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Sub-irrigation in wetland agriculture

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Abstract. Much has been written about the *chinampas* of central Mexico. One of the commonly repeated themes is that these wetland fields were self-irrigated from below in a process known as sub-irrigation. According to this model, water infiltrates the planting platforms from adjacent canals and then rises to the root zone by capillary action. Thus, chinampas are thought to have needed little supplemental irrigation, and produced dependable and high yields. Here I report the results of field and lab studies of soils of 10 chinampas in the region east of Xochimilco, in the Mexican Federal District. These interpretations are combined with discussion of maize rooting tendencies, regional rainfall patterns, and the presence of willow tree roots in chinampa soils. I also consider whether farmers strive to create and maintain optimum field morphologies for subirrigation when faced with both flood and drought risk, and when manual irrigation is a ready option. I conclude that while sub-irrigation is possible under certain combinations of field morphology, crop type, and soil properties, it was a relatively minor factor in the overall decision-making process of past chinampa farmers, and should not be a major determinant of future planning for chinampa preservation or reconstruction. Furthermore, sub-irrigation must be modeled carefully in relation to soil properties, crop types, and seasonality if it is to be considered a significant function of wetland fields in any context.

Key words: *Chinampas*, Mexico, Sub-irrigation, Wetland agriculture, Xochimilco

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Introduction

A process of sub-irrigation has been asserted by almost all who have written on the subject of *chinampas*, the famed island fields of the Xochimilco region of the Basin of Mexico, as well as in more general discussions of intensive wetland agriculture (e.g., Ciudad Real, 1976; Denevan and Turner II, 1974; Orozco y Berra, 1864; Santamaría, 1993; Schilling, 1993; Sluyter, 1994; Torquemada, 1975; West and Armillas, 1950; Wilken, 1987; Ruddle and Zhong, 1988). Moisture provision from the subsurface – by seepage from adjacent canals and capillary rise from the fields' adjusted water table – is thought to have reduced or eliminated the need for manual watering, thus reducing the risk of poor harvests, potentially increasing crop yields, off-setting the tremendous labor costs of field construction and maintenance, and negating the need for supplemental irrigation engineering (Armillas, 1971; Denevan and Turner II, 1974; Parsons, 1976; Parsons et al., 1982; Sanders et al., 1979; Santamaría, 1993; Schilling, 1993; West and Armillas, 1950).

In order to evaluate the importance of sub-irrigation in Basin of Mexico chinampas and other wetland fields, I review the few detailed statements about how this is thought to occur and propose a model of a sub-irrigating, *raised field*.[1] I then present the results of my research on chinampa soil properties and field profiles as they pertain to capillary rise. In the second section I expand this evaluation of sub-irrigation by reviewing aspects of maize root growth and moisture requirements, and rainfall patterns in the Southern Basin of Mexico. I then consider farmer perspectives on the potential for, and desirabilty of sub-irrigation. Finally, I apply the insights and observations from the chinampa context to wetland fields in other regions.[2]

Wetland field sub-irrigation

Matter-of-fact statements that chinampas and other wetland fields are, or were, sub-irrigating belie the tremendous complexity of the soil and plant properties required for subirrigation to occur naturally, and function significantly. In contrast to the broad and long-term study and testing of engineered sub-irrigation systems (e.g., Bengtson, 1993; Green and Green, 1895; Philip, 1991; Rane, 1896; Sanborn, 1893; Wright and Adamson, 1993), and even though natural sub-irrigation has been widely accepted as an inherent characteristic of wetland agriculture, thusfar there has been no attempt to verify the phenomenon.

After initial field construction drains excess moisture into ditches, it is thought that moisture seeps from adjoining canals into the subsurface of the raised platform, resulting in higher soil moisture content, thus improving plant growing conditions (Denevan and Turner II, 1974; Ruddle and Zhong, 1988; Sanders, 1993; Santamaría, 1993; Schilling, 1993; Siemens, 1983; West and Armillas, 1950; Wilken, 1987). High soil porosity, which would facilitate lateral seepage, and which increases as soil texture coarsens, is most often mentioned in support of this assertion (Denevan and Turner II, 1974; Santamaría, 1993; Schilling, 1993; West and Armillas, 1950). Over several centuries of study, only a few authors (Alzate y Ramírez, 1993 (originally published in 1791); Wilken, 1985; Willey and García Prada, 1939) have addressed the more important property of capillarity, the tendency for soil to conduct moisture upward through narrow channels between particles, which increases as soil texture becomes finer.[3]

Both platform width and the height of wetland fields above the water level in adjacent canals have been denoted as the critical variables for sub-irrigation (Alzate y Ramírez, 1993; Armillas, 1971; Denevan and Turner II, 1974; Denevan, 1970; Ruddle and Zhong, 1988; Sanders, 1993; Schilling, 1993; West and Armillas, 1950; Wilken, 1985, 1987). Discussion of these factors, though, has seldom been combined with analysis of soil properties (other than high porosity) of the fields in question. Similarly, while it has been asserted that seepage brings moisture "right to the roots" (Armillas, 1971), no previous study of chinampas discusses rooting depth or moisture requirements for any chinampa crop, nor how these factors might relate to the efficacy of sub-irrigation.[4] Moreover, potential problems under sub-irrigating conditions such as root damage and yield decline due to prolonged saturation, and capillary rise-induced salinization are rarely mentioned (Alzate y Ramírez, 1993; Wilken, 1985; Willey and García Prada, 1939). Strikingly, the authors who raised these concerns concluded that chinampa farmers guarded against these risks by ensuring that field platforms were sufficiently high that crops may actually have been unable to benefit from sub-irrigation (Alzate y Ramírez, 1993; Wilken, 1985; Willey and García Prada, 1939).

A model of sub-irrigation

A naturally occuring sub-irrigation system would need to have the following characteristics:

1) the planting platform must be high enough above the water table that the root zone drains sufficiently to allow root growth (Wilken, 1985, 1987);
2) a subsoil composed primarily of fine sand and coarse silt in order to produce a capillary fringe that extends high enough to be within several centimeters of crops' fine root hairs (Brady, 1974; Carman, 1941; Slatyer, 1967; Whiteside et al., 1967);
3) the active root zone of the crops to be subirrigated needs to be less than 85 cm above the groundwater; otherwise the relatively slow moisture supply by capillary rise will not match the more rapid loss of soil moisture by transpiration (Brady, 1974; Daubenmire, 1959; Slatyer, 1967);[5]
4) the active root zone cannot be too deep into the capillary fringe or oxygen starvation and other effects of near saturation become problematic (Stolzy, 1974); and
5) in soils prone to salinity problems, at least during periods of high evaporation, the top of the capillary fringe needs to be more than 30 cm below the surface – the typical depth to which soil moisture is lost to evaporation – to avoid salinization of the soil (Slatyer, 1967; Wilken, 1985).

Accordingly, a subirrigated planting platform would have a minimum height determined primarily by the water table (which likely fluctuates), soil texture, and depth of the rooting zone, and a maximum height of about 85 cm plus the rooting zone depth.

Figure 1 models these controlling factors. In diagram (a) the water table is too high relative to the planting surface that drainage is necessary for agriculture to be feasible. In situation (b) a deeper water table and a silt loam soil allow development of a capillary fringe that reaches to within the zone subject to evaporation and may lead to salt accumulation in the root zone. In diagram (c), the soil profile is too deep (or too coarse) for the capillary fringe to be reached by even the deepest plant roots. In (d), a deeper soil profile created by field raising allows development of a zone of well-drained soil for initial root growth, and deep rooting crops, or mature phases of root growth may benefit from moisture in the capillary fringe above the water table. Situation (d), then, is the one envisioned by those who have suggested that chinampas and other wetland fields sub-irrigate.

Do chinampas have these characteristics? Today in the Xochimilco region (Figure 2) one can observe numerous chinampas that are so low waterlogging

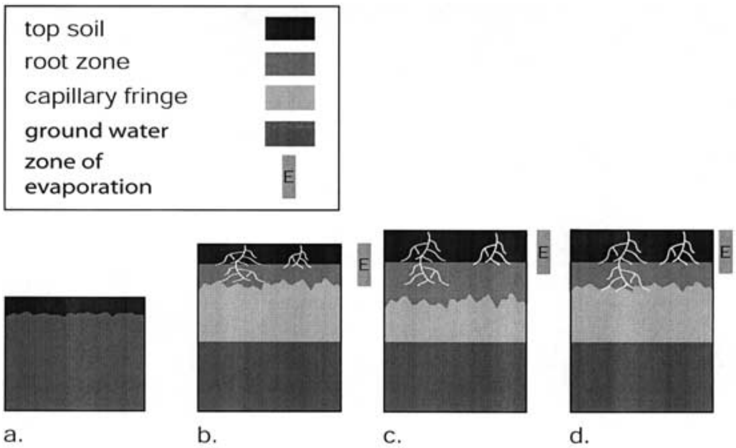

Figure 1. Model of wetland sub-irrigation.

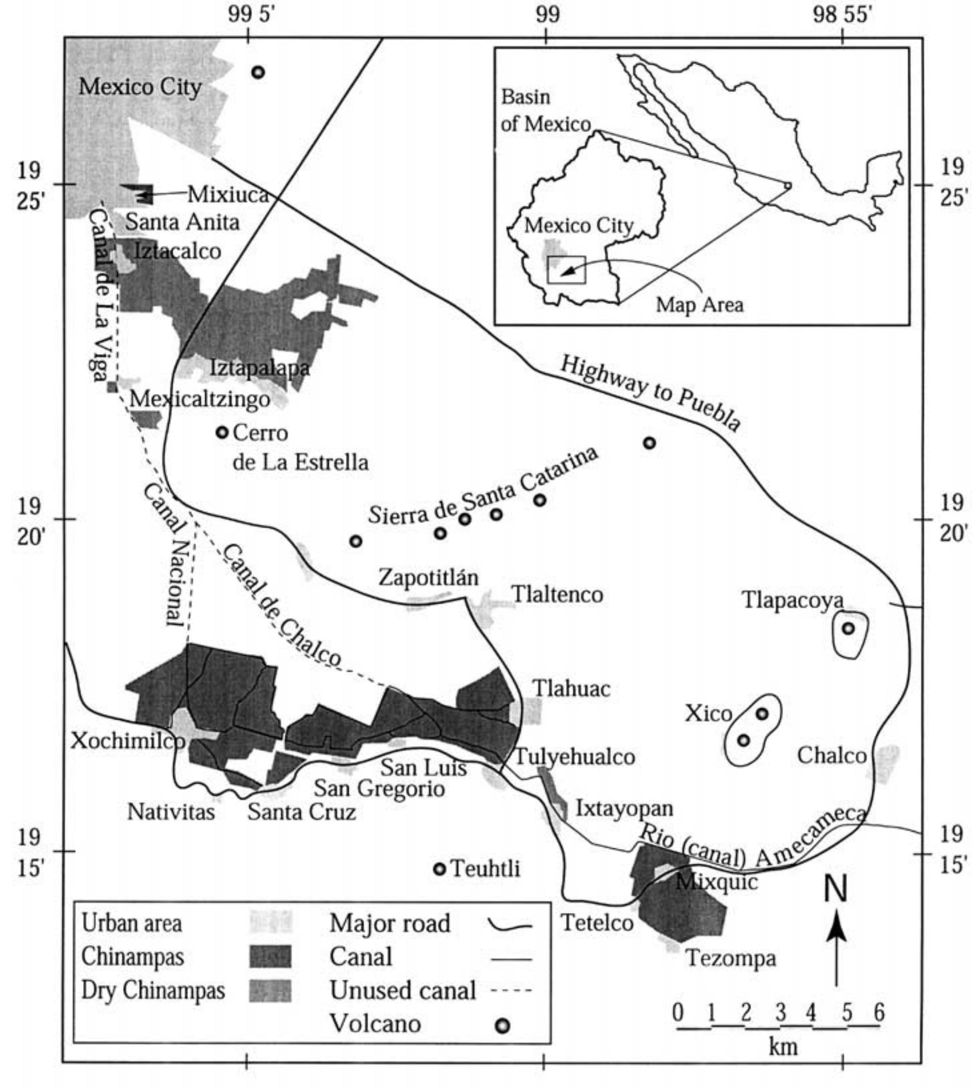

Figure 2. Historic and contemporary chinampa zones of the basin of Mexico (adapted from West 1998, Figure 3).

is problematic, others that far exceed the maximum suggested above, and many others within the height range defined above. Irrigation by bucket and hoses connected to gasoline-powered pumps are common practices on chinampas of all heights.

The contemporary situation is, of course, dramatically different than that of pre-Hispanic and Colonial periods due to alteration of the regional hydrology by drainage, aquifer pumping, spring capture, canal infilling, canal dredging, treated wastewater pumping, basin compartmentalization, and urbanization (Bojórquez Castro, 1995; Canabal Cristiani, 1991; Ezcurra, 1990; Marroquín y Rivera, 1910; Outerbridge 1987; Rojas Rabiela, 1991; Romero Lankao, 1993). Nevertheless, the range of chinampa heights reported in earlier periods – from 25 to 100 cm (e.g., Avila López, 1992; Santamaría, 1993; von Humboldt, 1966) – suggests that some chinampas may have been naturally subirrigating.

Recent field research

During 1996–1997, I attempted to measure the actual height of capillary rise in chinampas of varying amplitude, and to correlate these estimates with soil texture, organic matter content, soil salinity, and field profile observations. The height and rate of capillary rise in a given soil can be measured in the field or laboratory, and calculated or predicted from other soil properties such as hydraulic conductivity, porosity, pore geometry, and mean pore diameter; factors also determined in the field or laboratory.[6] Without access to the equipment normally used for such investigations, however, a simpler method (described below) was developed for this study and carried out in conjunction with routine soil sampling.

Study sites throughout the present day *chinampería* of Xochimilco, San Gregorio, San Luis, and Míxquic in the Southern Basin of Mexico (Figure 2) were examined in order to incorporate a range of soil textures and groundwater chemistries, and fields farmed according to a variety of agricultural strategies and intensities. Additionally, the 16 sites finally chosen reflect a range of platform heights, distance from the nearest water-filled canal, and position relative to the former lakeshore. Current utilization and farmers' preferences were also substantial factors in the final selection of sampling locations within each study chinampa.[7]

Each sampling trench (2–3 m wide × 1.5 m across) was hand dug by the author and a hired assistant as close as possible to the mid-point of the field and deepened until water began seeping into the pit (at depths ranging from 80–280 cm). Groundwater depth was considered to be the level at which the freshly cut profile surface immediately began to ooze water. Groundwater depth was recorded immediately and again after 24 hours, during which time about 10 cm of water had usually pooled (the capillary fringe is the moist, but not saturated, zone above the groundwater level).

Standard procedures of soil horizon identification and description were then followed and samples removed from each horizon for textural and other lab analyses. A shaded exposure was then sampled every 10 cm for moisture content analysis.[8] In order to accurately assess moisture content, these samples were withdrawn from 10–15 cm into the profile rather than from the exposed surface, and were then immediately packed into labeled film canisters, sealed with tape, and transported in sealed plastic bags. Any moisture lost to evaporation after excavation or in transit (minor condensation on the film canister lids occurred in a few instances), will have influenced the data interpretation by making samples appear drier than they had been in situ. Six of the sixteen chinampa profiles were examined but not sampled for moisture content analysis.[9]

Gravimetric moisture content measurement was performed, and the data plotted in combination with soil texture, organic matter content, pH, and EC (electrical conductivity) measurements (Note: gravimetric measurement consists of weighing a moist soil sample, drying it out in an oven set at 105 °C, then weighing the dry sample. The initial moisture content is then calculated as the weight of the water lost divided by the weight of the dry sample, expressed as a percentage. Thus, soil moisture content values >100% are common, since a small volume of very light soil can contain a small volume of water that is significantly heavier than the soil particles themselves, particularly if the sample contains a lot of very light, moisture absorbent, organic matter as do chinampa soils).

Results

A very moist zone of soil above the groundwater was clearly evident during excavation, and was confirmed by the data. In most profiles, a band 35–55 cm thick had a moisture content of 175–200%, though much higher values were recorded for individual samples in two profiles. Moisture content then declined sharply between the next measurements, usually by about half the magnitude of the deeper value. Steady moisture content values between 75–100% were characteristic of the upper 40–50 cm of each profile (Figure 3, Table 1). There were several anomalous data points

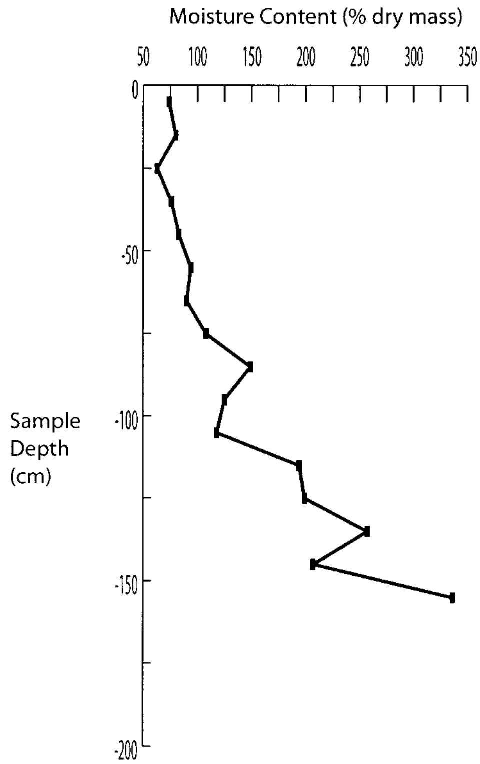

Figure 3. Moisture content, profile SL6, San Luis Tlaxialtemalco.

and two profiles did not exhibit this pattern, perhaps due to slight rainfall on the day prior to sampling in Míxquic.

For each profile, I estimated the height of the capillary fringe according to the following criteria: (1) a sharp drop in the moisture content down to 100% or less – in most cases from 200% or more; (2) maintenance of the moisture content below 100% in the subsequent (higher) samples; (3) a significant decline in moisture content despite increasing or steady OM content; and (4) confirmation of this position for the capillary fringe from the salinity values and field observations.

The values for the estimated depth to the top of the capillary fringe, and the height of the fringe above the water table are summarized in Table 2. According to my interpretation of the data, across the chinampa zone, an effective capillary fringe of 30–45 cm above the groundwater can be expected, and in some cases it may extend up to 50–75 cm. These figures based on moisture content analysis, then, correspond well with the expected efficacy of sub-irrigation in controlled settings common in analyses of other soil/water phenomena where a water table is maintained at a depth of 40 cm or greater (e.g., Cooper et al., 1991; Patel et al., 1999; Stanley and Clark, 1995). The 30–45 cm range of capillary rise, though, is somewhat less than predicted by the standard model of soil capillarity (see Brady, 1974) for soils as fine as those sampled from the study sites (Figure 4).[10]

In summary, it appears that where chinampa planting surfaces are at least 45–65 cm (30–45 cm capillary fringe + 15–25 cm rooting zone) above the canal water level, sub-irrigation may be possible for shallow rooting crops. For deeper rooting crops, or in soils that produce the higher range of capillary rise, field platforms could be as high as 88–135 cm above the canals (50–75 cm capillary fringe + 38–60 cm root zone) and some plants could still experience sub-irrigation.[11] These estimates of optimal field height closely approximate the range of typical and ideal platform height reported by earlier researchers (e.g., Santamaría, 1993; von Humboldt, 1966; West and Armillas, 1950), and by chinampa farmers today, and suggest that sub-irrigation may have been a feature of chinampa agriculture.

Discussion: Additional considerations

While the uncertainties inherent in the method alone may account for the apparent discrepancy between predicted capillary rise and the lower range of functioning capillarity suggested above, several other possible contributing factors should also be considered. Subsoil properties other than texture, the presence of tree roots in the chinampa platforms, the nature of maize root growth, and the seasonality of precipitation in the Basin of Mexico are all relevant to the question of the significance of sub-irrigation.

First, long term farmer disturbance of the soils both during field construction and maintenance, as well as by cultivation practices has been significant; ceramics were commonly noted down to 45 cm during excavation, and as deep as 160 cm in one profile.[12] This disturbance has undoubtedly resulted in creation of larger macropores than would otherwise be the case, and may have resulted in interupted and reduced capillarity.

Second, the subsoil of the chinampas studied is highly stratified, containing fibric, almost wholly organic, peaty horizons, diatomite units of varying thickness, and a single, widespread, thin layer of reworked volcanic ash (Figure 5). While the mineral texture of these units is very similar to that of the surface soil, each is likely to have significantly different, but unknown, hydraulic properties of which the following should be mentioned:

i) whether highly organic soil units composed primarily of horizontally layered fibers – extremely capable of holding moisture – induce greater or lesser capillarity than tightly packed mineral grain horizons is unclear; (see Figure 6)

Table 1. Moisture and organic matter content of chinampa soils.

Sample	SG3		Xo1		SL6		SL3		Mi2		SL4		Mi3		SL5		SG1		SG2	
depth (cm)	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %	H_2O %	OM %
0–10	85		98	12	74				103				98				60		79	
10–20	85	23	105	11	80	12	66	8	116	35	85	15	99	10	84	15	67	23	95	16
20–30	81		127		63	10			133				94	9	101	14	79	11	96	
30–40	84	24	126	9	76	7	67	5	108	12	101	12	93		123	9	99		116	17
40–50	95		129	10	83				136		114	12	100	8			174	34	213	
50–60	94	13	131		94	9	72	6	156		89	9	112		170	7	236	13	173	18
60–70	95		129	10	90				178	13			109	11			85	14		
70–80	85		129		108	8	156	8	126		135	7	112		164	7	225	21		
80–90	85		161	9	149	5			209	21			127	10						
90–100	119		130		125	12			147		111	6	144			14				
100–110	129	14	97	13	118		176	27	143				136	14						
110–120	125		94		194	10	96	43	134	15	181	10								
120–130	95	9	105	14	199	20	54	5	141		243	50								
130–140	119	10	117		257	29	237	24	150											
140–150	281		200	44	207	35														
150–160	307	59	297		336	26														
160–170	241		270	16																
170–180	319	54	168	14																
180–190	184																			
190–200	422	55																		
200–210	425																			
210–220	331																			
220–230	250	50																		
230–240	172																			
240–250	170	21																		
260–270	186	4																		
270–280	191	19																		

Notes: % H_2O = % of soil dry mass; % OM = % dry mass LOI. Moisture sampled every 10 cm, except profiles SL3, 4, 5, 6. Organic matter sampled each horizon. Full details of field and lab methods and results available from the author.

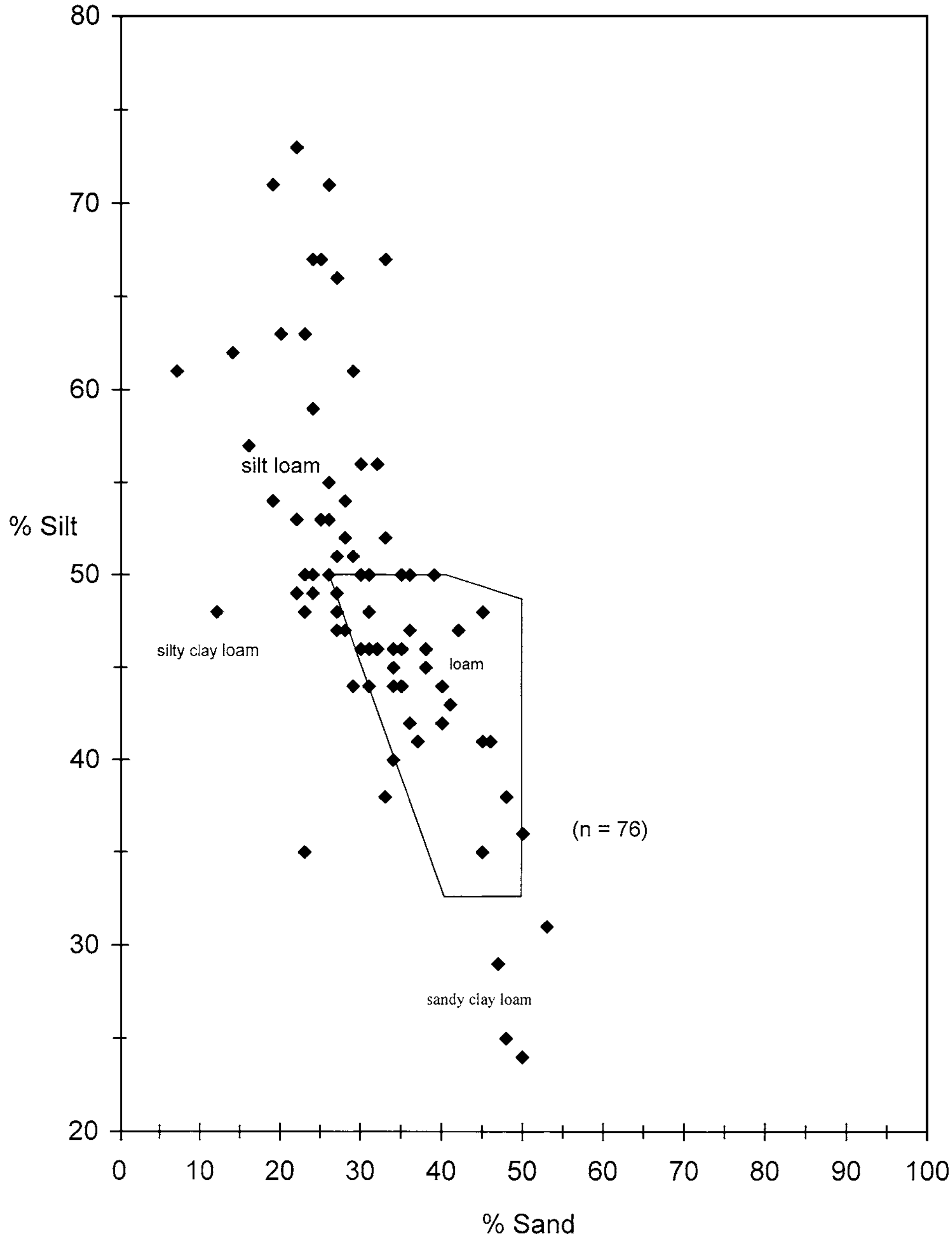

Figure 4. Soil texture distribution of chinampa soils.

ii) similarly, the diatomite units contain diatoms that are primarily cylindrical (*Fragilaria* spp.) and "banana"-shaped (*Cyclotella* spp.) and no information has been found on the nature of water movement through diatomite;[13]

iii) the slightly coarser texture of the 3 cm thick ash layer may interfere somewhat with total capillary rise. It should also be noted, though, that both its presence near the base of the field profiles (close to the groundwater level), and the fact that coarser textures, while limiting total capillary rise actually induce a more rapid capillary transmission, may counter any limiting effects of the ash horizon; and

iv) the upper soil horizons contain some of each of these types of sediments in unknown proportions. Perhaps most important is that the mineral grains of the chinampa soil in general are primarily derived from weathered lava fragments and redeposited volcanic ash. While, as in this case, they may be as fine as typical soil mineral grains, such particles tend to contain many internal pores where moisture is held hygroscopically and is not moved by either gravity or capillary forces (Iwata et al., 1988).

Table 2. Depth of water table and capillary fringe.

Depth below surface (cm)					Height above water table (cm)	
Profile	Water table	Top of capillary fringe	Tree roots	Max. salinity	Top of capillary fringe	Tree roots
SG1	80	40–50	None	55–65	30–40	None
SG2	75	35–45	None	10	30–40	None
SG3	>320	140–145	None	170–195	55–65	None
SL3	150	75–95	None	40–60	55–75	None
SL4	150	95–115	70–90	30	35–55	60–80
SL5	105	40–55	60–90	40	45–60	15–45
SL6	155	95–105	None	10–15	50–60	None
Mi2	140	40–55	60–80	15	85–100	60–80
Mi3	120	75–90	70–90	10–20	30–45	30–50
Xo1	185	130–140	110–140	35	45–55	45–75

There are, then, several different characteristics of chinampa soils that make interpretation of the soil moisture content trends difficult. The chinampa profiles studied here reveal a stratified subsoil whose horizons are of very different sediments with hydraulic properties that are probably quite different but were not studied separately.[14]

Thus far I have focused entirely on soil characteristics, particularly texture, since these are the primary determinants of capillarity. Though it has not been noted previously, during the excavation of sampling trenches it became clear that live roots from the famed *ahuejote* trees (Bonpland willow, *Salix bonplandiana*) along the field-edge are often present in the subsoil – even when the nearest tree was 15 m away! While mostly coarse (1–3 cm) roots had to be cut through during digging, in one case (profile Mi2) it was clear that finer roots extended down a further 30–40 cm. Willow trees in general (*Salix* spp.) are phreatophytes and need to have their roots in the capillary fringe in order to thrive (Barbour et al., 1987; Daubenmire, 1959). The evidence from the excavations confirms that the Bonpland willow is no different. It is highly probable, then, that in all chinampas with ahuejotes lining the canals, the capillary fringe is permeated with fine, live tree roots.

How much moisture rises past these roots? In four of the five profiles studied in which roots were noted, the moisture content dropped by about half at, or just above, the height of the coarse tree roots (the fine roots were not always noted in my enthusiasm to finish digging, particularly before I realized their significance).[15] Rootless profiles exhibited similar declines in moisture content at similar heights above groundwater, however. The effect of the ahuejote roots on availabilty of moisture supplied by capillary rise, then, remains uncertain, but must be considered a likely limitation on the significance of sub-irrigation for provision of moisture to crop roots. On the other hand, the supply of moisture to the tree roots by capillary rise, itself may be a significant function in that it reduces the draw by the willow trees on moisture supplied to crops by precipitation or supplemental irrigation.

Lining platforms with ahuejote trees, while characteristic and perhaps defining of the chinampa landscape over the last century (today, the trees are disappearing rapidly), is probably a relatively new characteristic of the farming system, likely implemented along with widening of fields and a loss of platform-edge integrity as water levels dropped.[16] The fact that a tree that can take advantage of capillary fringe moisture was chosen for the purpose of platform-edge strengthening, then, may have enabled farmers to continue cultivation without concern for competition for available moisture.

Even without the complication of tree roots in the subsoil, it remains to be shown that the rooting depth of actual chinampa crops extend deep enough to benefit from moisture in the capilllary fringe. I have focused my comments on maize since it is presumed to have been the main crop grown on chinampas during both the preHispanic period (see Calnek, 1972; Parsons, 1976) and, though not exclusively, in modern times (see Rojas Rabiela, 1993a, for a thorough discusssion of chinampa crops).

Though maize is capable of extending its roots very deeply into soils of low bulk density, it is most likely to do so when moisture is scarce (Reader et al., 1992; Sharp and Davies, 1985). Moreover, maize root systems tend to grow in distinct stages with the phase of greatest downward root extension occuring just over

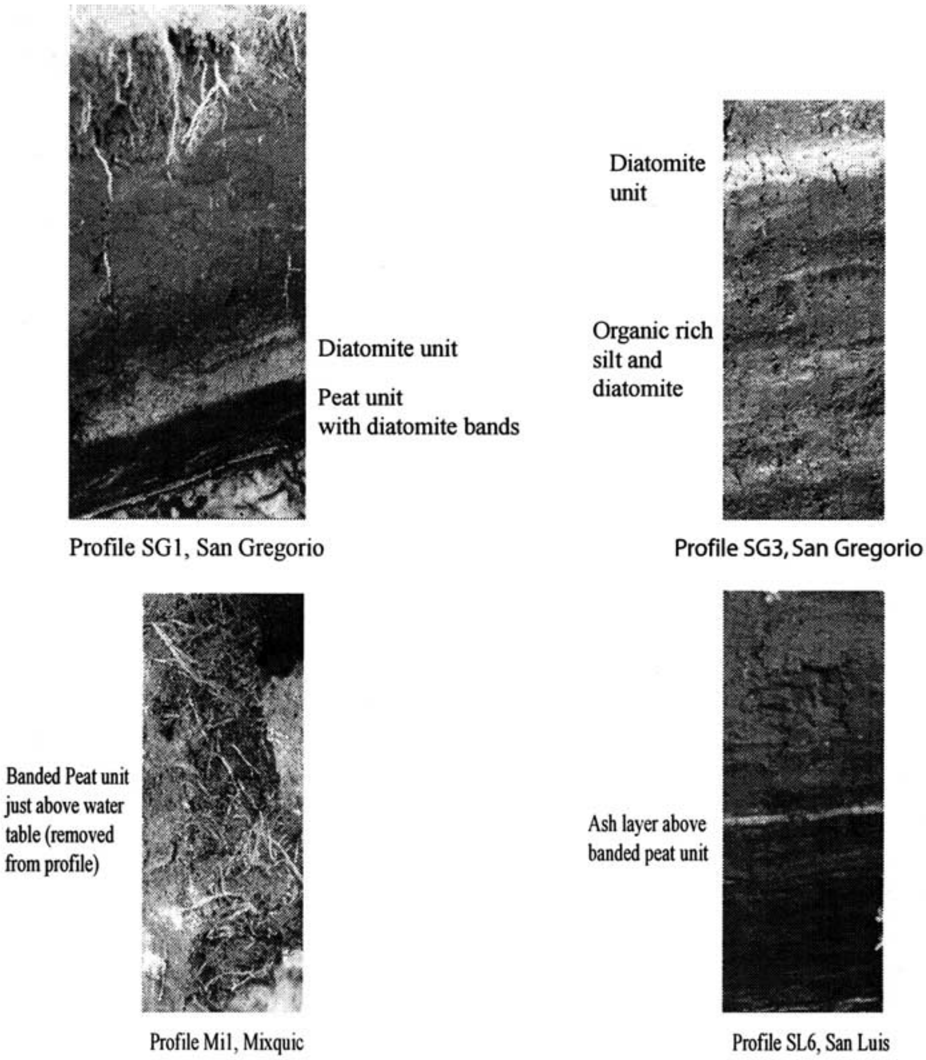

Figure 5. Diatomite, peat, and ash in 4 chinampa profiles.

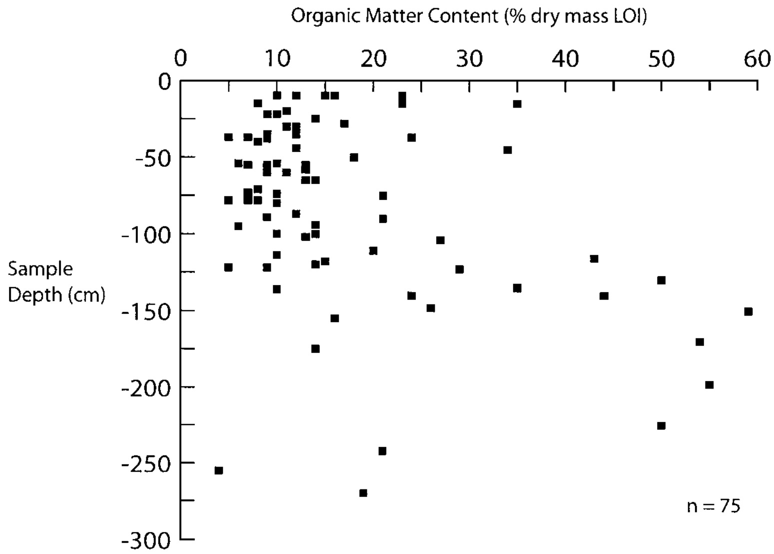

Figure 6. Organic matter content of chinampa soils.

half-way through the growing cycle – between the 54th–67th day after germination (Foth, 1962). Only during this period does root growth normally occur below 38 cm (15 in) (Foth, 1962). Since actively growing roots are primarily responsible for the uptake of moisture (Slatyer, 1967), maize would be most likely to benefit from sub-irrigation during this deepest stage of root growth.

In the Southern Basin of Mexico, where maize is typically seeded in March and April (Peña, 1978; Sanders, 1993), this phase of deepest root extension would normally be reached at the onset of the daily, torrential rains of the summer wet season (SMN, 1952–1988)! It is during this period that the high soil porosity and infiltration rate, and the existence of the raised planting beds become crucial in keeping the root zone *dry* enough. There is no need for additional moisture provision by sub-irrigation, nor would the rate of capillary rise come close to matching the rate of infiltration of precipitation down to the root zone.

However, if the crop was seeded early, in years when the rainy season arrived late or began with light, rather than heavy showers, as they often do (SMN, 1952–1988) sub-irrigation is more likely to have been a significant form of moisture provision.

Summary

The field study of chinampa soil moisture content has demonstrated that a capillary fringe of 30–45 cm, and in some cases from 50–75 cm, does develop above the groundwater in a chinampa platform. The reasons for two different ranges of capillary rise are unclear but likely relate to local differences in soil texture and additional subsurface horizon properties, and perhaps to differences in the cultivation history of the studied fields. How much of this moisture is actually available to crop roots is unclear, though, due to the draw on sub-surface moisture by the willow trees. Further, the fact that most of the rainfall in the Basin of Mexico occurs during the summer months suggests that sub-irrigation may have been most important for moisture provision during "bad" years, times when the rainy season arrived late or began with lighter than normal rains.

Rather than leave the matter at the level of the *possibility* of subirrigation in chinampas, however, I suggest that it is also important to consider the *probability* of whether chinampa farmers actually attempted to construct or maintain their fields in such a way as to optimize the potential for sub-irrigation.

Optimal sub-irrigation vs. risk of waterlogging

The range of chinampa heights reported in the literature, from 25 to 100 cm (Santamaría, 1993; von Humboldt, 1966), as well as a range in "ideal" height asserted by various *chinamperos* today, indicate that some fields were, and are, of the height necessary to facilitate sub-irrigation of some crops some of the time. Reports of deliberate adjustment of platform height after fields became too high also suggest farmer awareness of, and interest in creating and maintaining optimal morphologies for sub-irrigation (West and Armillas, 1950). However, several indications that farmers did not prioritize maintenance of their fields at the appropriate height to take advantage of potential sub-irrigation must also be noted.

First, water level in the chinampa zones was not static but fluctuated significantly during the year, and from one year to the next (Silviano Cabello, personal communication), even before the local springs were captured and their flow replaced by treated waste water pumped from elsewhere (Canabal Cristiani, 1997; Mansilla Menéndez, 1995; Marroquín and Rivera, 1910; Moncada Maya, 1982). Complaints by chinampa farmers regarding hardships caused by flooding of their fields were noted in the 16th and 19th centuries (Ciudad Real, 1976; Nuttal, 1992; Rojas Rabiela, 1993b). Several of Robert West's fall, 1946 photographs are of an inundated Tláhuac chinampería (West, 1946–1947). Some chinamperos recall harvesting corn from canoes as children, and while up to their knees in water (José Pérez, Antonio Sánchez, Francisco Martínez, personal communication). In 1998, heavy June rains flooded several chinampas, including some in San Luis that are often pointed out to visitors as being "the way chinampas are supposed to be" (José Pérez, personal communication). Today, the San Luis chinampería is experiencing inundation of many fields that were being farmed in 1997, including 3 of the study sites discussed here.[17]

Second, in spite of this evidence of persistent flood risk, low and declining water levels in the canal system have also been a major concern for over 50 years (Canabal Cristiani, 1991; Mansilla Menéndez, 1995; Moncada Maya, 1982; Silviano Cabello, personal communication). Field lowering, though, while reported in the literature (West and Armillas, 1950), has apparently been infrequently employed as a response to the water crisis. While the high labor cost of removing soil from a chinampa is clearly a significant factor, another reason for not lowering chinampas as canal water levels declined is that the risk of field flooding is more worrisome than the easier to predict, and resolve, problem of inadequate soil moisture (Antonio Sánchez, personal communication).

Indeed, numerous observers have noted chinampa farmers watering crops with the traditional *zoquimatl*, a long-handled, ladle-like tool, and by bucket (Coe, 1964; Crossley, 1999; Nuttal, 1992; Peña, 1978; Sanders, 1993; Santamaría, 1993). Presumably, such hand or splash watering is carried out when crops show signs of moisture deficiency or, more likely, on a regular schedule derived from farmers' experience with their own soils, knowledge of plant requirements, and interpretations of weather indicators.

Once such a watering schedule is in effect, as the days become longer, hotter, and drier, and conversations increasingly focus on when the rains will begin, I suggest it is highly unlikely that a farmer would stop watering, just because invisible, subsurface processes may begin to supply unknown amounts of moisture to the most mature plants. Rather, hand watering is likely to be continued until the summer rains arrive. Further, the rate of capillary rise into the root zone is not likely to match the rate of farmer-supplied moisture infiltrating from the field surface.

Thus, while it seems clear that chinampa soils make sub-irrigation possible, and that in years when the rainy season is late, this function could be significant for crop health, and thus subsequent yields, it also seems unlikely that chinampa farmers would have relied on this phenomenon, or even tried to build their fields such that it was facilitated, particularly when the risk of losing an entire crop due to late summer flooding is also considered.

Conclusions

In conclusion, I offer three sets of observations: those pertaining to ancient and historical chinampa cultivation; implications of this study for the present and near future of the chinampa zone; and finally, considerations for an understanding of intensive wetland agriculture in general.

Sub-irrigation in chinampa agriculture

While this study has shown that chinampa soils do produce sufficient capillary rise to potentially provide moisture to some crops in some fields in spite of several capillarity-inhibiting features of the platform subsoil, other factors have also been shown to be of crucial significance. After considering implications of the prevalence of willow roots in the capillary fringe, maize root growth phases, rainfall patterns in the region, and likely farmer attitudes toward both waterlogging risk and early summer moisture deficiency, I suggest three major conclusions:

1) sub-irrigation was probably important for crop moisture provision only under conditions of moisture crisis when onset of the rainy season was delayed or when the normally wet summer months were unusually dry;
2) sub-irrigation may have reduced slightly the amount and frequency of irrigation necessary, but did not likely lead farmers to refrain from hand watering;
3) the high organic matter content of the chinampa soils is likely an important feature of the chinampa system for moisture retention and availability, in addition to its fertility and other functions; and
4) sub-irrigation may have actually been more important for supplying moisture to the willow trees, thereby reducing competition for the moisture supplied from the surface, than in actually irrigating chinampa crops.

Implications for contemporary chinampa farmers

One of the initial aims of the research reported here was to establish how high the water level in the chinampería should be increased, and then maintained, in order to restore a sub-irrigation function to the remaining chinampas. Even if such a goal was feasible, restoration of sub-irrigation should not be the major motivation for further research or hydrological manipulation. This research indicates that numerous subsoil characteristics that vary over short distances result in differences in capillary rise that preclude definition of a single ideal platform height. The indication that sub-irrigation was probably most important as a factor in reduction of moisture deficit risk, which most contemporary chinamperos resolve with use of electric and gasoline powered pumps and hoses, further suggests that efforts to restore water levels for sub-irrigation would be misguided. There remain other reasons why it may still be adviseable to maintain or even increase the canal network, and to increase water provision to the area, among them the possibility of contributing to, or increasing the nighttime frost-amelioration effect (Crossley, 1999).

Significance for intensive wetland agriculture

While the observations made in this discussion have been specific to chinampa soils, crops, and climate in the Basin of Mexico, several implications for understanding wetland agriculture elsewhere may still be drawn. First, discussion of field morphology alone is insufficient to allow evaluation of the importance of sub-irrigation in wetland fields. Analysis of soil texture, particularly in fluvial environements where both coarser and finer sediments than those of the lacustrine chinampas are likely, must be combined with assessment of the organic matter content, and the nature of the subsoil before the magnitude of capillary rise can be estimated with confidence. Second, the importance of also considering the rooting depth of known or probable crops, seasonality and regularity of rainfall in relation to crop maturation phases, and the likelihood of highly fluctuating water levels have also been clearly demonstrated. Sub-irrigation may well have been more important in wetland fields in areas with a summer dry season than in the Basin of Mexico. But, without consideration of all of the factors discussed here, to assume so is unwarranted.

Notes

1. *Raised*, *drained*, *ditched*, *wetland*, *dike*, and *island* fields, as well as many vernacular terms have all been used by scholars to describe agricultural platforms in high water table environments. Some of these imply a particular function or construction process while others are common only in particular locations. In general, I prefer the term *wetland fields* both for its wide applicability and for its emphasis on the ecological setting rather than a putative function.
   In other contexts, I consider it important to maintain a distinction between *proto-chinampas* (Siemens, 1998) – earlier forms of wetland fields in the Basin of Mexico about which little is known – and chinampas, the fields described by many authors over the past century and the form still visible – in rapidly declining numbers – in the Xochimilco-Míxquic region today (Figure 2).
2. Careful, constructive, and insightful suggestions by an anonymous reviewer have contributed greatly to the overall quality of this paper, and to the strength of several of its arguments, and I am grateful for these contributions.
3. Many factors influence the rate of capillary conduction, including soil temperature, water chemistry, the history of wetting and drying of the soil (since this tends to affect pore arrangement and size), and whether the soil retains some moisture from a previous wetting episode (Childs, 1969; Iwata et al., 1988). The fact that soil pores are aligned in such a way as to form a tortuous path, rather than a simple vertical tube also contributes to a rather slow rate of capillary rise in the soils capable of producing the greatest height (Iwata at al., 1988; Tabuchi, 1966). Sandier soils, then, tend to reach their maximum capillary height within a few minutes or days while siltier soils achieve the same height of capillary rise over a period of hours or weeks (Brady, 1974; Carman, 1941; Whiteside et al., 1967).
4. Ruddle and Zhong (1988) do note a correlation between platform height and the rooting depth of the major Xi (Pearl) River delta crops, but provide no accompanying soil analyses.
5. The time required for capillary rise of this magnitude (approximately 85 cm) is on the order of 3–4 weeks (Brady, 1974).
6. See the following for discussion of the instruments, procedures, and mathematical models: (Brady, 1974; Carman, 1941; Childs, 1969; Iwata et al., 1988; Salter, 1966, 1967; Tabuchi, 1966).
7. When the center of a field was in use, farmers often suggested a nearby location would be more suitable. I chose the most central of the available sampling locations at each study site.
8. On the initial field visit, moisture samples were only obtained for each horizon. It was then determined that a tighter sampling increment would be more informative.
9. Reasons for this included significant rain and/or hail between excavation and sampling, prior excavation by others at an unknown date, splashes due to collapse of the profile into the pooled groundwater, etc.
10. Soil texture was consistently fine throughout the study area, with very fine sands and coarse to fine silt dominant in each sample. While flocculation problems during the sedimentation analysis make the texture analysis somewhat unreliable, these problems would have tended to produce results that indicated a soil texture with a higher sand and silt, and lower clay content than the soils may actually have. If the soils are actually slightly finer than my analysis indicates, then the expected capillary rise would be even higher, not lower, than the observed and interpreted ranges suggested here. However, I believe that the limitations on capillary rise due to the factors identified in the following discussion significantly outweigh the uncertainties due to unreliability of the texture analysis.
11. These figures for root zone depth are based on my experience in the garden ("shallow root depth") and on Foth's (1962) photographic evidence of late season maize root depth.
12. It is quite likely that the study chinampas were initially constructed (chinampa farmers consistently refer to *raising (levantar)* a chinampa, rather than building one) at very different times. Those sampled in Míxquic contained numerous Late Aztec ceramics, while those in San Luis were probably formed, or at least rebuilt, early in the 1900s. It is also highly likely that all of the fields have been significantly transformed, rebuilt, raised, and reworked numerous times over the period of their existence.
13. These diatom identifications were kindly made by Ed Theriot.
14. Soil/water interaction models are usually based on either testing with impermeable, spherical balls, non-volcanic soils, or on equations based on estimated mean pore diameter (e.g., Tabuchi, 1966; Iwata et al., 1988; Jury et al., 1991).
15. All of the profile descriptions, lab data, and graphs of the data for each of the 10 profiles are presented elsewhere (Crossley, 1999) and are available from the author.
16. Evidence of the widening of fields since earlier times can be found in numerous sources (e.g., Alzate y Ramírez, 1993; Avila López, 1992; Frederick, 1996; Nichols and Frederick, 1993; Parsons et al., 1982) and is reviewed in detail in Crossley (1999) and Frederick (1999) who also discuss the question of incorporation of the willow trees into the chinampa system.

17. Whether these recent inundations are caused by several years of high rainfall, subsidence due to aquifer depletion, disruption of the canal network that used to drain the flooded areas, or all of these, remains unclear and unstudied.

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