoon to lake indicates land emergence—a local regression—during the postglacial, eustatic sea-level rise (Fig. 9). Yet the intermediate transitions do not suggest a continuous regressive sequence, which from lower to upper would comprise lagoon, tidal flat, estuary, mangrove forest, and lake facies. Instead, the transition from mangrove forest to estuary signals a reversal in the
gross trend and a period of land submergence, a local transgression. Several processes, possibly acting in concert, explain this partially inverted sequence.

The primary process relates to variation in the rate rather than the direction of sea-level change. Red mangrove can only colonize tidal flats during rising sea level and initiate a regressive facies sequence by aggrading peat and allochthonous sediment to maintain the surface of the substrate ca. 0.15–0.30 m above msl (Woodroffe, 1981). Therefore, mangrove forest could not have become established before the rate of sea-level rise began to slow ca. 7000 yr B.P. Regarding peat aggradation, the maximum rate for red mangrove remains only generally known. The Laguna Catarina data themselves, on the basis of interpolation between the three earliest radiocarbon ages (Fig. 8), yield an apparent aggradation rate of 1.6–2.5 m/1000 yr and a mean rate of 1.76 m/1000 yr. However, compaction due to overburden accumulation likely yields an apparent rate lower than the actual rate. Ellison and Stoddart (1991) suggest a maximum rate of 1.88 m/1000 yr, but that figure is based on island data, where allochthonous sediment inputs are relatively low. Determination of recent rates at Laguna de Terminos, some 500 km eastward along the Gulf Coast, provide a better analog. Research there, employing $^{210}$Pb and $^{137}$Cs and correcting for compaction with depth through bulk-density normalization, indicates a maximum of 2.9–3.3 m/1000 yr for red mangrove fringing the lagoon and subject to tides and high salinities, 3.8–4.6 m/1000 yr without correcting for compaction (Lynch et al., 1989). Regarding eustatic sea-level rise, the Caribbean coral record indicates an early Holocene, eustatic sea-level rise rate ca. 24 m/1000 yr, a decrease through the middle Holocene, and a late Holocene rate ca. 1 m/1000 yr (Fairbanks, 1989). According to the Fairbanks curve, the rate did not slow to ca. 3 m/1000 yr until between 7000 and 5000 yr B.P.

The core data and the eustatic curve suggest that red mangrove colonized the lagoon ca. 5500 BC when the transgression rate had slowed to ca. 3 m/1000 yr and relative sea level was $-6.25 \pm 0.5$ m (Figs. 8 and 9). Subsequent peat aggradation kept pace with sea-level rise until ca. 4250 BC, when relative sea level was $-4.3 \pm 0.5$ m. Then the rate of sea-level rise increased; the mangrove forest retreated (e.g., Ellison, 1993); and beds of turtle and manatee grass became established along with associated molluscs such as olive nerite. At ca. 1500 BC, the prograding delta of the Antigua River sealed the

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**Fig. 9.** Profile through Laguna Catarina along 19°16'53" north (see Fig. 1 for location). Vertical exaggeration is ca. $\times 100$ in order to allow delineation of basin fill facies (data sources: INEGI, 1983-1984, INEGI, 1983-1985; SRH, 1973b, SRH, 1973c).
lagoon's tidal inlet and limnetic conditions replaced marine, resulting in the catastrophic termination of much of the estuarine flora and fauna and the eventual displacement of any remaining mangrove forest by terrestrial and limnetic flora. As the basin's major allochthonous sediment source, the Antigua River would have aggraded its immediate axis at a higher rate than the rest of the basin, as evident in Fig. 9. Therefore, upon contacting the dune belt, the aggrading, prograding delta and levees would have isolated the basin—although still at msl—from marine influence.

Problematically, neither the available sea-level curves for the northern Gulf of Mexico (Bloom, 1977; Pirazzoli, 1991) nor the eustatic curve (Fairbanks, 1989) indicate an accelerating sea-level rise ca. 4250 BC, and therefore the reversal in the gross trend of land emergence suggests local factors. Sediment compaction or tectonic subsidence might have increased the rate of relative sea-level rise. In support and on the basis of tide-gauge data analyzed in geological context, Emery and Aubrey (1991) suggest that the port of Veracruz has been subsiding due to tectonism at the mean rate of 1.6 m/1000 yr since 1953. Also problematically, the Laguna Catarina data, even discounting compaction effects, suggest higher sea levels than the eustatic curve (Fairbanks, 1989): for example, ca. -6.25 m as opposed to -12 m at 5500 BC. As demonstrated by the Bermuda peat sequence (Neumann, 1971), that difference might relate to the ecology of Fairbanks' sea-level indicator—a coral with an elevational range of 5 m—or to his tectonic and isostatic assumptions. Ultimately, "the" eustatic sea-level curve cannot substitute for regional, relative sea-level curves.

Two other processes might also obtain. First, distributary avulsion might have diminished the supply of allochthonous sediment to the core locality, limiting the maximum peat aggradation rate and catalyzing mangrove retreat. The extremely slow sedimentation rate for the estuarine unit supports that inference; the rate of 0.35 m/1000 yr, even given the possibility of compaction, suggests an estuarine backwater far from allochthonous sediment supplies (Shepard, 1953). Second, although improbable, a succession of severe tropical cyclones could have forced mangrove retreat. The frequency and severity of hurricanes is directly proportional to sea-surface temperature (Emanuel, 1987), and the $^{18}$O foraminiferal record does indicate that sea-surface summer temperatures for the North Atlantic were comparable to present ca. 4250 BC (Duplessy, 1991). However, although the study region does experience flooding due to hurricanes, their trajectories, at least during the past century, have typically intersected the coast at least 200 km north of the port of Veracruz (SRH, 1970).

Some tentative results of field reconnaissance and of map and aerial photographic interpretation of analogous basins to the north and south support the above interpretation. To the north, the Actopan and Agua Fría rivers display a distributary morphology suggestive of a vestigial delta which prograded across a lagoon, now nearly completely obscured by the coastal plain (Fig. 1). To the south, the Larga, Redonda, and Mandinga lagoons are the now discrete subbasins of a single protolagoon (Fig. 1). In contrast to Laguna Catarina, the southern lagoons have persisted due to allochthonous sediment starvation. The Atoyac River might once have flowed into the protolagoon but subsequently suffered capture by the Jamapa River. The Horcones tidal creek and Laguna Larga probably represent the vestigial lower reaches of the Atoyac River, with a relic deltaic lobe separating Laguna la Redonda from Laguna Mandinga.

In addition to supporting the above interpretation of the genesis of Laguna Catarina, therefore, the broader perspective confirms that the process and timing of basin aggradation and coastal-plain development depends on specific spatial context as well as on the timing of sea-level change, resulting in intrazonal landform variation. Testing of the above hypotheses and determination of a local sea-level curve will require more coring along spatial-temporal gradients, both in the Laguna Catarina Basin and in the other basins to the north and south.

Lack of precision (as distinct from accuracy or veracity) in previous research inhibits the integration of data from throughout the study region. As a function of the different problems being addressed, previous studies (Hebda et al., 1991; Siemens et al., 1988) do not characterize the nature of sediments precisely enough to allow correlation of stratigraphic units. For example, whether the basal sands in their sections are eolian, littoral, or fluvial remains ambiguous. Further, imprecise locations, elevations, and
chronologies similarly prohibit spatial and temporal correlations with the Laguna Catarina data and a fuller, four-dimensional understanding of the basin’s facies.

4. Basin land use

Despite the current impossibility of making direct intraregional correlations and delimiting facies distributions in space and time, the above hydrological-depositional sequence, comparison with analogous contexts (Thom, 1967), and models of lagoon aggradation (Thom, 1982; Roy, 1984; Nichols, 1989) all indicate a dynamic patchwork of environments that varied spatially and temporally at macro- through microscales. Inhabitants would have had access to diverse resources. At the spatial macroscale, a host of environments would have presented floral, faunal, and mineral opportunities: lagoons, lakes, ponds, marshes, salt pans, forests and meadows in interdistributary basins; dunes, interdunes, and beaches along shorelines; reefs and open water in the Gulf; channels, floodplains, levees, and gallery forests along streams; and savannas on the piedmont. At the temporal macroscale, the extent of some of those environments would have changed with basin aggradation, reducing estuarine and increasing limnetic, particularly agricultural, opportunities. At the microscale, vegetation and soil moisture, for example, would have spatially varied from wetland margins to centers and temporally from dry season to wet season. Higher stream discharge during the wet season would have lowered the salinity of lagoons (Thom, 1967; Vázquez-Yanes, 1971). As in the Amazon Basin (Goulding, 1980), seasonal flooding of interfluvial forest would have provided habitat for and access to fish and crustaceans. Lakes and wetlands would have yielded an annual round of floral and faunal resources (e.g., Wilken, 1970; Nietschmann, 1972). Moreover, as annual floodwaters receded, leaving behind a fresh increment of mud, renewed soil nutrients and moisture would have offered agricultural potential.

4.1. Previous studies

Because the numerous prehistoric settlements around Laguna Catarina have lacked archaeological attention, the data relating to land use remain few. Only Buena Vista and Loma Iguana on the eastern margin of the basin (Fig. 1) have yielded relevant data. People living at Buena Vista beginning in the second millennium BC practiced agriculture, fished, and gathered molluscs (Casimir, 1990). Specific data remain unpublished, and the ceramic chronology is relative and tentative (Tolstoy, 1978), but a prehistoric settlement near Laguna Alvarado (Fig. 4) provides a suggestive analog for early occupation of the Laguna Catarina basin. At Laguna Alvarado, people lived in a mangrove forest, practiced agriculture and arboreoculture, and utilized a wide range of fauna: mammals, birds, amphibians, reptiles, fish, crustaceans, and molluscs—including common rangia, Carolina marsh clam, and olive nerite (Stark, 1977).

During the first millennium AD, Loma Iguana became the new population center, propinquitous to the intensive wetland cultivation at Mata de Chile (Fig. 1). On the basis of ceramic and microfossil data, Siemens et al. (1988) established that maize cultivation took place at El Yagual and Mata de Chile by the first several centuries AD “and perhaps earlier” (Fig. 8). Maize pollen occurs from 125 to 135 cm below the surface of vestigial planting platforms. Since pollen grains oxidize with tillage, they indicate a period of maize cultivation in the watershed, not in the wetlands themselves, a conclusion which the absence of associated ceramics supports. After a hiatus of 15 cm, maize phytoliths occur from 90 to 110 cm in association with ceramics diagnostic of the early first millennium AD. Since phytoliths typically remain in situ and do not oxidize (Piperno, 1988), they indicate a period of intensive wetland cultivation. While—like any soil particle—phytoliths can translocate, the associated ceramics support the inference of primary deposition and intensive wetland cultivation of maize.

4.2. Methods

The pollen record from core 93LC2 (Fig. 10) provides the first absolute chronology for maize cultivation in the basin, confirming the previous, relative chronology for Mata de Chile and El Yagual. Maize pollen identification assumed all subspherical, monoporate, annulate, psilate to scabrate grains ≥ 65 μm in diameter refer to maize. Teosinte (Z. mays
spp.), the putative ancestor of maize (Iltis, 1983), is the only other Neotropical taxon which produces morphologically similar pollen as large as 65 μm (Whitehead and Langham, 1965) but has a semiarid highland range and does not occur in Veracruz (Wilkes, 1967, 1972). The geochemical record from core 93LC3 (Fig. 10) complements the palynological record. Only the top 2.5 m of core were analyzed due to financial constraints. The carbon (C) and carbon-to-nitrogen ratio (C/N) were estimated by Carlo Erba CHN automated elemental analyzer at the Soils and Physical Geography Laboratory of the University of Wisconsin–Milwaukee. The exchangeable phosphorous (P_{EX}) was estimated by colorimetry at the same laboratory.

4.3. Data and analysis

In all, four maize cultivation periods are evident (Fig. 10). The first begins at just below radiocarbon sample OS-2528, yielding an interpolated date of ca. 4100 BC for the debut of maize cultivation. This period lasts until ca. 3300 BC and represents eight centuries of maize cultivation. The pollen is not a laboratory contaminant since it occurs in five adjacent samples over a depth of 50 cm. Moreover, the pollen’s stratigraphic location represents its temporal location since bioturbation in lakes and consequent downward mixing of sediment and microfossils generally is less than 10 cm (Jones and Bowser, 1978). Although infraunal bivalves in the estuary facies suggest the possibility of greater bioturbation effects, that great a degree of downward mixing would have obscured the hiatus between cultivation periods one and two, from 440 to 465 cm depth. The second cultivation period spans the nearly three millennia between ca. 2400 BC and AD 550. It brackets the change to limnetic conditions ca. 1300 BC and is punctuated by the charcoal lamina ca. 450 BC. A hiatus of five centuries precedes the brief resumption of maize cultivation during the third period, ca. AD 1100–1200. Maize pollen then disappears from the record until an interpolated date of ca. 1750.

The maize pollen represents cultivation in the
environs of Laguna Catarina. Eolian transport of maize pollen beyond ca. 100 m is minimal (Raynor et al., 1972), and its relatively good preservation in core 93LC2 does not suggest long periods of fluvial transport. A surface sample from ca. 0.5 km northwest of the core locality did not yield maize pollen, unsurprising since pasture and sugarcane currently dominate the basin, maize being relegated to interstices such as field margins and the earthen mounds of prehistoric settlements. Since no observable maize pollen occurs at the surface and since maize is typically under-represented in pollen spectra because of restricted transport (Bryant and Hall, 1993), all of the cultivation periods represent substantially more maize cultivation than obtains at present in Laguna Catarina’s watershed.

The first period and most of the second period signal cultivation in the watershed. The wetlands did not become limnetic, and therefore could not have supported wetland agriculture, until ca. 1300 BC. The upward trend in the proportion of \( \text{P}_{\text{EX}} \) from ca. 1250 to 500 BC demonstrates increasing population and slash-and-burn forest clearance in aid of shifting cultivation. Phosphorous indicates anthropic disturbance because it does not readily mobilize, the main dissolved and particulate fluxes to basins being through runoff from ash, feces, and garbage (Eidt, 1977; Deevey et al., 1979; Brenner, 1983; Gillingham, 1987; Metcalfe et al., 1989). An increase in the proportion of clay parallels the phosphorous trend, consistent with anthropic disturbance in the watershed, specifically with preferential erosion of colloids due to shifting cultivation (Binford, 1983; Lal, 1987, pp. 524; Larabert, 1992, pp. 246–264). The slightly increasing trend in the proportion of C and the overall decreasing but fluctuating C/N might indicate variation in the input of allochthonous organic matter and charcoal in combination with general eutrophication due to phosphorus loading, C/N presumably inversely correlated to trophic level (Binford et al., 1987; Metcalfe et al., 1989).

The last millennium of the second period does relate to intensive wetland agriculture and, perhaps, to propinquitous piedmont agriculture. The lamina of charcoal which initiate this ca. 450 BC to AD 550 subperiod suggest widespread forest clearance in the wetlands themselves rather than shifting cultivation in the watershed. The quantity of charcoal and its \( \delta^{13}C_{\text{PDB}} \) value of \(-22.36\%o\) indicate derivation from arboreal vegetation (Lerman, 1972). The laminar deposition indicates the proximity of forest clearance to Laguna Catarina, wind carrying the charcoal to the lake surface (Clark, 1988). Moreover, that millennium straddles the BC/AD division and temporally correlates with the maize phytolith stratum at Mata de Chile and El Yagual. The proportion of C and C/N both sharply decrease at the beginning of this period, despite an increase in the proportion of calcium carbonate, thus indicating a diminishing flux of allochthonous organic matter and charcoal but a possible continuation of eutrophication. Investment in intensive wetland agriculture and, perhaps, sloping-field terracing (Sluyter and Siemens, 1992) reduced slash-and-burn clearance and the carbon flux into the basin. A pulse of C and \( \text{P}_{\text{EX}} \) at the end of this period, ca. AD 500, correlates with a dramatic influx of angular to subangular, unfrosted sand. As in the Maya region (Deevey et al., 1979) and the Central Highlands (Metcalfe et al., 1989; O’Hara et al., 1993), protracted intensification of land use eventually resulted in slope destabilization.

During the subsequent, 500-year hiatus in maize cultivation the C/N and the proportions of C and \( \text{P}_{\text{EX}} \) steadily decrease, indicating restabilization of slopes. The third period of maize cultivation, ca. AD 1100–1200, remains indiscernible in the geochemical stratigraphy and seemingly was as restricted in space as in time. The fourth period of maize cultivation pertains to ca. AD 1700 and was similarly restricted; the increasing proportions of allochthonous C and \( \text{P}_{\text{EX}} \) are referable to increasing livestock population and burning of pasture during the colonial period (Sluyter, 1995).

4.4. Discussion of land use

Generally, the meanings of trends in C, \( \text{P}_{\text{EX}} \), and C/N remain somewhat ambiguous, particularly considering the possibility of horizontal heterogeneity in sedimentation and taphonomy (Engstrom and Wright, 1984). Nonetheless, the data do indicate that during the millennium-long period of intensive wetland agriculture, the basin would have aggraded under a regime of annual flooding. Subbasins would have formed and created a complex and dynamic pattern of local base levels. That secular dynamism would
have necessitated ongoing, incremental modifications (Doolittle, 1984) to canals and platforms. For example, the balance between drainage and subirrigation functions would have been delicate (Sluyter, 1994) and changed at various scales in both space and time. Moreover, these initial data suggest hypotheses and avenues for further analysis to clarify the linkages between the geochemical fluxes and wetland agriculture. The trend in $P_{EX}$ suggests the possibility of a linkage between eutrophication and the cessation of field use—a process previously hypothesized for the sixteenth-century transition to European ecologies in the Central Highlands of Mexico (Whitmore and Turner, 1992).

Promisingly, a project to excavate several field complexes and address just such issues is currently underway (A.H. Siemens, pers. comm., 1995). Other necessary additions to the data base include further refinement of environmental context and of sloping-field terrace chronology, distribution, and function (Sluyter and Siemens, 1992). Further geochemical, diatom, charred particle, magnetic susceptibility, and pollen analyses on the cores will test and elaborate the above interpretations.

5. Conclusions and prospects

The regional, Holocene record of the human dimensions of global change along the Gulf of Mexico remains tentative in many aspects but has begun to reveal the long-term, reciprocity between land-use and environmental change. Postglacial sea level's eustatic rise was a key variable in defining land-use change along a dynamic coast. But that variable was not monolithic; the longest period of continuous agriculture lasted nearly three thousand years—despite rising sea level throughout. Rather than submergence of coastal lowlands, the eustatic rise resulted in emergence. People were cultivating maize in wetlands near the port of Veracruz from ca. 400 BC to ca. AD 550, after sea-level rise and basin aggradation resulted in limnetic conditions. Yet the landscape displayed great spatial-temporal complexity and comprised much more than intensive wetland agriculture. Macro- through microenvironments changed in extent and nature during the Holocene and offered a wide and dynamic range of opportuni-
ties. Moreover, the trends in geochemical fluxes reveal a reciprocity between land-use and environmental change. Changing land use caused slope destabilization and, probably, eutrophication, stream avulsion, and changes in local base levels; all of which in turn had consequences for the wetland agroecosystem. Rather than relating to eustatic sea-level rise, the end of the three millennia of maize cultivation ca. AD 550 probably has socioeconomic linkages to the emergence of Teotihuacán in the Basin of Mexico, that state increasing its influence in the study region during the first millennium AD (Sluyter, 1995).

This regional, Holocene record thus emphasizes the need to consider spatial-temporal context in the interpretation of coastal facies. Spatially, lagoonal mangroves (in contrast to littoral mangroves) are subject to impacts only indirectly dependent on secular sea-level change. Tidal-inlet closure rather than sea-level change per se catastrophically alters hydrochemistry and biology. Stream avulsion reduces sediment supply to mangrove substrates and results in forest retreat. Temporally, regressive-transgressive, mangrove advance-retreat sequences do not necessarily indicate “low stands” and “high stands”. Rather, in particular contexts a slowing of the rate of relative sea-level rise rather than a change in direction can produce an emergent facies sequence and shoreline progradation (Ellison, 1989; Ellison and Stoddart, 1991).

Those theoretical implications apply to policy as well as to basic research (Maul, 1993). Redeploying ancient agroecologies in such dynamic environments necessitates reconstructing the changing operational contexts of putative high productivity and sustainability. Moreover, mangrove forests constitute a buffer against transgression as well as fulfilling many other ecological and cultural roles (Clough, 1982). Their maintenance in the face of global warming and eustatic sea-level rise necessitates an understanding of relative, regional sea-level trends and watershed geography—particularly important given a preponderate coastal population (Wind, 1987; GSC et al., 1990). Physiological limitations on the rate of peat aggradation suggest that the key threshold value is the difference between the rate of transgression and the rate of peat aggradation, including compaction, and that the latter rate partially depends on al-
lochthonous sediment supply which, in turn, depends on vegetation, climate, and land use in the watershed and on stream avulsion in deltas. A diachronic focus on dynamic rates of change rather than a synchronic focus on such dubious concepts as "still stands" begins to interrogate such processes.

More fully understanding sea-level rise along the Gulf of Mexico coast and its local expression as a regressive facies sequence at Laguna Catarina requires a chronometric analysis of the eolian sand belt and a regional, relative sea-level curve. The distribution of dunes in space and time is complex and deserves systematic study. The potential is for a significant contribution to the paleoecology of the southern Gulf of Mexico tropical lowland and to coastal eolian theory. Dating of basal mangrove peat deposits would yield a detailed sea-level curve for the middle and late Holocene. Leveled bucket-auger transects of the basins associated with the lower reaches of the major streams have the potential to yield such a record.

Perhaps most significantly, the earliest indication of maize cultivation in the Laguna Catarina watershed dates to ca. 4100 BC, predating the earliest evidence for that cultivar anywhere else in the lowlands of Mesoamerica (McClung de Tapia, 1992). Such an early date for a cultivar so central to Neotropical agroecology and environmental change (Deevey et al., 1979; Rue, 1987), suggests the need for further research in the study region. Agroecological innovations in subhumid, central Veracruz might have been instrumental in transferring maize cultivation from its semiarid, highland hearth to the humid lowlands. Once established in the lowlands, maize cultivation became central to the emergence of Mesoamerican states, such as the Olmec and Maya, and to associated patterns of anthropic environmental change, such as deforestation.

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