El Niño resilience farming on the north coast of Peru

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El Niño–Southern Oscillation has been treated as a disruptor of environmental and socioeconomic equilibrium both in ancient times and in modern-day Peru. Recent work in the coastal desert plain, known as the Pampa de Mocan, challenges this view by demonstrating that prehispanic irrigation systems were designed to incorporate floods and convert them into productive waters. Archaeological investigations in this landscape reveal a 2,000-y history of floodwater farming embedded in conventional canal systems. Together with a pollen record recovered from a prehispanic well, these data suggest that the Pampa de Mocan was a flexible landscape, capable of taking advantage of El Niño floodwaters as well as river water. In sharp contrast to modern-day flood mitigation efforts, ancient farmers used floodwaters to develop otherwise marginal landscapes, such as the Pampa de Mocan, which in turn mitigated risk during El Niño years. These archaeological data speak to contemporary policy debates in the face of increasingly intense and frequent natural disasters and question whether El Niño Southern Oscillation events should be approached as a form of temporary disorder or as a form of periodic abundance.

archaeology | irrigation agriculture | ENSO | pollen | floodwater farming

Natural disasters, and in particular, flood events, are predicted to intensify as the planet continues to warm. Much of today's disaster management strategies draw on a theoretical perspective that located the origin of catastrophes in nature, and views them as external to society (1–7). Consequently, policy and research efforts are largely directed at improving predictive models and detection methods (2, 5, 8, 9). Yet, despite significant advances in technology, the cost of disasters, both in human lives and material damage, rises each year, prompting the need for further research (4, 10, 11). Archaeology is uniquely suited to address questions of diachronic processes and event-based change. The environmental conditions and rich cultural history of the north coast of Peru makes for fertile testing ground for investigations of human–environment dynamics.

The north coast of Peru is categorized as a hyperarid desert (12), yet some of history's earliest complex farming societies developed in this region. The coast is a relatively flat alluvial plain interrupted by rivers, which descend from the high Andes and empty into the Pacific Ocean (Fig. 1). Beginning at least as early as 5400 calBP, farmers in the region constructed small-scale "gravity canals" to draw water off of these rivers and direct it to gardens and fields (13). By AD 200, the Moche had mastered irrigation agriculture and their extensive trunk canals and branches extended across coastal river valleys and tributary alluvial fans (14–18). In the subsequent centuries, the Chimu (AD 900 to 1460) pushed the limits of hydraulic engineering, constructing an intervalley canal and building on earlier works to extend a massive adobe aqueduct near the town of Ascope, measuring 13-m high in some places, and irrigating an area of at least 4,000 ha (16, 19–24). Some studies estimate that the prehispanic irrigated landscape was 40% larger than the area under cultivation today (25).

The Moche, Chimu, and to a lesser-known extent the Cupisnique (1100 to 500 BC), relied on irrigation for more than just subsistence. The kinetic properties of channeled water, the maintenance of canals, and maize (*Zea mays*), cotton (*Gossypium barbardense*), and other crops played central roles in ritual life (26–30). Social, economic, and ritual life on the north coast depended on water management, making the threat of aperiodic destructive floods a potential catalyst for systemic change.

Groundbreaking work by Michael E. Moseley and his colleagues in the Field Museum's Proyecto de Riego Antiguo analyzed the relationship between technology and natural disasters. Moseley and Parsons are credited as the first scholars to compare the effect of El Niño flood events in preceramic times (8000 to 3000 BC) to periods when a highly integrated irrigation system was in use (8, 31, 32). They found that as irrigation technology became more complex and required specialized labor, agricultural society became increasingly vulnerable to floods. To model how society changed alongside technology, archaeologists borrowed a concept from systems ecology—thermodynamic equilibrium—which posits that a given system eventually reaches a state of homeostasis and remains stable unless disturbed by an outside force (8, 33–40). In the context of the ancient north coast, interactions between abiotic and biotic factors, such as population size, canal extension, erosion, salinization, aridity, river volume, riparian vegetation, and temperature, were viewed as constantly progressing toward equilibrium (39); however,

Significance

Disaster management policies are aimed at system resistance: Maintaining or quickly returning to operations established during normal periods. The Peruvian approach to El Niño follows this model, but the cost of reconstruction rises with each event. Meanwhile, archaeological evidence demonstrates that El Niño events were successfully managed by prehispanic farmers, who developed resilient hybrid canal systems that utilized both river water and floodwater for agricultural production. Ancient farmers treated the El Niño phenomenon as part of the norm, and likewise accounted for floodwaters in their irrigation technology. This study calls for a conceptual shift as effective disaster management policy is developed in the context of the global climate crisis.

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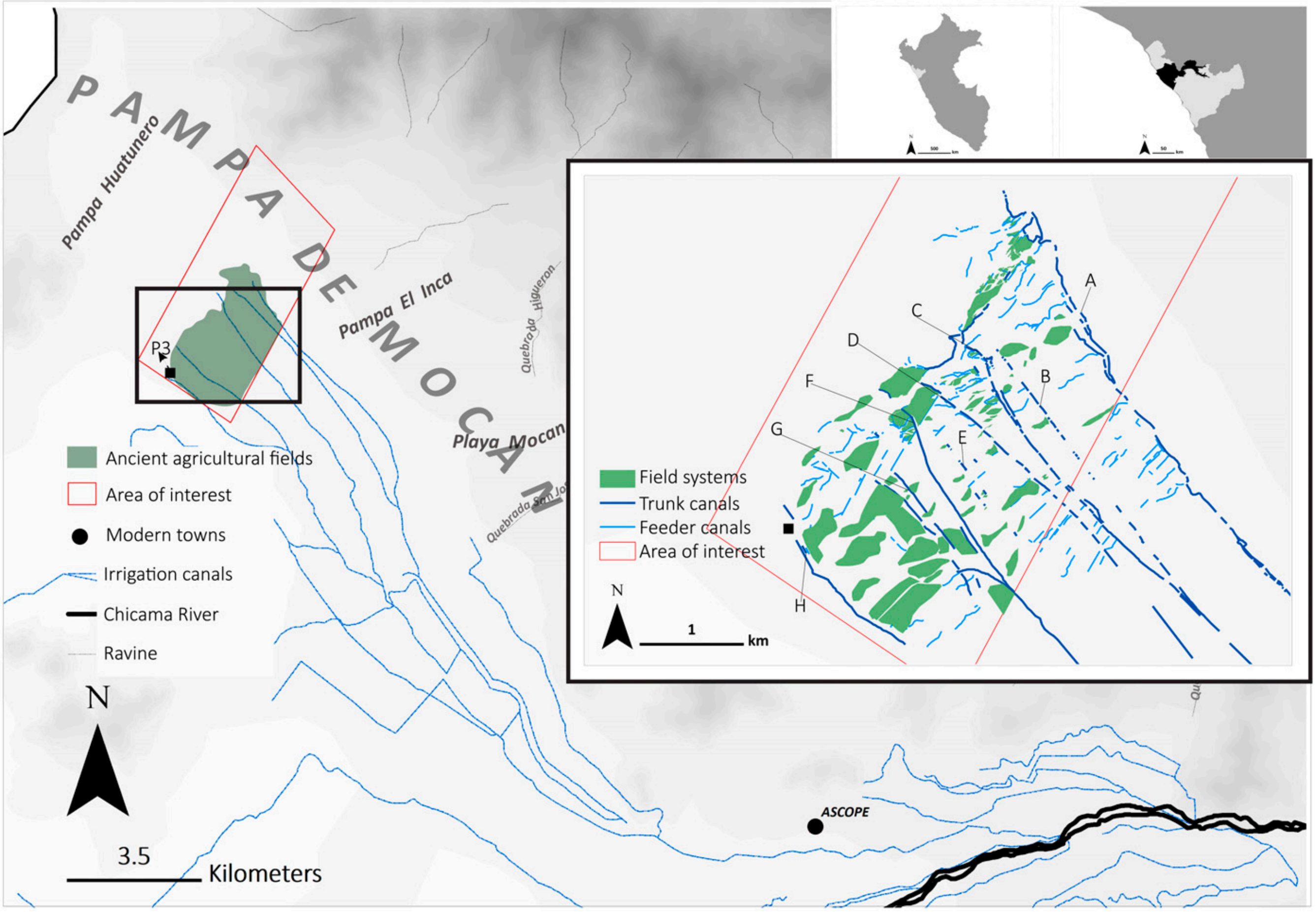

Fig. 1. The Pampa de Mocan canal and field system, with *Insets* of Peru and the Department of La Libertad and the Chicama Valley.

the system was prone to disruption or "punctuation" by El Niño floods due its dependence on irrigation technology (39).

Environmental Conditions on the North Coast of Peru

Despite the apparent stability of the north coast environment, the region undergoes near-constant intra- and interannual change. Due to seasonal rainfall in the neighboring high Andes, north coast river systems experience "wet" and "dry" seasons every year: Average monthly discharge of the Chicama River can be just 10.25 m^3/s in the month of September, while in March volume can reach 469.84 m^3/s (12). These fluctuations in discharge combine with short- and long-term anthropogenic processes on the landscape to affect the microenvironment of each valley, resulting in seasons of heavy cloud cover, high humidity, and increased biotic activity (41–43). In addition to seasonal shifts, the north coast experiences the effects of El Niño–Southern Oscillation (ENSO) every 6 to 20 y (44–46). However, while change in river volume occurs regularly, ENSO can manifest in a variety of ways that are difficult to predict.

ENSO describes a continuum of shifting pressure cells between the western Pacific (Australia) and the central (Tahiti) and eastern Pacific. ENSO has three phases that affect sea level pressure (SLP) and, consequently, sea level, sea surface temperature (SST), wind direction, and precipitation in the eastern Pacific: ENSO-neutral years, the cold phase La Niña, and El Niño. In ENSO-neutral and cold phase years, the eastern Pacific is characterized by strong trade winds blowing east to west, high SLP, and a shallow thermocline (the boundary between warm SSTs and colder, deeper water), which, in combination with the rain shadow from the nearby Andes, result in dry conditions on the Peruvian coast (17, 47). Meanwhile, during the El Niño phase, trade winds weaken and occasionally reverse, causing warm waters to migrate back across the equatorial Pacific to the east. El Niño results in a deeper thermocline, lowered SLP, and elevated the sea level along the Peruvian and Ecuadorian coasts, which combine to cause unusually wet conditions in the eastern Pacific.

Along the north coast of Peru and the southern coast of Ecuador, the El Niño phase results both in diminished oceanic upwelling, which causes mass death events among marine and near-coastal fauna, and intense rainfall (48). Precipitation events have a multitude of effects, depending, in part, on where they occur. Rainfall along the western flanks of the Andes collect and drain into the coastal rivers, causing water levels to rapidly rise and rivers to overflow their banks, destroying canal intakes and farmland located on or near the floodplain. Meanwhile, when rainfall occurs on the coastal plain and nearby Andean foothills, high-energy flow moves quickly down dry ravines or *quebradas*, triggering flash floods, damaging irrigation canals, fields, and any urban settlements in the path of the active drainage channel. Secondary effects include widespread disease, such as dengue fever, crop loss, sediment transport on a grand scale, and, in some localities, the influx of water can cause blooming events, a replenished water table, and ephemeral springs.

Even with sophisticated forecasting technology, predicting the location, timing, and scale of El Niño events is difficult. As recently as 2017, a rare, localized event known as "El Niño

Costero" went largely undetected until the warm waters had already appeared along the coasts of Peru and Ecuador (49, 50). Between the months of March and May 2017, the varied effects of El Niño were distributed unevenly and often asynchronously across the valleys of the north coast of Peru: While torrents of rain fell on Chiclayo, just two valleys south in Ascope skies were clear (50). The lack of uniformity across and within events makes finding correlates in the archaeological record particularly challenging.

ENSO and the Archaeological Record

Records from glacial cores (51–53), thermally anomalous molluscan assemblages (54–58), and beach ridge stratigraphy (59, 60) point to broad paleoenvironmental trends over time. El Niño events reappeared and north coast waters cooled at 5800 calBP and were low frequency from 5800 to 2900 calBP (56–58, 61–64), when event frequency increased to the modern-day regime (ranging from every 6 to 7 y to every 10 to 20 y) (44–46). In other words, early farmers on the north coast were encountering a significent shift in El Niño timing and frequency as they began to develop sophisticated irrigation technology (65–69). However, these regional-scale data do not necessarily correspond to evidence of flood events at the local or site-scale, further complicating attempts at identifying a causal relationship between societal crisis and El Niño in the archaeological record (56, 64).

The human ecology model held that complex irrigation, the same technology that allowed coastal societies to thrive in an arid environment, exposed prehispanic and early colonial farmers to instability, and even collapse (8, 25, 39). Archival records capture the reaction of both indigenous and Spanish inhabitants of the north coast Lambayeque Valley to an El Niño event in 1578 (70). Accounts describe torrents of rain, rotting crops, breached canals, flooded fields, and later, locusts, and disease (70). Similarly, in the archaeological record, some events had clearly devastating effects (48, 71, 72), while others had little or no detectable impact (73–76).

Archaeological data also demonstrate prehispanic practices of El Niño risk-management strategies. Dillehay and Kolata (77) describe flood infrastructure, such as check dams, along the coastal hills in the Jequetepeque Valley, in and around irrigation canals, and in the desert, suggesting that at times ancient populations invested in opportunistic technologies. In the area of the Osmore drainage, prehispanic farmers took advantage of ground aquifers replenished by El Niño events to support agricultural production (76, 78, 79). Instead of focusing on causal links between evidence of sociocultural change and El Niño disaster, scholars have increasingly directed their studies toward identifying thresholds: The scale of events (45, 46, 80–84), the "convergence" of events with other disasters (85–90), or the social and environmental preconditions that, when combined with El Niño, pierced equilibrium (91, 92).

Collectively, these studies have recorded a wide spectrum of human-ENSO dynamics; however, the underlying laws of the equilibrium concept classify data either as part of the "norm" or as "system noise" (93). In other words, this deeply embedded theoretical paradigm has the effect of flattening data into two, often opposed categories, such as stable or unstable; and this trend has far-reaching implications both for interpretations of the past and for disaster management policies of the present and future. New archaeological evidence from the coastal desert landscape of the Pampa de Mocan calls for a reconceptualization of north coast Peruvian system dynamics. Rather than understanding the local environment as one that exists largely in stasis until punctuated by an El Niño event, paleobotanical results from the Pampa de Mocan demonstrate that the local environment is almost constantly undergoing ENSO-related change. "Instability" is the norm and this prehispanic irrigation system was designed to account for instability: It was capable of flexibly transitioning from river water distribution to floodwater farming, making it resilient to El Niño events.

Results

The Pampa de Mocan is a 5,800-ha coastal desert plain located in the Ascope Province of the Region of La Libertad bordering both the Chicama Valley and the southern edge of the Pampa de Paijan. The area is comprised of coalesced Quaternary alluvial fans and is crossed by ephemeral stream channels that are only active during El Niño-related rainfall events (17) (Fig. 1). The present study is concerned with just under one-third of that area, a 1,707-ha area of interest in the northeastern extreme of the plain, adjacent to the Andean foothills and upslope of the highest present-day irrigation canal, beyond the limit of modern agriculture. Cupisnique ceramic sherds point to agricultural production beginning by 1100 BC and features eight trunk canals supplied by the Chicama River that were active at different times in the prehispanic past.*

The local ecology in this portion of the Pampa de Mocan has been described as marginal and unfavorable for agricultural purposes: The soil is low in organic matter and mean precipitation in the inner Chicama Valley is less than 2 cm per year (12, 96). Plant life in the Pampa de Mocan is characterized by xerophytic communities of cacti, desert scrub, *Capparis*, or sapote trees, and scant *Prosopis* or algarrobo stands. The Pampa de Mocan appears to represent a landscape in stable climax or in a state of equilibrium; however, pollen evidence from an archaeological context indicates that vegetation, and by extension the local microclimate, was highly dynamic in the past. Observations made in 2017, point to similar dynamism in the present.

Paleobotanical Environmental Reconstruction. The Proyecto Arqueoambiental de la Pampa de Mocan (PAAPM) excavated a formal prehispanic water feature (P3) that was identified as a small (175 cm × 86 cm) *kocha* or *pozo*: A well fed by underground seepage. Similar features, some just 1-m deep, have been studied as components of the larger Nasca *puquio* system or subterranean water galleries (97). Agronomist Sabogal-Wiesse (98) recorded his observations of *kochas* in the inner Chicama Valley in the 1970s and reported that these were used during periods of El Niño-related water abundance. P3 is located in the southwestern end of a long stone and adobe platform that leads to an ancient road segment (Fig. 2). The feature was sealed by extensive wall-fall, which was dated to the Late Intermediate Period (AD 1000 to 1476) using diagnostic ceramics.

The platform and the opening of P3 were built up above the active drainage channels, and therefore P3 has been unaffected by quebrada flooding. However, episodic El Niño rainfall and slopewash from the edges of the feature itself formed laminae near the base of the feature. Six strata, labeled A (top) to F (bottom) of fine, water-lain sandy silt were sampled from P3 for ancient pollen (Table 1). Historical El Niño frequency suggests that these six layers probably formed in less than 100 y (45, 47). The samples were not directly dated; however, the horizontal layers were undisturbed and, therefore, the data provide a time-series of plant life change and, by proxy, environmental dynamism in the Pampa de Mocan's prehispanic past.

The P3 pollen diagram is divided into groups based on the typical environmental conditions of the identified taxa. *Alnus* and *Podocarpus* data were not factored into the reconstruction of the local environment surrounding P3; the pollen of these taxa are capable of long-distance wind travel, and rather than reflecting local conditions, these genera likely represent broader

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*Fields covered in Cupisnique sherds provide a limiting age for early agricultural activities in the Pampa de Mocan; this age coincides with contemporaneous canal building activity in the broader area (94, 95).

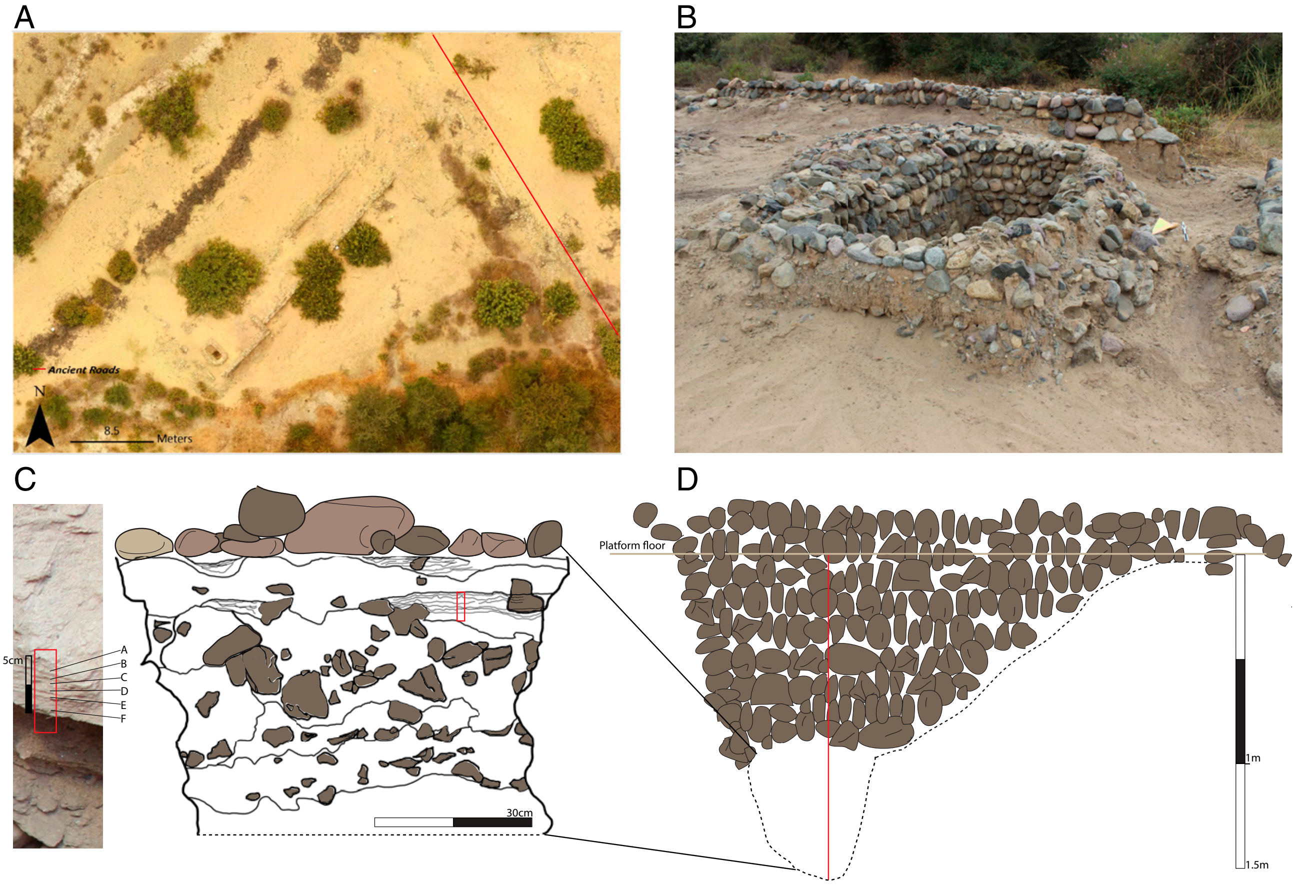


Fig. 2. The P3 water feature. (*A*) Drone photograph of P3 showing the feature itself in the lower left corner, the rectangular platform where P3 is located, and their relationship to an ancient highway. (*B*) Ground view of P3 feature. (*C*) Excavation profile of southern face of feature with strata A to F indicated with red rectangle. (*D*) Excavation profile of western face of P3 feature.

regional plant life patterns (99).[†] Therefore, the following results include only those taxa grouped according to their relative humidity requirements.

Principle component analysis and richness (S) scores of these data confirm that the P3 record represents four different plant communities or phases (*SI Appendix*, Figs. S1 and S2). The stratigraphically lowest, and therefore earliest, layer F indicates a phase of abundant water. Layer E points to agricultural activity, while layers D and C are best interpreted as a phase when nearby fields were fallowed. Finally, layer A, when compared to a modern-day collection created after the El Niño Costero in 2017, is proposed to represent an El Niño blooming phase.

Layer F has a high concentration of *Typha* or cattail, a common sedge of marshy and wetland areas on the Peruvian coast.[‡] Cattail is a useful proxy for the presence of abundant, standing water, conditions consistent with an El Niño event. Cattail is present in layer F, but decreases in the subsequent layer E and disappears from the pollen record in layers D and C.

Layer E witnesses a fall-off in water-dependent taxa, such as cattail and Asteraceae, alongside an increase in cultigens, including maize and *Pachyrrhizus* (jicama or "yam bean") (62). It is notable that throughout the pollen record, there is a negative relationship between the presence of maize and weedy taxa—Asteraceae, *Sonchus* (synonym *Picrosia longifolia*), Poaceae >50 µm—and cattail. layer E also has the lowest richness score, pointing to a decrease in species diversity in this phase.

Cultigens diminish in layers D and C, while invasive species and hardy grasses including algarrobo, *Alternanthera* (*Amaranthus*), Asteraceae (flowering shrubs and weeds), grasses (Poaceae > 50 µm), *Waltheria* (flowering mallow), and Solanaceae (nightshades) appear. Layer C has a high richness score, meaning plant diversity (although not necessarily crop diversity) increased from previous phases. Meanwhile, layer B is a transitional layer, exhibiting the presence of water-loving species, alongside invasive plants.

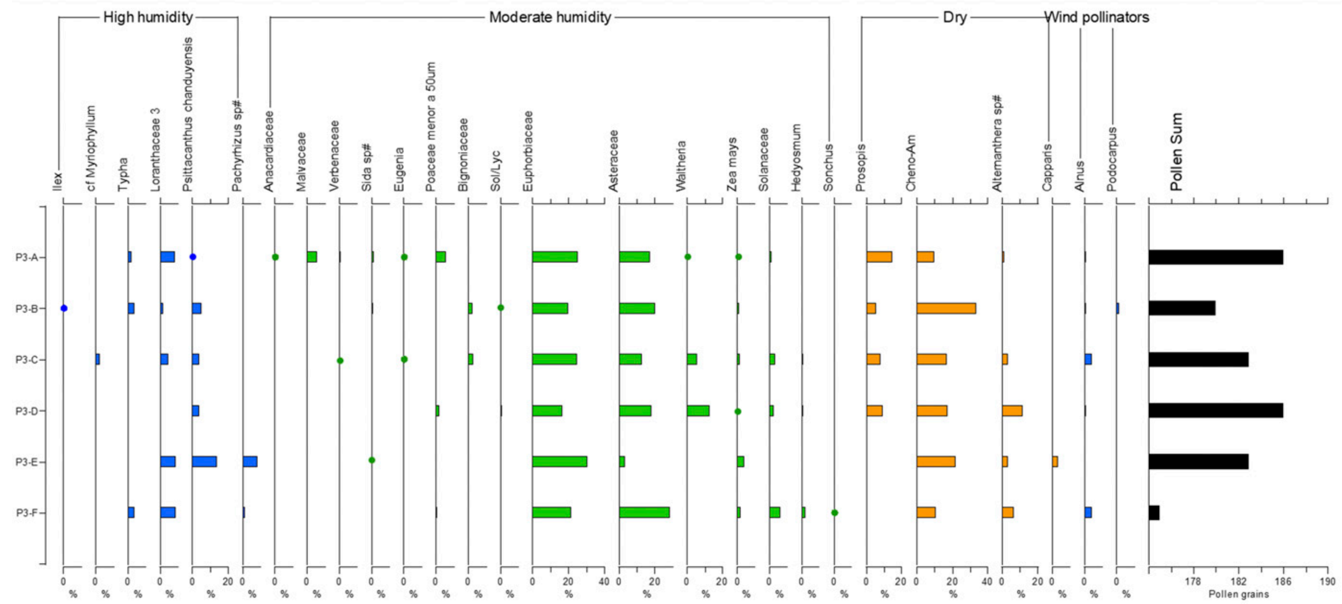
Finally, layer A represents another increase in species diversity (S) and in humidity-loving species, including cattail (*SI Appendix*, Figs. S2). Moreover, many of the plants that appear in this layer are known as "first responders," plants with extensive seed banks and long dormant periods that react when water suddenly enters the environment (103). In the P3 record, these include *Sida*, Verbanaceae, and several members of Asteraceae.

Even today, the north coast deserts undergo spectacular vegetative transformations in the aftermath of El Niño flooding due to seed banks that have accumulated over time (103, 104). During the 1982/1983 and 1997/1998 "El Niño" events, rainfall reached 25 times the norm (103, 105). This pulse of water resulted in an over 100% increase in vegetative ground cover, with staggered appearances of fast-growing herbaceous plants, followed by shrubs, and finally trees (106).

[†] *Ilex* is native to the Eastern slopes of the Andes and Amazonian regions of Ecuador, Colombia, and Peru; however, at least one species has been identified in the Departament of La Libertad, and evidence suggests it was traded as a medicinal product in the prehispanic period. Therefore, *Ilex* was included in the statistical analysis of P3 (100–103).

[‡] Although cattail can be used as a fiber and its edible rhizome may have been collected as a food resource, there is little evidence that this plant was actively managed for its caloric value in the Pampa de Mocan (102).

Table 1. P3 pollen data



The *y*-axis labels the sample from each layer from the P3 feature. Taxa are grouped based on their typical environmental conditions. Bars represent the relative abundance of each taxa (number of pollen grains of taxa/pollen sum of sample). Circles are used when the relative abundance is less than 1%.

In 2017, the event known as the El Niño Costero affected the north coast and the Pampa de Mocan (50). Floodwaters on the Pampa were confined to incised channels in the proximal portion of alluvial fans, while the lower bajada experienced overbank flooding and the deposition of sediment and organic detritus. In the first months after the event, the Pampa de Mocan experienced an El Niño blooming period and the PAAPM carried out the first systematic collection of El Niño-related plant species for this area. The collection consisted of 37 species, more than 80% of which appeared in the aftermath of the 2017 El Niño Costero (Table 2). El Niño-bloom plants included wild tomatoes, flowering herbs, gourds, and legumes, along with sturdy shrubs, young trees such as *Capparis* (also known as caper bush or sapote), and algarrobo.

Although the datasets differ in taxonomic precision, many families and some species identified in layer A of the P3 feature also appeared as part of the 2017 El Niño bloom. The overlap exhibited between layer A and the 2017 plant collection suggests that layer A can be identified as an El Niño blooming phase.

The pollen data from P3 reflect the environmental dynamism that resulted from El Niño flooding on the Pampa in prehistory. The presence of maize in each of the layers suggests that farming activities continued even during the episodic appearances of runoff on the Pampa de Mocan. Farmers would have benefitted from the secondary effects of ENSO flooding: Higher water table, flushing out of salts, faunal migration, and new plant growth. However, the archaeological record also demonstrates that farmers directly benefitted from El Niño floodwaters on the Pampa.

Archaeological Evidence of Floodwater Farming. Previous researchers hypothesized that the Pampa de Mocan was never successfully developed for agriculture in prehispanic times, due in part to challenging environmental conditions (96, 107). However, the PAAPM identified habitation sites with stratified midden features, agricultural tools, such as clod-breakers, and a variety of field-systems with clear evidence of use and modification across the area that span a 2,000-y occupation. The examples presented below date to the Late Intermediate Period (AD 1000 to 1476), the Middle Horizon (AD 600 to 1000), and the Early Intermediate Period (AD 1 to 600), respectively.

Agricultural practices in arid environments with a predictable rainy season often include floodwater farming, which involves water capture and distribution through devices such as check-dams, diversion canals, and prepared fields. On the north coast, rainfall occurs during particularly strong El Niño events and these are both aperiodic and spatially unpredictable (47), occurring as frequently as every 6 to 7 y or as infrequently as every 10 to 20 y (44–46). The evidence collected from the Pampa de Mocan suggests that floodwater farming technologies nonetheless were integrated into the perennial river-based canal system.

In the Pampa de Mocan, trunk canals carrying river water crossed numerous ephemeral stream channels that descended from the adjacent quebradas. During El Niño events, these trunk canals would have been cut off from the river source due to flood damage to intakes along the riverbanks. Over time, multiple trunk canals in the Pampa de Mocan became inactive. Inactive canals were identified archaeologically by dating agricultural fields located in the canal bed or in stream channels that breached canal lengths. These defunct riverine canals—still monumental features on the landscape—were converted into floodwater-diversion canals. As El Niño runoff flowed down the bajada, it was captured, diverted using these inactive canals, and directed to prepared floodwater fields.

Evidence for El Niño floodwater farming, or El Niño agricultural opportunism, is embedded in three field types in the Pampa de Mocan: Embankment fields, border-strip fields, and rockpile fields.

Field Types. Embankment fields are defined here as a level area of cultivation bordered by a bund, or low mound, where runoff flow and organic debris are collected (108). Floodwaters reached the embankment via small ephemeral streams and an inactive trunk canal; the Late Intermediate Period embankment in Fig. 3*A* was fed by Canal C, which had been inactive since in the Early Intermediate Period, as evidenced by Early Intermediate Period fields placed within the canal bed further upstream. In this same example, the organic-rich sediments and debris in floodwater

Table 2. Plants collected in the Pampa de Mocan in the months after the 2017 El Niño Costero event and potential overlap with pollen identifications from P3 layer A

	Family	Species collected in 2017	Possible overlap with P3 layer A
1	Amaranthaceae	*Althernanthera halimifolia*	*Althernanthera sp#*
2	Amaranthaceae	*Alternanthera peruviana*	*Althernanthera sp#*
3	Amaranthaceae	*Amaranthus haughtii*	Cheno-Am
4	Amaranthaceae	*Atriplex rotundifolia*	Cheno-Am
5	Apocynaceae	*Matelea aliciae*	
6	Asteraceae	*Encelia canescens*	Asteraceae
7	Asteraceae	*Isocarpha microcephala*	Asteraceae
8	Boraginaceae	*Heliotropium angiospermum*	
9	Boraginaceae	*Tiquilia dichotoma*	
10	Boraginaceae	*Tiquilia paronychioides*	
11	Bromeliaceae	*Vriesea cereicola*	
12	*Capparaceae	**Cappacoricordis crotonoides*	
13	*Capparaceae	**Capparis avicennifolia*	
14	*Capparaceae	**Capparis scabrida*	
15	Cucurbitaceae	*Luffa operculata*	
16	Euphorbiaceae	*Chamaesyce serpens*	Euphorbiaceae
17	Leguminosae	*Dolichos purpureus*	
18	Leguminosae	*Hoffmannseggia viscosa*	
19	Leguminosae	*Macroptilium lathyroides*	
20	*Loranthaceae	**Psittacanthus chanduyensis*	*Psittacanthus chanduyensis*
21	Martyniaceae	*Proboscidea altheifolia*	
22	Nyctaginaceae	*Allionia incarnata*	
23	Nyctaginaceae	*Boerhavia verbenaceae*	
24	Nyctaginaceae	*Commicarpus tuberosus*	
25	Nyctaginaceae	*Cryptocarpus pyriformis*	
26	Oxalidaceae	*Oxalis dombeyi*	
27	Plantaginaceae	*Galvezia fruticosa*	
28	Poaceae	*Aristida* sp.	Poaceae > 50 μm
29	Plantaginaceae	*Scoparia dulcis*	
30	Polygalaceae	*Monnina herbacea*	
31	Solanaceae	*Exodeconus postratus*	Solanaceae
32	Solanaceae	*Lycopersicon pimpinellifolium*	Solanaceae
33	Solanaceae	*Nicotiana glutinosa*	Solanaceae
34	Solanaceae	*Nicotiana plumbaginifolia*	Solanaceae
35	Solanaceae	*Solanum* sp.	Solanaceae
36	Verbenaceae	*Lantana svensonii*	Verbenaceae
37	Zygophyllaceae	*Tribulus longipetalus*	

Those taxa that were identified both as a part of the El Niño-related bloom and in pre-2017, non-El Niño years are marked with an asterisk (*). Identifications carried out by Luis R. Huaman Mesia, Director of the Herbario HUPCH "Magdalena Pavlich" of the Universidad Peruana Cayetano Heredia (Inistitucion Cientifica Nacional Depositaria de Material Biológico y Registro de material biológico de flora silvestre: Número de Registro Nacional 004 y Resolución de Dirección General N 197-2016-SERFOR/DGGSPFFS del Ministerio de Ambiente del Perú).

settled out of suspension and crops were planted in fields placed within the embankment. Embankment fields were also filled with rockpiles, used to slow the velocity of water before distributing it to nearby fields (Fig. 3*C*).

Border-strip fields were also designed for the application of El Niño runoff. In several examples of this field type, natural stream channels were cleared, and their banks reinforced with cobbles and boulders to direct flow to these fields (Fig. 3*B*). Border-strip fields consist of long terraces, often arranged parallel to the direction of slope, and separated by low bunds or stone-piled borders. Floodwater runoff was directed to these strips, where the slowed sheet flow allowed silts and organic debris to settle in each section. These fields are irrigated through a ditch at the top of the field and are more common in areas of low gradient (0.1 to 1.0%) (96).

In the Pampa de Mocan, these fields were laid out to accommodate the location of the alluvial fan channels, surface characteristics, and slope. For example, the border-strip field system of Fig. 3*B* was fed from water first collected in an embankment field. Collecting the runoff first in the embankment allowed the water to reach the border strips at a lower velocity. This same field was sampled for microfossil analysis. Starch grains included *Phaseolus* sp. (beans) and phytolith analysis reveal the presence of grasses (Festucoideae) and diatoms pointed to the presence of standing water.

A third type, rockpile fields, are found throughout the Pampa de Mocan (Fig. 3*C*). Rockpile fields, also known as mounded heaps or "grape mounds," are known in the Sonoran and Negev deserts (109–112), although they have not been well-studied in the Peruvian context. While sometimes confused as the product of field-clearance, these fields serve several functions in the context of runoff farming. The clearance of stones and piling into mounds allows floodwater to move downslope in the desired direction while minimizing water loss. The mounded stones also trap silts, sediments, and organic debris suspended in floodwaters. Fish et al. (113), in their excavations of rockpiles in the Sonoran Desert, found evidence for cultivation of *Agave Americana*, also known as maguey (114). Evenari et al. (109) and Lahav and Steinberger's (115) studies of rockpile fields in the

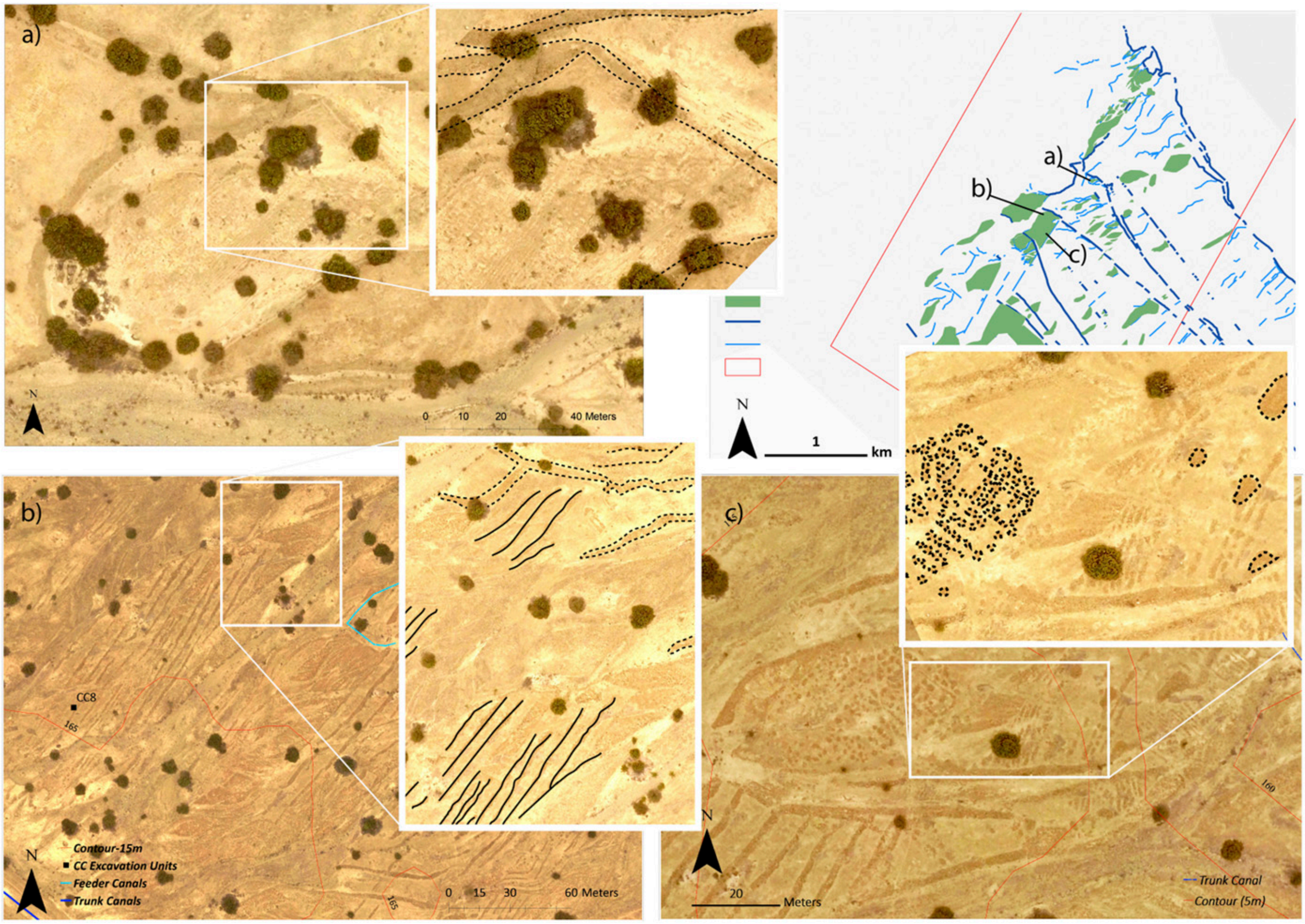


Fig. 3. Floodwater fields of the Pampa de Mocan and *Inset* of preserved fields systems. (*A*) Embankment field with *Inset* showing serpent-shaped field furrows within embankment and stone-reinforced banks of natural channel. (*B*) Border-strip fields with *Inset* highlighting stone-reinforced natural channel banks. (*C*) Rockpile fields within an embankment field.

Negev prove that these features encourage biotic activity by increasing moisture retention and preventing erosion.

During El Niño events, floodwater runoff flowed down ephemeral alluvial fan channels. Ancient farmers directed floodwater runoff using inactive riverine trunk canals, small dams and rockpiles, and even stream channels reinforced with stone-piled bunds, toward the three types of floodwater fields. Unlike fields prepared for the delivery of river water in canals, these fields were constructed to withstand and take advantage of the unique characteristics of alluvial fan flooding, such as its high energy, rich silts, and organic debris. These floodwater fields would have been under production precisely at a time when parts of the active river-based irrigation system would have been disrupted. Pampa de Mocan farmers, and likely ancient farmers elsewhere in coastal Peru, built flexible irrigation systems that allowed them to alternate between river water distribution and runoff harvesting.

Discussion

The equilibrium concept casts society and the environment in passive roles, while El Niño is considered a disruptive, external force capable of up-ending otherwise stable conditions. Consequently, scholarly debate has centered on the scale of events as a proxy for thresholds, rather than on the variability of responses or their historical contingency. However, in recent decades, ecologists have moved toward a so-called 'new ecology' that models nonequilibrium dynamics rather than closed systems progressing toward stability (116–118). This approach recasts those components previously considered outside noise, random fluctuations, or external disruptions, as part of the norm. The equilibrium concept—once so pervasive that it was considered a paradigm (93)—has been largely replaced in the environmental sciences, but it continues to dominate theoretical approaches to human–environment interactions (6, 7, 40, 119).

Instability is the norm in the Pampa de Mocan. Long-term processes of erosion, aggradation, and aeolian transport occur in the landscape alongside aperiodic events, such as El Niño, seasonal changes in river volume and cloud cover, anthropogenic effects, tectonic uplift, and in recent decades, global warming. Moreover, these processes combine with the enduring effects of landesque capital, such as canals, ditches, fields, and dams, to form constantly new landscapes, which are in turn encountered and managed by each subsequent generation of farmers (67, 120, 121). In light of these ongoing and concurrent factors, El Niño appears to be less of a system-outlier, and instead, a part of the normal conditions of the north coast environment (116–118, 122, 123). The archaeological remains of the Pampa de Mocan irrigation system reflect this reality: Ancient agriculturalists constructed canal networks that incorporated floodwater farming technologies. The irrigation system was designed to flexibly transition from river water distribution during non-El Niño years to floodwater diversion and harvesting during coastal flood events.

Despite the dominant belief that arid lands are marginal and vulnerable to natural disasters (93), evidence from the Pampa de Mocan suggests that these landscapes are highly pliable, including during El Niño events. Ancient pollen data demonstrate the dynamism of human–environment interaction on the Pampa de Mocan and confirm that, rather than resulting in widespread system disruption or collapse, El Niño was an integral part of the system. El Niño events can range from weak to strong and their effects vary accordingly. Very strong El Niños, with 7 to 12 °C warmer near-coastal water temperatures, have long-lasting impacts on the rural and urban landscape, fisheries, and agriculture (45, 46). These aperiodic events can cause extensive damage to canal systems, destroying intakes, breaching canals along their length, flooding fields, and changing the course of the river (91, 124). But El Niño can also provide a flux of water and sediment in an otherwise desiccated environment and bring about blooming events that stimulate dormant ecosystems. Ancient farmers in the Pampa de Mocan engineered interventions to convert high-energy flow into productive resources, including fine sediments, organic material, and irrigation water, which further modified local conditions, even long after abandonment. Twenty-eight percent of the prehispanic fields recorded in the PAAPM project universe were developed for floodwater or opportunistic farming; if that metric were true for the entire expanse of the Pampa de Mocan, it could be estimated that 1,600 ha of this segment of the Chicama Valley was dedicated to floodwater farming. Meanwhile, according to the Peruvian authority INDECI (Instituto Nacional de Defensa Civil), the Ascope Province lost a total of 7,661 ha of agricultural land during the most recent 2017 El Niño (125). The archaeological data from the Pampa de Mocan suggest that large areas of the modern coastal landscape represent untapped risk-management resources.

Today, the lower Chicama Valley is dedicated to sugarcane (*Saccharum officinarum*) farming. Almost all remaining smallholders are dependent on a single industrial producer for the distribution of water via canals. Consequently, the 2017 El Niño Costero temporarily brought agricultural activity in the valley to a halt. In fact, the widespread destruction caused by the 2017 event, and the state's policy for economic recovery in the aftermath, embody the idea of "punctuated equilibrium" (39). During recent El Niño events, however, examples of floodwater farming were observed (15, 126). Similarly, the PAAPM recorded several modern-day floodwater fields in the months after of 2017 El Niño Costero.

During the 2017 ENSO event, first- and second-order ephemeral streams formed small ponds as floodwater collected behind the ancient adobe construction of the Ascope aqueduct. As waters receded, local farmers established fields of maize, beans, and squash in the sedimentary build-up (Fig. 4). These are modern-day versions of embankment fields, fed entirely by runoff and planted in the layers of silt and organic detritus carried by floodwater. The 2017 event offered two insights: That the equilibrium concept may better describe the modern-day scenario, one of highly centralized and industrial-level agriculture; and that some of the strategies of resilience farming identified in the ancient Pampa de Mocan continue to relieve stress caused by El Niño floods on the conventional irrigation system today.

On the north coast, when ENSO is modeled as one variable among many in a local environment characterized by the constant reorganization of variables, a suite of technologies, adaptations, and water management strategies become evident and these have implications for interpretations of the past and for preparing for natural disasters in the present and future. The Pampa de Mocan represents a highly flexible, hybrid riverine-floodwater irrigation system that can serve as a model for modern agricultural systems as they are forced to adapt to a new environmental "normal" in the face of climate change.

Fig. 4. Modern-day examples of floodwater fields located upstream southeast of the Pampa de Mocan. (*A*) Unmanned aerial vehicle photograph of erosional gullies filled with floodwater from the 2017 El Niño Costero dammed by the prehispanic Ascope aqueduct. (*B*) View of 2017 floodwater-fed field from the Ascope aqueduct. (*C*) Ground view of 2017 floodwater field of maize, beans, and squash.

Materials and Methods

The PAAPM was carried out over 5 y (2012 to 2017) to record the prehispanic agricultural landscape and irrigation system of the Pampa de Mocan. Archaeological fieldwork, including a first phase of complete pedestrian survey and surface collection, followed by a second phase of 18 excavation units focused on irrigation features, domestic contexts, and field systems. Archaeobotanical samples from field systems and one water storage feature (P3) were analyzed; field systems were tested for microbotanical remains, including phytoliths and starch grains, and P3 was processed for pollen remains (127, 128). Finally, the results of environmental reconstruction from ancient fields and P3 were later compared to modern-day vegetative communities in the area, both in non-ENSO years (2016) and in the midst of the 2017 El Niño Costero-related blooming event.

Dating in the Pampa de Mocan. Fluvially active landscapes such as the Pampa de Mocan present unique challenges to absolute dating. Water transport makes determining the origin of organic material found in canal beds and in canal cleaning features extremely difficult. While optically stimulating luminescence sampling can yield solutions to the issue of canal dating (129), the

PAAPM relied solely on relative dating with diagnostic ceramic types in secure contexts to establish the chronology referenced in this study (18, 130–137).

Irrigation System of the Pampa de Mocan. The PAAPM identified eight trunk canals (A to H) in the Pampa de Mocan, each of which had been modified at different times in prehistory (Fig. 1). Seven of these canals had been previously identified by Richard Watson through observations of aerial photographs (96). Claude Chauchat et al. (138), Leonard and Russell (139), and Thomas Pozorski (107) also confirmed the existence of these trunk canals. The PAAPM determined that each canal had several distinct use-lives and were deemed unreliable chronological proxies. Instead, diagnostic ceramic material derived from fields surfaces and excavations were the sole reference for evaluating age.

Field systems across the Pampa de Mocan were covered in ceramic sherd scatter, possibly deposited with household middens, and in some cases as a strategic method for moisture retention, known elsewhere as “lithic mulch” (140, 141). Overall, the field systems exhibited shallow time depth. Over the 235 ha of field systems studied in detail by the PAAPM, none exhibited more than one archaeological-culture ceramic type, and excavations revealed infrequent reuse of the same field. The combination of shallow use-lives and discrete ceramic types indicates that fields were used and discarded over short periods, likely after a few seasons, and rarely if ever cross-culturally reused. This characteristic of field-use also allowed for the recognition of inactive trunk canals that were used in floodwater irrigation.

Archaeobotanical Collection and Analysis. Plant life in the Pampa de Mocan in ENSO-neutral and cold-phase years is restricted to xerophytic communities of cacti, desert scrub, sapote trees (*Capparis*), and algarrobo (*Prosopis*) stands. However, during El Niño years, the desert converts to an herbaceous meadow-like environment, a phenomenon known as a blooming event.

Archaeobotanical sampling in the Pampa de Mocan revealed diachronic patterns of both environmental change and agricultural practices. Field systems were sampled for both phytoliths and starch grains, while P3 was tested for pollen grains. The modern-day irrigation landscape just west and south of the Pampa de Mocan is dominated by the agro-industrial production of sugar cane, however, no sugar cane pollen or other nonindigenous plants were identified in the samples.

Data Availability. All study data are included in the main text and *SI Appendix*.

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