Long-term human response to uncertain environmental conditions in the Andes

Tom D. Dillehay[*][†] **and Alan L. Kolata**[†][‡][§]

[*]Department of Anthropology, University of Kentucky, Lexington, KY 40506; and [‡]Department of Anthropology, University of Chicago, Chicago, IL 60637

Communicated by Michael E. Moseley, University of Florida, Gainesville, FL, January 30, 2004 (received for review March 23, 2003)

Human interaction with the physical environment has increasingly transformed Earth-system processes. Reciprocally, climate anomalies and other processes of environmental change of natural and anthropogenic origin have been affecting, and often disrupting, societies throughout history. Transient impact events, despite their brevity, can have significant long-term impact on society, particularly if they occur in the context of ongoing, protracted environmental change. Major climate events can affect human activities in critical conjunctures that shape particular trajectories of social development. Here we report variable human responses to major environmental events in the Andes with a particular emphasis on the period from anno Domini 500–1500 on the desert north coast of Perú. We show that preindustrial agrarian societies implemented distinct forms of anticipatory response to environmental change and uncertainty. We conclude that innovations in production strategies and agricultural infrastructures in these indigenous societies reflect differential social response to both transient (El Niño–Southern Oscillation events) and protracted (desertification) environmental change.

The desert coast of Perú is a fragile habitat subject to multiple transient and longer-term environmental impacts (1, ¶). These impacts include tectonic activity that drives coastal uplift, occasional catastrophic earthquakes, episodic droughts of variable intensity and duration, long-term desertification generating massive dune fields, and El Niño–Southern Oscillation (ENSO) events that induce coastal flooding (3, 4, ¶). In our study, environmental uncertainty refers to the cumulative effects of sequential impact events on human decision-making and adaptation. These geo-climatic processes can occur serially and may generate potentially catastrophic changes in the landscape, as well as induce transformations in the social organization of regional populations (5–7).

Documenting the frequency, duration, and severity of such impact events is important, but their sequence of occurrence is also of critical concern (8). Historic records indicate that El Niños occur at a frequency of 2–10 years (9) with durations that range from 2 to 6 years. In the 297-year period from 1690 to 1987, for instance, El Niño events occurred in 87 years (10, 11). These events often trigger significant Peruvian coastal flooding and related social disruption of variable intensity. Catastrophic floods that devastate agricultural and transportation infrastructure are not uncommon (e.g., the significant disruptions occasioned by the 1925 and 1982–1983 El Niños). Severe El Niños, such as the 1982–1983 event, are also correlated with intense, short-term droughts in the southern Andean highlands (3).

Protracted (i.e., multiyear and multidecade) droughts in the Central Andes (the highlands and desert coastal regions of Perú) and the Andean altiplano (the high plateau of extreme southern Perú and northwestern Bolivia) occur with less frequency but generate significantly greater, longer-term problems for humans adapting to these rigorous environments. Evidence for widespread, regional droughts between anno Domini (A.D.) 524 and 540, A.D. 563 and 594, A.D. 636 and 645, and A.D. 1245 and 1310 has been derived from the Quelccaya ice core in southern Perú (3, 12, 13). The evidence for the A.D. 1245–1310 drought was corroborated by geo-chemical, isotopic, and pollen analysis of sediment cores taken from Lake Titicaca (14), although the lake core data indicate that the onset of this drought in the Andean altiplano occurred approximately one century earlier, *ca.* A.D. 1150. In the five decades after the mid-12th century onset of this drought, the level of Lake Titicaca dropped between 12 and 17 m. By employing a simple climate–water budget model, we calculated that a 10–12% decrease in net precipitation from the modern average could cause a decline of this magnitude in the lake level (14, 15).

Such protracted droughts occasioned both significant social disruptions and innovative cultural, demographic, and technical adaptations among indigenous societies in the Andes. The severe aridity during the period from the mid-12th century to the early 14th century was the proximate cause for the disintegration of the pre-Inca state of Tiwanaku centered along the southern shores of Lake Titicaca (14, 16). Between A.D. 1150 and 1200, Tiwanaku cities and their sustaining farms were abandoned when populations dispersed as a result of drastically reduced agricultural productivity. Tiwanaku as an agrarian society invested heavily in an intensive system of water-dependent cultivation termed raised-field agriculture (17, 18). With the onset of this protracted drought, stream flow and groundwater levels were significantly reduced. Tiwanaku's extensive regional landscape of raised fields (>19,000 hectares in the city of Tiwanaku's immediate sustaining hinterland alone) became unsustainable (15). In response to this protracted drought, formerly urbanized populations became more mobile and adopted a lifestyle that emphasized pastoralism based on native, drought-adapted camelids (llamas and alpacas) and opportunistic dry farming (15).

Droughts of such duration can be punctuated by ENSO events associated with significant coastal rains. Convergent climatic and environmental events such as these can impose significant constraints on a society's ability to respond to such changes. Individual events, such as excessive flooding, may have relatively small immediate impact. But occurring simultaneously (the case of drought punctuated by ENSO events) or in series, they can induce a cascade of cumulative, small-scale effects over a period of decades that set the conditions for future human adaptations (13). That is, these cumulative effects structure the landscape in ways that partially determine the nature and extent of future human responses to such environmental uncertainty.

Postimpact landscape alterations can be more severe, or potentially more beneficial, than the event itself. A specific environmental event or change in resource base may elicit varied responses from different population segments (19). In addition, a severe impact event can be detrimental to some sectors of society, and an opportunity for others. For instance, heavy ENSO-generated rains can devastate permanent irrigation sys-

---

Abbreviations: A.D., anno Domini; ENSO, El Niño–Southern Oscillation.

[†] T.D.D. and A.L.K. contributed equally to this work.

[§] To whom correspondence should be addressed at: Department of Anthropology, University of Chicago, 1126 East 59th Street, Chicago, IL 60637. E-mail: a-kolata@uchicago.edu.

[¶] Moseley, M. E., Tapia, J., Satterlee, D. & Richardson, J. B., III (1992) in *Paleo-ENSO Records, International Symposium, Extended Abstracts*, eds. Ortlieb, L. & Machare, J. (ORSTOM, Lima), pp. 207–212.

tems and fixed agricultural fields but stimulate opportunistic groundwater agriculture in low-lying areas of the desert and increase grazing opportunities for ruminant herd animals in normally arid upland zones.

Events of environmental uncertainty are not entirely outside the potential for human recognition and anticipatory response. That is, these are knowledge conditions of partial, not complete, uncertainty. We assume that ENSO events, as repeated and noninstantaneous phenomena, were experienced, monitored, and responded to by human populations through cumulative, generational response mechanisms. In premodern times, these events may even have been predicted to the extent that their effects were anticipated by populations through identification of specific environmental precursors to the ENSO phenomenon, such as changes in marine species and other natural regimes that signal oncoming changes (20). Similarly, longer-term environmental changes such as desertification and dune migration were relatively slow processes that permitted anticipatory human response over a temporal scale of generations.

We have studied instances of environmental instability and the history of human decision-making under conditions of partial uncertainty on the Peruvian north coast, particularly during the period from *ca.* A.D. 500 to 1500. Indigenous, urban-based polities economically dependent on large-scale irrigation agriculture emerged in the region during this period. Although spanning the entire range of human occupation of the north coast, our research focuses particularly on the socially complex cultures designated as Moche and Chimú. Moche populations were organized as autonomous, competing polities in the period from *ca.* A.D. 100 to 750. Moche as a distinctive cultural phenomenon disappears *ca.* A.D. 800. During the post-Moche period (*ca.* A.D. 800–1000), the Chimú began to consolidate and centralize political authority. Between *ca.* A.D. 1200 and 1470, they dominated a large expanse of the north and north central Peruvian coast. Subsequently, the Inca Empire conquered and politically assimilated the Chimú state in the late 15th century.

Our specific study area is the Jequetepeque River valley and adjacent areas in the Chaman and Zaña river drainages (Fig. 1). A broad, incised riverbed flanked by alluvial plains and coastal hills that rise steeply to ≈800 m characterizes this valley. The climate on the coastal plain is dry and warm (21, 22). Mean annual precipitation is 23 mm/year. River discharge is highly variable and directly dependent on precipitation in adjacent highland watersheds. Despite the extreme aridity of the coast, the valley provides access to a broad spectrum of natural resources. Fertile agricultural land is abundant in the valley floor and on irrigable desert plains. The riparian environment, coastal lagoons, and ocean littoral are rich breeding grounds for fish, shellfish, and other aquatic resources.

Archaeological Evidence of the Nature, Scale, and Frequency of Geo-Climatic Events

Our research results demonstrate that episodic valley-wide floods and droughts, as well as longer-term deforestation, dunation, and desertification processes, occurred at numerous sites in our research area. Evidence derives from conventional and accelerator mass spectrometry radiocarbon dating of occupational floors in multiple residential sites associated with diagnostic Moche, post-Moche, and Chimú artifacts, and in related geomorphological features (Table 1).[‖] ^{14}C assays from sealed excavation contexts in strata associated with substantial rebuilding episodes at the archaeological sites of Farfán Sur, Cañoncillo, Talambo, and JE-1 dated four major ENSO events to *ca.* 2150 B.C., A.D. 500, A.D. 1230, and A.D. 1770 (Fig. 2). This latter date corresponds with the historically documented El Niño of A.D. 1770 that caused significant economic losses among the agricultural populations along Perú's north coast (23). Other flood events that appear in the archaeological record have been dated through association with diagnostic ceramics, but have not yet been radiocarbon dated (19). Stratigraphic profiles taken from excavations in 34 sites in the Jequetepeque Valley reveal consistent patterns of periodic flooding (as evidenced by thick colluvial or alluvial deposits of rock and sorted gravel), dunation events (as evidenced by clean, aeolian sand deposits), and habitation use and abandonment cycles (as evidenced by sequential prepared habitation floors intercalated with natural water-borne and sand deposits). Although the extent of physical damage from these events was widespread throughout the study area, impact severity was localized and varied significantly in terms of effects, depending on local hydrology, slope, and topographic characteristics.

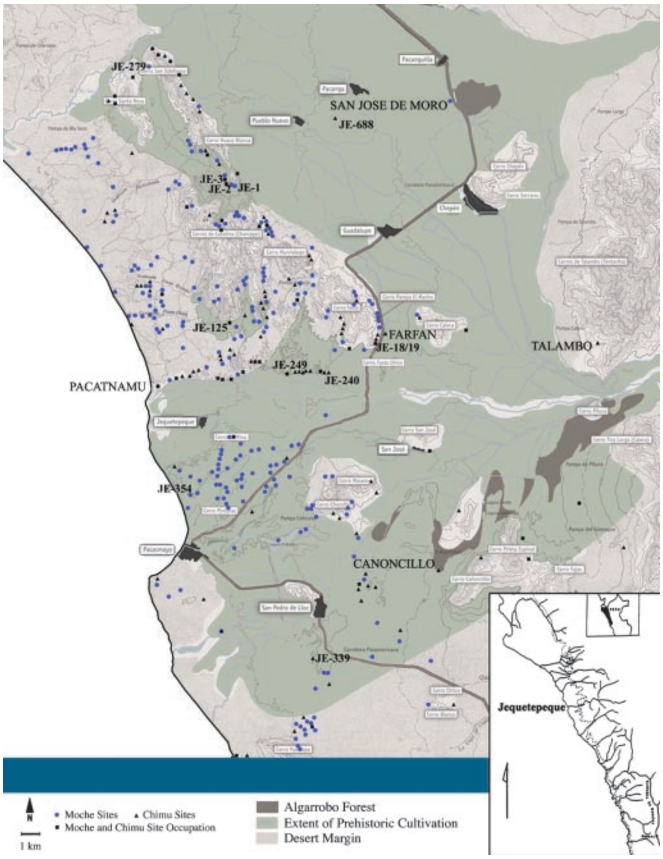

Fig. 1. Map of the Jequetepeque Valley, Perú, with the location of the principal Moche- and Chimú-period settlements

---

[‖] In sealed contexts from multiple excavated sites, archaeological evidence for ENSO events consists of thick (20–80 cm) colluvial and/or alluvial deposits of rock, sorted gravel, and fine-grained silt. In larger sites with substantial standing architecture, such as Cañoncillo, Talambo, and Farfán Sur, destroyed, water-churned adobe walls interdigitated with deposits of rock and sorted gravel appear in multiple excavations. In addition, several areas of the Jequetepeque Valley and the adjoining Chaman and Zaña river valleys exhibit geomorphological evidence of mass wasting that can be attributed to one or more sustained episodes of ENSO-driven rainfall. We have temporally correlated this geomorphological evidence for mass wasting with the archaeological record within the resolution permitted by multiple ^{14}C accelerator mass spectrometry dates. We anticipate that ongoing paleolimnological and geomorphological research will generate more highly resolved temporal associations and more accurately delineate the spatial scale and landscape effects of these ENSO events. Dunation and desertification events clearly indicated by massive, clean aeolian sand deposits occur in the archaeological record of multiple sites, particularly on the south side of the Jequetepeque Valley.

Table 1. Radiocarbon dated events of major flooding at excavated archeological sites in the lower Jequetepeque Valley

Site no.[*]	Context	Conventional age, years	Calibrated age	Sample no.
JE-205[†]	Occupation layer	4,190 ± 40 B.P.	B.C. 2895–2610	Beta-109092
JE-205	Occupation layer	2,560 ± 50 B.P.	B.C. 840–520	Beta-109091
JE-354	Occupation layer	2,530 ± 50 B.P.	B.C. 805–485	Beta-109089
JE-205	Occupation layer	2,520 ± 50 B.P.	B.C. 800–415	Beta-117746
JE-205	Occupation layer	2,370 ± 50 B.P.	B.C. 530–375	Beta-117747
JE-125	House floor	1,520 ± 60 B.P.	A.D. 415–650	Beta-143883
JE-339	House floor	1,370 ± 70 B.P.	A.D. 560–780	Beta-143885
JE-273	Platform floor	770 ± 50 B.P.	A.D. 1185–1295	Beta-143884
JE-1	Platform floor	720 ± 40 B.P.	A.D. 1180–1230	Beta-109093
JE-18	House floor	710 ± 40 B.P.	A.D. 1245–1390	Beta-109090
JE-2	House floor	700 ± 60 B.P.	A.D. 1235–1400	Beta-114185
JE-240	Buried furrow	670 ± 70 B.P.	A.D. 1245–1420	Beta-114186
JE-19	House floor	640 ± 40 B.P.	A.D. 1285–1405	Beta-143880
JE-249	House floor	640 ± 70 B.P.	A.D. 1265–1425	Beta-114187
JE-19	Platform floor	620 ± 40 B.P.	A.D. 1290–1410	Beta-143879
JE-619	House floor	620 ± 50 B.P.	A.D. 1280–1420	Beta-161940
JE-3	House floor	580 ± 70 B.P.	A.D. 1285–1445	Beta-143882
JE-688	House floor	230 ± 40 B.P.	A.D. 1640–1690	Beta-161941
JE-205	Flood deposit	180 ± 50 B.P.	A.D. 1650–1950	Beta-109092

B.C., before Christ.

[*] All dates are single chunks of charcoal taken from intact strata with archeological floors and/or features that lie either directly under or over major outwash deposits.

[†] JE-205 corresponds to the urban center of Cañoncillo.

Buried dunes and severely deflated surfaces indicate indirect evidence of drought conditions. Prolonged drought conditions were more detrimental to sustained agriculture than transient ENSO events. We documented the widespread presence of multistratified paleodunes particularly on the south side of the Jequetepeque Valley. Here, extraordinary examples of barchan sand dunes extend from the coast into the mid-valley region some 25 km inland (Fig. 3). These paleodunes exhibit ancient cultivation and habitation surfaces interbedded with aeolian sand and major but intermittent outwash deposits. The earliest evidence of these barchan dunes dates to the Moche period occupations of the 6th century, and therefore may be correlated with the droughts of A.D. 524–540, A.D. 563–594, and perhaps A.D. 636–645 (3, 13, 24). However, the most extensive spatial development of these dune systems is associated with the middle Chimú period in the mid-13th century, clearly cooccurring with the protracted drought of A.D 1245–1310 (14). The major Chimú site of Cañoncillo was abandoned by the late-14th century, possibly as a result of massive dune encroachment on the urban environment.

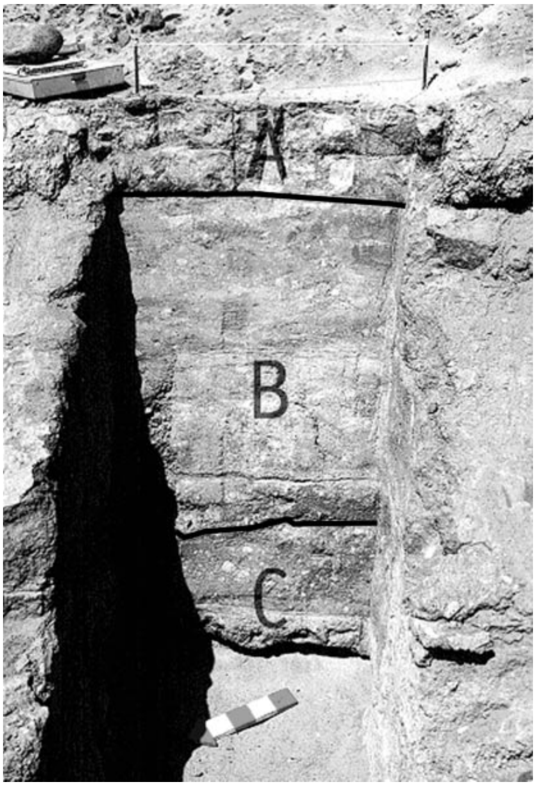

Fig. 2. Stratigraphic profile of archaeological excavation locus at the Chimú urban center of Cañoncillo. A and C show eroded adobe deposits resulting from major El Niño impact events. B illustrates a rebuilding phase represented by an adobe wall foundation.

Consistent stratigraphic patterns imply repeated episodes of flood impact events alternating with this dune development sequence. Our research revealed sand sheets and dune formations that choked irrigation canals, buried old cultivation surfaces, and covered residential structures. We also documented episodes of large-scale labor mobilization to reconstruct damaged buildings and agricultural infrastructures, particularly at the urban sites of Farfán Sur and Cañoncillo. Indigenous populations rapidly reconstructed agricultural infrastructure and urban architecture after ENSO events but were ultimately unable to respond effectively to longer-term processes of desertification.

These complex stratigraphic relationships indicate a long-term, regional pattern of repeated shifts in human occupation at both urban and rural sites in the valley. Changes in agricultural management practices along with demographic, social, and economic reorganization of populations, especially in the Late Moche (A.D. 600–750) and Middle to Late Chimú (A.D. 1200–1470) periods, are associated with distinct environmental impact events (both ENSO and drought conditions). Yet the nature of social response to transient and protracted environ-

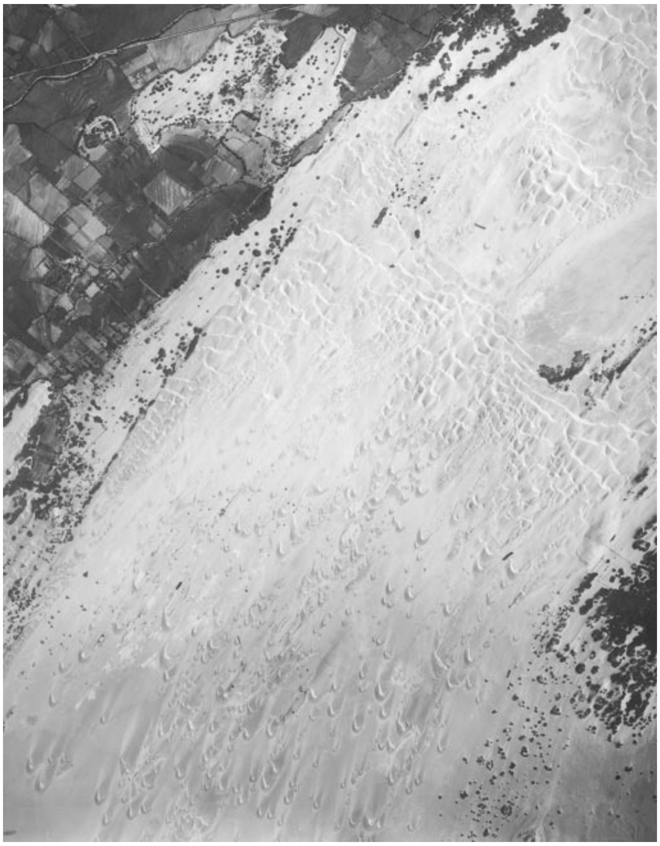

Fig. 3. Aerial photograph of dunation processes on the south side of the Jequetepeque Valley. Note the extensive field of active barchan sand dunes.

mental change varied significantly between the Moche and Chimú, illustrating variability in effective human adaptation to environmental uncertainty.

Social and Technological Response to Environmental Uncertainty

The repertoire of social and technological responses to environmental uncertainty in north coastal Perú was diverse and ranged from relocation or periodic abandonment of agricultural lands affected by environmental impacts to large-scale technological interventions designed to mitigate or exploit these impacts. In general, we identified three major forms of socioeconomic response to environmental change that were deployed differentially over space and time in the Jequetepeque Valley and surrounding areas.

One common local response to environmental uncertainty was the development of flexible, opportunistic agricultural regimes. These include multiple, small-scale water management systems arrayed along coastal hills. Such systems maximized runoff from springs and occasional rainfall (Fig. 4). They are spatially extensive and associated with the Late Moche, Post-Moche, and, to a lesser extent, Chimú cultures. These flexible agricultural systems did not require large labor or technological inputs, and therefore could be rapidly reconstituted if affected by transient environmental impact events. The spatial ubiquity of these systems, particularly on the north side of the valley, implies that at certain times local populations were maximizing agricultural production by placing as much arable land in production as possible calibrated to available water resources. In Late Moche and Post-Moche times (AD 700–1000), periods of considerable political fragmentation, the practice of agricultural production in remote locations may also reflect conflict avoidance.

Fig. 4. Late Moche period opportunistic agricultural systems consisting of sequential cultivation terraces (A and B), check dams, and reservoirs fitted to a narrow quebrada.

A second response to extreme water resource fluctuation (ranging from severe drought to catastrophic flooding) entailed the development of anticipatory agricultural infrastructure. This infrastructure included a network of redundant irrigation canals measuring 30–40 km in length that supplied water to various sectors of the valley (Fig. 5). The north side of the Jequetepeque Valley alone contains >400 km of preserved, pre-Hispanic canals. Given the local hydrological regime, these canal systems could not have been supplied with sufficient river or spring water to function simultaneously. That is, at any given time, only part of the system could have drawn irrigation water. This implies that communities regulated the flow of irrigation water to different sectors of the valley through a coordinated means of water scheduling. The construction of redundant canal networks and the development of flexible, opportunistic agricultural systems served essentially as a diversification of landscape capital. If one part of the network was destroyed, or fell into desuetude, another

Fig. 5. Extensive Chimú period irrigated field system south of the urban center of Farfán. Note the field surfaces (A) and secondary and tertiary canals (B) that were linked to a large intravalley canal and aqueduct system with an intake near the site of Talambo (see Fig. 1).

part could be brought on line to compensate. At the same time, this anticipatory infrastructure would have been an effective device for mitigating environmental catastrophes, such as ENSO-driven rainfall, and responding to political uncertainty.

A third human response to uncertain conditions also entailed investment in technologies explicitly designed to withstand environmental perturbations. For instance, irrigation canals associated with the large Chimú urban centers of Farfán, Cañoncillo, and Talambo incorporated elaborate defensive overflow weirs, particularly in aqueducts that bridged deep ravines (22, 25). These overflow weirs were designed to reduce the pressure of turbulence and excessive flow rates in the aqueduct bed, and thereby avoid structural erosion during ENSO-driven flood events. In addition, the foundations of the largest aqueducts were furnished with large, stone-lined conduits that permitted water to flow through the base of the aqueduct without damaging the structure (26). Such defensive structures did not always prevent serious damage to agricultural infrastructure. Repeated rebuilding episodes also occurred at major canals, aqueducts, and residential structures. Rebuilt architecture directly overlaid thick outwash deposits, implying repeated reconstruction of agricultural infrastructure in the aftermath of large-scale floods. In a massive aqueduct associated with the site of Farfán, for instance, dated architectural contexts suggest these outwash deposits pertain to the El Niño flood that we have radiocarbon dated at *ca.* A.D. 1230.

Another form of defensive infrastructure also occurs widely distributed throughout the lower Jequetepeque Valley. In many near-coastal areas, hundreds of crescent-shaped, fieldstone sand breaks were built to inhibit the intrusion of saltating sands into irrigation canals, agricultural fields, and residences, particularly during the Chimú period (A.D. 1200–1470). The technologies of response to flood impacts were evidently more effective than those intended to combat desertification. As noted above, desertification on the south side of the valley apparently truncated the Chimú occupation of the major urban center of Cañoncillo and other related sites by the late14th century.

These forms of social and technological responses to uncertain environmental conditions were deployed differentially over space and time. In our study area, there is a clear distinction in the human response of Late Moche, Post-Moche, and Chimú societies to environmental instability and change. This differential response turns principally on major differences in the demographic, technological, and political character of these societies.

Settlement patterns reveal that the principal response of Late Moche society to environmental uncertainty was to maintain high population mobility across spatially extensive landscapes. The earlier Middle Moche phase (*ca.* A.D. 400–700) urban center of Pacatnamú had lost its dominant political and religious position by this time (27, 28). Late Moche society emphasized smaller scale sites broadly distributed across several different environmental settings, rather than concentrated populations in urban centers. Residential mobility was associated with a lack of intense investment in fixed landscape capital, such as major road networks, multivalley irrigation systems, costly aqueducts that accessed remote water sources, and large urban settlements.

The Late Moche anticipatory response to environmental impacts was to maintain spatially extensive agricultural systems with low investment costs (Fig. 4). Direct response to periodic or chronic environmental perturbations entailed moving populations and their associated agricultural activities to multiple intermediate and small-scale settlements around the valley. Late Moche phase populations also rapidly rebuilt low cost infrastructure in areas affected by flood impacts, as indicated by repeated refurbishing of walls and construction of expedient, vernacular housing at many sites. The Late Moche social landscape was characterized by intense intra-valley competition for access to suitable arable land and limited water resources, and by decentralized forms of agricultural management practices (29).

During the Post-Moche period (locally dated to *ca.* A.D. 800–1100), human response to uncertain environmental conditions entailed even more dispersed populations living in smaller hamlets and fortified hillside villages. Both urban and intermediate scale settlements characteristic of Middle and Late Moche society are either abandoned or sparsely occupied at this time. This suggests further political fragmentation and localization of agricultural systems. Although the flexibility of the opportunistic agricultural practices of Post-Moche society permitted rapid response to environmental impacts, these conditions made the local systems more vulnerable to major, region-wide environmental stress and to external political regimes not experiencing the same difficulties.

Increased fragmentation and defensive posture forced the Post-Moche populations to concentrate agricultural production in highly localized areas close to defensible hillsides. Political decentralization resulted in diminished capacity to manage production systems on a regional scale. The parochial, spatially restricted nature of Post-Moche populations in the Jequetepeque Valley undercut their ability to develop and maintain an anticipatory response to environmental change on a regional scale. We infer that the eventual incorporation of the Jequetepeque Valley under Chimú hegemony (*ca.* A.D. 1200–1300) was facilitated by these conditions of fragmentation evident in the political, social, and agricultural landscapes (30).

The Chimú response to environmental uncertainty was markedly different from that of the Late Moche and Post-Moche phases. The Chimú state's strategy involved a shift in emphasis to urban systems and associated regional scale development of agricultural landscapes. Unlike Late Moche and Post-Moche society, the Chimú invested heavily in fixed landscape capital, both in terms of constructing large-scale hydraulic infrastructure (Fig. 5) and in developing strategically located urban centers, such as Cerro Colorado, San Jose de Moro, Talambo, Farfán, Cañoncillo, and Pacatnamú. These large urban centers concentrated human populations and corporate labor in spatially discrete, high-investment locations. They were placed on huge alluvial fans with adjacent hillside populations, interconnected by road networks, and supported by extensive, centrally managed agricultural lands. The Chimú strategically aggregated populations, restricted residential mobility, and linked urban residents directly to costly integrated agricultural landscapes, such as the Talambo, Farfán, and Cañoncillo reticulated canal and aqueduct systems. The Chimú state also inaugurated extensive inter-valley irrigation systems with the intent of maximizing access to and redistribution of water resources. In contrast to the Late Moche pattern in which populations, settlements, and production systems were de-coupled, flexible, and spatially extensive, the Chimú pattern was one of centralized control of spatially concentrated populations closely linked with adjacent production systems.

The Chimú anticipatory response to environmental uncertainty may be characterized as a command and control strategy that attempted to "rationalize" the landscape by a directed restructuring and integration of human interactions with the environment. This integrated strategy permitted the Chimú to respond to environmental uncertainty and impact events at a regional scale, but, at the same time, entailed costly investment in landscape capital (regional agricultural and transportation infrastructure) and in direct surveillance and control of urban populations. Heavy capital and labor investment in this command and control strategy may have introduced structural rigidities into the political economy of the Chimú state through over-reliance on specialized forms of agricultural technology. The Chimú decision to structure human–environment relations through a complex strategy of large-scale agricultural management potentially rendered them more vulnerable to severe environmental and political shocks. Overinvestment in a highly complex, productive, but vulnerable agricultural infrastructure may explain why the Chimú were unable to respond effectively to the challenge of Inca military expansionism and succumbed with relative ease to the imperial ambitions of the Inca kings, Pachakuti (reigned A.D. 1438–1470) and his successor, Thupa Inka Yupanki (reigned A.D. 1471–1493).**

Conclusions

Severe ENSO events, periodic droughts, and desertification negatively affected sustained agricultural production and, at times, generated considerable social problems for the pre-Hispanic cultures of the Andes. Human communities apparently responded to major ENSO events by relocating settlements in landscapes less susceptible to flooding or simply by rebuilding damaged structures. At the same time, they opportunistically expanded cultivation in the short-term to exploit ENSO-driven rainfall. Individual farmers and communities responded to short-term drought through a variety of strategies such as settlement relocation, reducing the intensity or extent of irrigation, changing the composition of cultigens, or shifting production to heavier reliance on maritime or pastoral resources. Response to protracted droughts, on the other hand, may have required coordinated activities on a regional scale organized by higher-level political authorities.

In extreme cases of long-term environmental stress, such as the mid-12th- to late-14th-century drought conditions in the Andean altiplano, command and control strategies deployed by politically centralized authorities failed to respond effectively to severe socioenvironmental crisis. As noted above, in the specific case of the Tiwanaku state, these protracted drought conditions induced region-wide failure of agricultural infrastructure; the only effective response to this crisis was state collapse and the migration of human populations. Despite periodic episodes of political crisis and population decentralization in cases such as at the end of the Tiwanaku period in the Andean altiplano, and during the Late Moche period in north coastal Perú, many rural communities continued to survive, most likely through relocation to landscapes less susceptible to environmental stress, through restructuring of social organization and intercommunity relations, and through shifts in domestic and political economies.

In conditions of environmental uncertainty and vulnerability, human response can lead to multiple possible outcomes. The forcing factors that drive change to a new response strategy can be either internal or external to the old strategy. Further, the type and degree of response is not determined solely by a centralized or hierarchical political structure. Situational responses derive from reading the cultural and physical landscape at different social, spatial, and temporal scales. Responses to environmental uncertainty are constrained and shaped by human actions that must take into account the landscape-structuring effects of previous strategies and environmental impacts.

A defining aspect of complex preindustrial societies in the Andes was the ability to accommodate political and economic strategies to different demographic and social organizational scales. Although contemporary society has evident technological and informational advantages over premodern societies in responding to environmental change, the analysis of past social response to uncertain environmental conditions emphasizes the importance of adaptive strategies and policy-making decisions grounded in a full appreciation of such scalar and landscape structuring effects.

We acknowledge the collaboration of M. Pino, C. Ortloff, M. Binford, M. Brenner, and J. Curtis in the research, as well as the cooperation and help of Cesar Galvez, Jesus Briceño, and the staff of the Instituto Nacional de Cultura, Trujillo, Perú. This work was supported by grants from the National Science Foundation (to A.L.K. and T.D.D.), the Division of the Social Sciences and the Marion R. and Adolph J. Lichtstern Fund of the University of Chicago (to A.L.K.), and the T. Marshall Hahn, Jr., Fund of the University of Kentucky (to T.D.D.).

**Perhaps indicative of this vulnerability, the Spanish chronicler Miguel Cabello Valboa wrote that the Inca emperor Thupa Inka Yupanqui threatened to cut off the highland-derived water supplies of the Chimú coastal canal systems on which the state economy was highly dependent (2).

1. Moore, J. D. (1991) *Lat. Am. Antiquity* **2,** 27–47.
2. Cabello Valboa, M. (1951) *Miscelánea Antártica: Una Historia del Perú Antiguo* (Universidad Nacional Mayor de San Marcos, Instituto de Etnología y Arqueología, Lima, Perú).
3. Shimada, I., Schaaf, C. B., Thompson, L. G. & Mosley, M. E. (1991) *World Archaeol.* **22,** 247–270.
4. Moseley, M. E. (1999) in *The Angry Earth: Disasters in Anthropological Perspective*, eds. Oliver-Smith, A. & Hoffman, S. (Routledge, New York), pp. 59–71.
5. Walker, B. & Steffen, W. (1997) *Conserv. Ecol.* **1,** www.consecol.org/vol1/iss2/art1.
6. Vitousek, P. M., Mooney, H. A., Lubchenco, J. & Melillo, J. M. (1997) *Science* **277,** 494–499.
7. Lennihan, L. (1984) *Hum. Ecol.* **12,** 465–480.
8. Newman, J. H. (1998) *Science* **283,** 516–520.
9. Rasmusson, E. M. & Carpenter, T. H. (1982) *Mon. Weather Rev.* **110,** 354–384.
10. Quinn, W. H. & Neal, V. T. (1992) in *Climate Since 1500 AD*, eds. Bradley, R. S. & Jones, P. D. (Routledge, London), pp. 623–648.
11. Keefer, D. K., Moseley, M. E. & deFrance, S. D. (2003) *Paleogeogr. Paleoclimatol. Paleoecol.* **194,** 41–77.
12. Thompson, L. G., Mosley-Thompson, E., Bolzan, J. F. & Koci, B. R. (1985) *Science* **229,** 971–973.
13. Moseley, M. E. & Richardson, J. B. (1992) *Archaeology* **45,** 44–45.
14. Binford, M. W., Kolata, A. L., Brenner, M., Janusek, J. W., Seddon, M. T., Abbott, M. & Curtis, J. H. (1997) *Quat. Res.* **47,** 235–248.
15. Kolata, A. L. & Ortloff, C. R. (1996) in *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization*, ed. Kolata, A. L. (Smithsonian, Washington, DC), pp. 181–199.
16. Ortloff, C. R. & Kolata, A. L. (1993) *J. Archaeol. Sci.* **20,** 195–221.
17. Kolata, A. L. & Ortloff, C. R. (1996) in *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization*, ed. Kolata, A. L. (Smithsonian, Washington, DC), pp. 109–151.
18. Ortloff, C. R. (1996) in *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization*, ed. Kolata, A. L. (Smithsonian, Washington, DC), pp. 152–167.
19. Quinn, W. (1993) *Bull. Inst. Fr. Etudes Andines* **22,** 13–34.
20. Orlove, B., Chiang, J. & Cane, M. (2000) *Nature* **403,** 68–71.
21. Kosok, P. (1965) *Life, Land, and Water in Ancient Perú* (Long Island Univ. Press, New York).
22. Eling, H. (1986) in *Andean Archaeology: Papers in the Memory of Clifford Evans*, eds. Ramiro-Matos, M., Turpin, S. A. & Eling, H. (Univ. of California, Los Angeles), pp. 130–149.
23. Alcocer, F. (1987) *Ecologia E Historia: Probanzas de Indios y Españoles*, Referentes a las Catastroficas Lluvias de 1578, en los Corregimientos de Trujillo y Saña (CES Soliaridad, Chiclayo, Perú).
24. Moseley, M. E., Wagner, D. & Richardson, J. B. (1991) in *Paleoshorelines and Prehistory: An Investigation of Method*, eds. Johnson, L. L. & Straight, M. (CRC Press, Boca Raton, FL), pp. 236–249.
25. Hecker, G. & Hecker, W. (1982) *Pacatnamú: Vorspanische Stadt in Nord Perú* (C. H. Beck, Munich).
26. Ortloff, C. R., Feldman, R. A. & Moseley, M. E. (1985) *J. Field Archaeol.* **12,** 77–98.
27. Castillo, L. J. & Donnan, C. B. (1994) in *Vicus: Coleccion Arte y Tesoros del Perú* (Banco del Estado del Perú, Lima), pp. 143–181.
28. Donnan, C. B. & Cock, G. A. (1997) *The Pacatnamú Papers* (Univ. of California, Los Angeles), Vol. 2.
29. Dillehay, T. D. (2001) in *Art and Politics in Moche Perú*, ed. Pillsbury, J. (Natl. Gallery of Art, Washington, DC), pp. 259–284.
30. Conrad, G. W. (1990) in *The Northern Dynasties: Kingship and Statecraft in Chimor*, eds. Moseley, M. E. & Cordy-Collins, A. (Dumbarton Oaks Research Library, Washington, DC), pp. 227–242.