TREE-RING RECONSTRUCTED MAIZE YIELD IN CENTRAL MEXICO: 1474–2001

MATTHEW D. THERRELL[1,4], DAVID W. STAHLE[1], JOSE VILLANUEVA DIAZ[2], ELADIO H. CORNEJO OVIEDO[3] and MALCOLM K. CLEAVELAND[1]

[1]*Department of Geosciences, University of Arkansas, Fayetteville, Arkansas 72701, U.S.A. E-mail: therrell@uark.edu*

[2]*Instituto Nacional de Investigaciones Forestales y Agropecurias (INIFAP), KM 6.5, Margen Derecha Canal Sacramento, Gomez Palacio, Durango 35140, Mexico*

[3]*Departamento Forestal, Universidad Autonoma Agraria Antonio Narro Buenavista, Saltillo, Coahuila 25315, Mexico*

[4]*Current address: 316 Jessup Hall, Department of Geography, The University of Iowa, Iowa City, Iowa 52240, U.S.A.*

Abstract. Maize was domesticated more than 6,000 years ago in central Mexico, and remains a vital staple food and cultural symbol in Mesoamerica. Maize yield in the central highlands is strongly dependant on adequate rainfall early in the growing season (April–June) because late maturation of the crop may result in damage from autumn frost. Climate-induced crop failures with profound socioeconomic impacts have punctuated Mexican history. However, reliable records of maize harvest have not been available until very recently, and historical records of crop yield and price are discontinuous and can be difficult to interpret. We have developed a continuous, exactly dated, tree-ring reconstruction of maize yield variability in central Mexico from 1474 to 2001 that provides new insight into the history of climate and food availability in the heartland of the Mesoamerican cultural province. The reconstruction indicates that seven of the most severe agricultural crises in Mexican history occurred during decadal-scale episodes of reconstructed maize shortfalls.

1. Introduction

Mexico is the world's fourth largest producer of maize (USDA, 2003). Rainfed maize production is strongly influenced by climate variability particularly in the highlands of central Mexico (e.g., Conde et al., 1997, 1999; Eakin, 2000; Englehart and Douglas, 2000). The annual growing season for rainfed maize in this region is generally coincident with the summer rainy season that lasts from about April to October. Both the timing and quantity of wet-season rainfall can be highly variable because both are influenced by interactions between the highly mountainous terrain and large-scale circulation features such as the El Niño-Southern Oscillation, and the North American Monsoon System (NAMS; Wallén, 1955; Mosiño and García, 1974; Douglas et al., 1993; Magaña et al., 1999). The timing of rainfall onset in the spring is particularly important to maize yields because 1) the high elevation of much of central Mexico (generally greater than 2000 m) predisposes immature crops to early autumn frost events and 2) because late spring rains may result in maize crops that are less able to endure the 'canicula,' the

Climatic Change (2006) 74: 493–504
DOI: 10.1007/s10584-006-6865-z

mid-summer drought that typically begins in late July and lasts for several weeks (Eakin, 2000).

Historical descriptions of the impact of extreme climate on agriculture and society in central Mexico are available during colonial and modern times, and some events were even portrayed in prehispanic pictorial codices (e.g., Gibson, 1964; Florescano, 1976, 1986; Quiñones Keber, 1995). But there are no high quality, centuries-long records of regional maize production variability. Long historical records of maize prices in central Mexico have been compiled (Florescano, 1986; Garner, 1985; Garcia Acosta, 1995), but these data are often not well correlated with maize production due to the influence of variables other than climate, such as speculation and supply control (e.g., Gibson, 1964; Garner, 1985; Florescano, 1976, 1986).

2. Tree-Ring Studies of Climate and Crop Yield

The use of tree-ring records to estimate past crop yields was suggested as early as 1858 by Jacob Kuechler in Texas (Texas Almanac, 1861). Several studies on the relationship between tree-rings and crop yields were reported in the 1930s (Powell, 1932; Lyon, 1936, 1939; Senter, 1938). Hawley (1941) suggested that historical records could be used to validate tree-ring reconstructions of past climate and crop yields. Burns (1983) developed the first calibrated crop yield reconstructions. His work reconstructing maize and bean yields in southwestern Colorado was undertaken in an effort to test A.E. Douglass' 'Great Drought' hypothesis concerning Anasazi abandonment. Burns (1983) also used historical records to provide a measure of validation for his reconstructions. Van West (1994) utilized a geographical information system to develop spatially distributed crop reconstructions in southwestern Colorado. Anderson et al. (1995) used tree-ring derived precipitation reconstructions to estimate potential food reserves of prehistoric Mississippian societies in the Savannah River Valley of Georgia and South Carolina, and tested the colonial era portion of their estimates with information from historical Spanish documents.

3. Tree-Ring Research in Mexico

Tree-ring research in Mexico has increased dramatically in the last 10 years (e.g., Schulman, 1944; Scott, 1966; Villanueva Diaz and McPherson, 1996; Stahle et al., 2000a; Biondi, 2001; Diaz et al., 2001, 2002; Therrell et al., 2002; Cleaveland et al., 2003). As part of the continuing development of a network of tree-ring chronologies in Mexico, the University of Arkansas Tree-Ring Laboratory has recently developed new earlywood width (EW), latewood width (LW), and total ring width (TRW) tree-ring chronologies from Cuauhtemoc la Fragu, Puebla, the second-most southerly native stand of Douglas-fir (*Pseudtosuga menziesii*) trees known in the Americas (Figure 1).

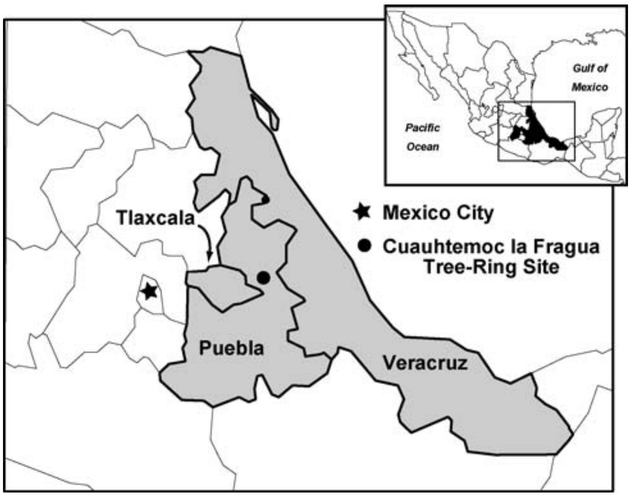

Figure 1. The three states for which the combined annual maize yield was reconstructed are highlighted (Puebla, Tlaxcala, and Veracruz) along with the locations of Mexico City and the new Cuauhtemoc tree-ring site. These three states have a population in excess of 12 million people and account for about 15% of the maize grown in Mexico. The Cuauhtemoc latewood width chronology was developed from a stand of ancient Douglas-fir growing in the mountains of northern Puebla (19.173N/97.312W; 3154 m elevation). Central Mexico has historically been the most densely populated region in the country.

In this study we have used our new LW data to reconstruct average annual maize yield anomalies (t/ha) from A.D. 1474 to 2001, for three states in central Mexico (Puebla, Tlaxcala, and Veracruz). We have also compared our reconstruction to historical records of crop failure and famine in order to cross-validate the tree-ring and historical records. We find that the tree-ring and historical data are in generally good agreement, particularly during the most extreme and prolonged episodes of reconstructed crop failure.

4. Tree-Ring Data

Douglas-fir is widely distributed in western North America. It reaches its southernmost limit in central and southern Mexico where a few small remnants of a larger Ice Age distribution can be found in relatively moist, high-elevation canyons (Martinez, 1963). Three small (~50 ha) stands of ancient Douglas-fir with trees 200–500 years old survive near the small town of Cuauhtemoc la Fragua, in the mountains of northern Puebla 16 km northwest of Pico de Orizaba (Figure 1).

We used 205 radii from 85 trees and fallen logs at this site to compile exactly dated EW, LW, and TRW chronologies extending from 1474–2001. Each tree-ring radius in the large Cuauhtemoc collection was exactly dated using standard dendrochronological methods described by Douglass (1941), and Stokes and Smiley

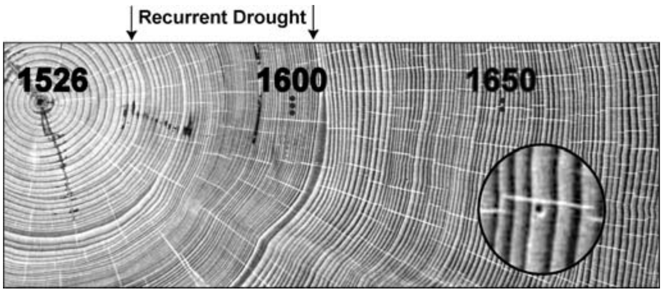

Figure 2. Annual growth rings of Douglas-fir seen on a highly polished cross-section cut off a dead log from the forest floor at Cuauhtemoc la Fragua, Puebla. The annual rings are a couplet of light-colored earlywood and darker latewood (enlarged). Note the suppression of growth, which began during the 16th century megadrought and continued through the drought of the 1590s to early 1600s. Historical records indicate crop failure, famine and epidemic disease during these decadal droughts.

(1996). The EW and LW growth increments were measured to a precision of 0.001 mm using a stage micrometer. The EW/LW boundaries were determined following simple optical criteria detailed in Stahle et al. (2000a; Figure 2). The results of the crossdating and measurement procedures were checked using the computer program COFECHA (Holmes, 1983). The COFECHA program was also used to indicate those LW series that were poorly cross-correlated with the common chronology in the outer portion of the individual series. This type of diminished variability and cross-correlation is sometimes seen in samples from older trees (Meko and Baisan, 2001; Therrell et al., 2002). A few LW segments with low variability were removed from the data set. The computer program ARSTAN was used to remove non-climatic growth trend in individual trees and differences in growth rate between trees, and to create a serially random, robust mean, index chronology (the so called 'standard chronology;' Cook, 1985).

5. Maize Yield Data

State-level maize production data have been compiled for most of Mexico from 1980 to 2001 by the Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion, and are available on the web (SAGRPA, 2002). For this study we use maize 'yield' data from the three states of Puebla, Tlaxcala, and Veracruz. The yield data represent statewide average production in tonnes (1000 kg) per ha. We use yield rather than total production to avoid the influence of non-climatic factors that might cause farmers to plant more or less land in maize in any given year and to avoid differences in total production between the states. The available data are arranged by growing season, and whether the crop was irrigated or rainfed.

In the highlands of central Mexico most of the annual maize crop is grown during the spring–summer growing season (92% from May to October) and of

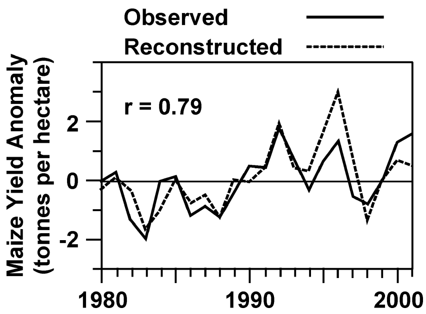

Figure 3. Normalized values of regionally-averaged observed (solid line) and reconstructed (dashed line) annual maize yield for Puebla, Tlaxcala and Veracruz are plotted from 1980 to 2001. The observed regional maize yield and our latewood width chronology are highly correlated over the calibration period 1980–2001 ($r = 0.79$; $P \leq 0.0001$). The strong relationship between Douglas-fir latewood width and regional maize yield in central Mexico is related to their mutual response to the timing and amount of spring (AMJ) rainfall. The slight trend in the observed maize yield is generally mirrored by the tree-ring data and appears to be primarily the result of climate.

that the majority is rainfed (84%). Therefore, we have chosen to use only the spring–summer maize yield data and will refer to it as 'annual' maize data. The average yield ranges from 1.48 t/ha in Puebla to as much as 1.74 t/ha in Veracruz. We combined these un-weighted state yield data for each year from 1980 to 2001 to create a regional average annual yield time series. The average yield over the 22-year period is 1.65 t/ha.

We use yield data rather than total production, but there may still be some level of 'technological trend' present in the maize yield data. Hybrid seeds, fertilizer, and other agricultural technologies used by modern growers, but not available to those in the past may help insulate modern crops from the impact of climate. There is some positive trend in the 22-year observational maize yield data (Figure 3), but the tree-ring estimates also exhibit a similar upward trend suggesting that this is largely the result of climate (Figure 3). Low maize yields and tree growth in the 1980s and high yields and growth in the early 1990s are coincident with unusually dry and wet periods, respectively. In fact, the lowest observed maize yields occurred in 1983 during one of the worst droughts on record in central Mexico (e.g., SMN, 2004).

6. Reconstruction of Central Mexico Maize Yield

The variability of Douglas-fir LW in central Mexico is well correlated with the onset of the rainy season in early summer, and with April–June rainfall totals (Therrell et al., 2002). Initial comparison of the Cuauhtemoc LW chronology with maize yield data from 1980 to 2001 indicates that the chronology is best correlated with a regional average of observed maize yield for the three states of Puebla, Tlaxcala, and Veracruz.

We performed several calibration analyses using bivariate regression between the LW chronology and the three-state crop record to develop the maize yield reconstruction, including an experimental split-period calibration-verification procedure typically used to develop dendroclimatic reconstructions (Fritts, 1976). To further validate the tree-ring reconstruction of prolonged maize yield in central Mexico we also compare the reconstruction with historical records of extreme climate and crop production.

The overall correlation (r) between the LW chronology and the combined three-state maize yield from 1980 to 2001 is 0.79, which is significant at $P < 0.0001$ for a sample size of 22. The regression model calculated for the tree-ring and modern maize data over the entire 22-year period of record explains 60% of the variance in maize yield ($R^2_{adj.} = 0.60$; Table I), and was used to reconstruct maize yield in

TABLE I
Calibration and verification statistics for the observed maize data and the Cuauhtemoc latewood chronology

	Time period		
Calibration	1980–1990	1991–2001	1980–2001
$R^2_{Adj.}$	0.50	0.42	0.60
Slope	1.230	0.645	0.862
Intercept	0.462^{ns}	1.066	0.796
Residual autocorrelation	-0.047^{ns}	0.476^{*}	0.344^{*}
Verification			
Correlation	0.74^{**}	0.69^{*}	
1st difference correlation	0.69^{*}	0.87^{***}	
Sign test (±)	5^{ns} 1	6^{ns} 1	
t test	-2.25^{*}	-0.81^{ns}	
Reduction of error	0.72	0.64	

Note. The 1980–1990 experimental calibration model is verified from 1991–2001, and the 1991–2001 model was verified during the 1980–1990 period. The statistics for the full calibration model are listed in column four (1980–2001, see Equation (1)). The variance explained was adjusted for loss of degrees of freedom ($R^2_{Adj.}$. The slope coefficients are all significantly different from zero, but there is no significant difference among the slope parameters of the three calibration models. All intercepts are positive, suggesting that even given zero latewood growth some amount of maize is still harvested. There is some autocorrelation in the residuals due mainly to the over-estimation of yield from 1994 to 1997 (see Figure 3). The significance of this residual autocorrelation is tested with the Durbin Watson statistic (Durbin and Watson, 1951). The two experimental calibration models both verify reasonably well against independent maize data in the alternate time period, with good correlation, sign test, and reduction of error statistics (Fritts, 1976; Fritts et al., 1990). But the mean is poorly estimated in the early experimental period.
ns = not significant $P > 0.05$.
$^{*} = P \leq 0.05$.
$^{**} = P \leq 0.01$.
$^{***} = P \leq 0.001$.

central Mexico for the past 528 years:

$$\hat{Y}_t = 0.796 + 0.862X_t \tag{1}$$

where $\hat{Y}_t$ is the estimated maize yield (tonnes per hectare) for year t, and X_t is the corresponding Cuauhtemoc LW value in year t. Although each subperiod is based on only 11 years of data, the experimental split-period calibration and verification analysis provides a measure of independent statistical validation for the regression model in Equation (1) (Table I). Most importantly, the regression coefficients for the two subperiods are not significantly different from the coefficients of the full model, and in all three cases the slope parameters are significantly different from zero (Table I). Furthermore, the two short subperiod calibration models pass most statistical verification tests when their estimates of maize yield are compared with the observed maize data in the alternate, statistically independent verification period (Table I).

Following calibration and verification, the observed and reconstructed maize yield data were normalized and represent standardized anomalies from the calibration period mean (1.65 t/ha; Figure 3). The reconstruction rarely underestimates the observed yield (e.g., 2000, 2001), suggesting that hidden agricultural technology trend has not seriously impacted the observed maize yield data.

7. Historical Records of Drought and Famine

Additional independent verification of the calibration model is difficult because we have found no reliable regional maize yield data for central Mexico before 1980. However, a number of qualitative historical references to climate and agricultural crises in central Mexico do provide a compelling measure of cross-validation between the historical data and the reconstruction, particularly during prolonged episodes of below average reconstructed maize yield. For example, the seven most intense and prolonged periods of deficit maize yield in the reconstruction coincide with well documented episodes of drought, famine, and social upheaval (Figure 4).

The 16th century megadrought that impacted much of North America (Stahle et al., 2000b) is apparent in the reconstruction beginning in the early 1540s. A number of crop failures and radical price increases are reported in the historical record during this time (Figure 4). It was also during this great drought that two of the most severe disease epidemics in Mexican history occurred (1546 and 1576) and these events appear to have been influenced by the drought and attendant famine (Gibson, 1964; Marr and Kiracofe, 2000; Acuña Soto et al., 2002).

Spring droughts and early autumn frosts contributed to poor yields in the 1590s. The lowest reconstructed value during this period occurred in 1597 when drought lasted until August, and prompted authorities to bring the Virgin de los Remedios into the metropolitan Cathedral from her shrine west of the city (Gibson, 1964; Figure 4). The movement of the Virgin to the metropolitan cathedral was the ultimate

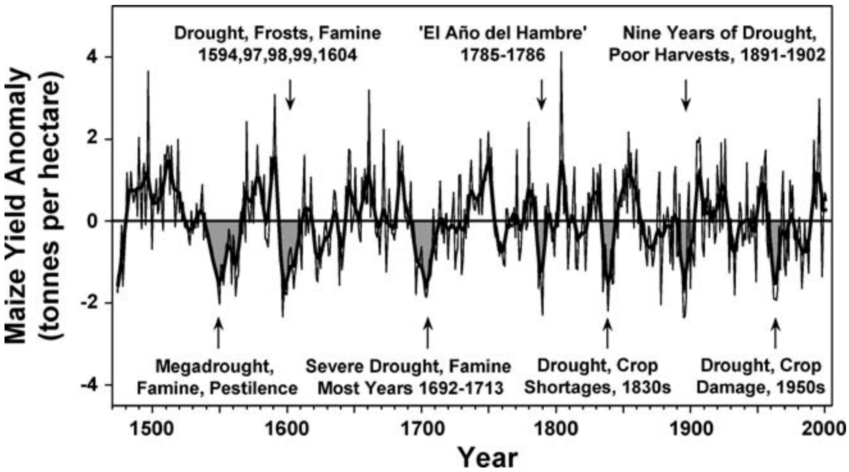

Figure 4. The annual (thin black line) and decadally-smoothed (heavy black line) anomalies of reconstructed maize yield in central Mexico from 1474 to 2001. The seven most severe and prolonged periods of poor maize yield after 1500 are indicated, along with highlights of historical references to drought and famine in central Mexico (Gibson, 1964; Florescano, 1980, 1986).

stage of an ecclesiastical process called rogation that was designed to encourage divine intervention to alleviate various crises, especially prolonged drought (e.g., Gibson, 1964; Martin Vide and Barriendos Valvé, 1995; Garza Merodio, 2002).

Below normal yields are reconstructed for 19 of 20 years from 1693 to 1712 (Figure 4). Drought, food shortages, and steep maize price increases are referenced for 11 of these years (Gibson, 1964; Garza Merodio, 2002).

A multi-year drought coupled with a severe August frost in 1785 resulted in a terrible famine in 1786, commonly known as ‘El Año del Hambre’ (The Year of Hunger; Florescano, 1986; Swan, 1981; Figure 4). Gibson (1964) describes this occurrence as “the most disastrous single event in the whole history of colonial maize agriculture.” This famine also apparently led to an outbreak of epidemic disease that killed as many as 300,000 people (Florescano, 1986). This extraordinary famine and epidemic apparently had a crippling effect on the economy and society of New Spain. Florescano (1986) has hypothesized that this episode contributed to lasting civil unrest that may ultimately have influenced the Hidalgo Rebellion in 1810 and independence from Spain.

Historical records are less widely available from the first half of the 19th century because of the turmoil and disorder that followed the War of Independence, which lasted from 1810 to 1821 (O’Hara and Metcalfe, 1995). But Florescano (1980) refers to severe drought and crop shortages in the Valley of Mexico during the 1830s, particularly in the spring of 1836, and ecclesiastical records indicate that drought occurred from 1838 to 1841 (Garza Merodio, 2002). The reconstruction confirms these conclusions, and indicates nearly a decade of deficit yields from 1835 to 1843 (Figure 4).

Prolonged crop failure is reconstructed again from 1890 to 1903 (Figure 4), in agreement with historical references to extraordinary drought and deficient harvests over much of the country from 1891 until 1906 (Florescano, 1980). O'Hara and Metcalfe (1995) suggest that deficit rainfall conditions and attendant food shortages in the first 15 years of the 20th century may have also contributed to social unrest resulting in the Mexican Civil War.

Extreme drought afflicted much of Mexico and the southwestern United States in the 1950s. The historical record suggests that intense drought occurred throughout the 1950s and early 1960s, particularly in northern Mexico (Metcalfe, 1987). The maize reconstruction indicates that yields were deficient for 11 of the 14 years between 1954 and 1967 (Figure 4). Damage to the agricultural sector in Mexico was described as "irreparable" and thousands of campesinos left rural areas looking for work in the cities of Mexico and the United States (Florescano, 1980).

8. Conclusions

The long tree-ring chronology from the relict stand of ancient Douglas-fir at Cuauhtemoc la Fragua, Puebla, has been used to develop a continuous, exactly-dated, high quality reconstruction of annual maize yield for the late prehispanic, colonial, and modern eras in the heart of highland Mexico. The strong agreement between tree growth, crop yields and social crises in the past highlights the significance of climate variability on rainfed agriculture in modern Mexico and the importance of prolonged drought and deficient yields in Mexican history.

The national economy of Mexico has become increasingly buffered against climate variability, but rural subsistence farmers remain vulnerable. For example, more than half of the maize produced in Tlaxcala is used for home consumption (Eakin, 2000) and nearly 70% of the daily caloric intake in rural Mexico is supplied by maize as tortillas (Salvador, 1998). Indeed, the cultural affinity for maize is particularly strong among the rural poor in Mexico. Subsistence farmers cultivate half of the cropland area planted in maize. As Sanderson (1986) describes, maize in Mexico is " . . . a crop produced by the poor for the poor." This rural bond to maize cultivation may heighten the socioeconomic impact of early-season drought in highland Mexico because many subsistence farmers are reluctant to grow other crops that are less sensitive to drought (Eakin, 2000).

Douglas-fir is exceedingly rare in central Mexico. Only six small Douglas-fir stands are known to exist south of latitude 22°N (San Luis Potosi), and Cuauhtemoc la Fragua is the largest of these stands with some of the oldest trees. In spite of the impressive biodiversity of forests in central Mexico, very few native tree species are known to produce reliable annual rings suitable for dendrochronology and none are known to be as sensitive to climate and crop yields as is Douglas-fir. The paleoclimatic and historical value of the ancient Douglas-fir at Cuauhtemoc la Fragua have only begun to be exploited, and it may be possible to extend this exceptional chronology further into the prehispanic era using relic wood preserved at the site. We are advocating special protection for the Cuauhtemoc la Fragua Douglas-fir site as a research natural area (e.g., http://www.uark.edu/dendro/cuauhtemoc.pdf) so it can continue to provide unique information about the environmental history of central Mexico.

Acknowledgments

We thank Anwar and Mariano Roman, R.D. Griffin, and Ricardo J. Salvador. This work was supported by the NSF Paleoclimate (ATM-9986074 and 0400713) and Geography and Regional Science Programs, the National Geographic Committee for Research and Exploration, and the Inter-American Institute for Global Change, Tree Lines Project. The observed (1980–2001) and tree-ring reconstructed (1474–2001) maize yields for central Mexico can be obtained from the National Geophysical Data Center at: http://www.ngdc.noaa.gov/paleo/recons.html.

References

Acuña Soto, R., Stahle, D. W., Cleaveland, M. K., and Therrell, M. D.: 2002, 'Megadrought and Megadeath in 16th century Mexico', *Emerg. Infect. Dis.* **8**, 360–362.

Anderson, D. G., Stahle, D. W., and Cleaveland, M. K.: 1995, 'Paleoclimate and the potential food reserves of Mississippian societies: A case study from the Savannah River Valley', *Am. Antiquity* **60**, 258–286.

Biondi, F.: 2001, 'A 400-year tree-ring chronology from the tropical treeline of North America', *Ambio* **30**, 162–166.

Burns, B. T.: 1983, *Simulated Anasazi Behaviour Using Crop Yields Reconstructed from Tree Rings: A.D. 652–1968*, Ph.D. thesis, University of Arizona, Tucson.

Cleaveland, M. K., Stahle, D. W., Therrell, M. D., Villanueva Diaz, J., and Burns, B. T.: 2003, 'Tree-ring reconstructed winter precipitation and tropical teleconnections in Durango, Mexico', *Clim. Change* **59**, 369–388.

Conde, C., Ferrer, R. M., Araujo, R., Gay, C., Magaña, V., Pérez, J. L., Morales, T., and Orozco, S.: 1999, 'El Niño y la Agricultura', in Magaña, V. (ed.), *Los Impactos de El Niño en Mexico*, Direccion General de Proteccion Civil Secretaria de Gobernacion, Mexico D.F., pp. 103–135.

Conde, C., Liverman, D., Flores, M., Ferrer, R., Arújo, R., Betencourt, E., Villareal, G., and Gay, C.: 1997, 'Variability of rainfed crops in Mexico to climate change', *Clim. Res.* **9**, 17–23.

Cook, E. R.: 1985, *A Time Series Approach to Tree-Ring Standardization*, Ph.D. Thesis, University of Arizona, Tucson.

Díaz, S. C., Therrell, M. D., Stahle, D. W., and Cleaveland, M. K.: 2002, 'Chihuahua winter–spring rainfall reconstructed from tree-rings: 1647–1992', *Clim. Res.* **22**, 237–244.

Díaz, S. C., Touchan, R., and Swetnam, T. W.: 2001, 'A tree-ring reconstruction of past precipitation for Baja California Sur, Mexico', *Int. J. Climatol.* **21**, 1007–1019.

Douglas, M. W., Maddox, R. A., Howard, K., and Reyes, S.: 1993, 'The Mexican monsoon', *J. Clim.* **6**, 1665–1677.

Douglass, A. E.: 1941, 'Crossdating in dendrochronology', *J. For.* **39**, 825–831.

Durbin, J. and Watson, G. S.: 1951, 'Testing for serial correlation in least squares regression. II', *Biometrika* **38**, 159–177.

Eakin, H.: 2000, 'Smallholder maize production and climatic risk: A case study from Mexico', *Clim. Change* **45**, 19–36.

Englehart, P. J. and Douglas, A. V.: 2000, 'Dissecting the macro-scale variations in Mexican maize yields (1961–1997)', *Geogr. Environ. Model.* **4**, 65–81.

Florescano, E.: 1976, *Origen y desarrollo de los problemas agrarios de Mexico 1500–1821*, Edicion Era, Mexico D.F. (in Spanish).

Florescano, E. (ed.): 1980, *Analisis historico de las sequias en Mexico*, Comision del Plan Nacional Hidraulico, Mexico, D.F. (in Spanish).

Florescano, E.: 1986, *Precios del Maiz y Crisis Agricolas en Mexico*: 1708–1810, Ediciones Era, Mexico D.F. (in Spanish).

Fritts, H. C.: 1976, *Tree Rings and Climate*, Academic, London.

Fritts, H. C., Guiot, J., Gordon, G. A., and Schweingruber, F.: 1990, 'Methods of Calibration, Verification, and Reconstruction', in Cook, E. R. and Kairiukstis, L. A. (eds.), *Methods of Dendrochronology*, Kluwer Academic, London.

Garcia Acosta, V.: 1995, 'Comparacion entre el movimiento de los precios del trigo y del maiz y el alza generalizada de precios a fines de la epoca colonial', in Garcia Acosta, V. (ed.), Los precios de alimentos y manufacturas novohispanos. Mexico: Centro de Investigaciones y Estudios Superiores en Antropologia Social and Instituto de Investigaciones Dr. Jose Maria Luis Mora, pp. 173–194.

Garner, R. L.: 1985, 'Price trends in eighteenth-century Mexico', *Hispanic Amer. Hist. Rev.* **65**, 279–325.

Garza Merodio, G. G.: 2002, 'Frecuencia y duración de sequías en la cuenca de México de fines del siglo XVI a mediados del XIX', *Invest. Geogr., Bull. Inst. Geogr., UNAM* **48**, 106–115 (in Spanish).

Gibson, C.: 1964, *The Aztecs Under Spanish Rule: A History of the Indians of the Valley of Mexico*, Stanford University Press, Stanford, CA.

Hawley, F. M.: 1941, *Tree Ring Analysis and Dating in the Mississippi Drainage*, Publications in Anthropology Occasional Paper No. 2., The University of Chicago Press, Chicago.

Holmes, R. L.: 1983, 'Computer-assisted quality control in tree-ring dating and measurement,' *Tree-Ring Bull.* **43**, 69–78.

Lyon, C. J.: 1936, 'Tree ring width as an index of physiological dryness in New England', *Ecology* **17**, 457–478.

Lyon, C. J.: 1939, 'Objectives and methods in New England tree-ring studies', *Tree-Ring Bull.* **5**, 27–30.

Magaña, V., Pérez, J. L., Vázquez, J., Carrisoza, E., and Pérez, J.: 1999, 'El Niño y el Clima', in Magaña, V. (ed.), *Los Impactos de El Niño en México*, Dirección de Protección Civil Secretaría de Gobernación, pp. 23–66 (in Spanish).

Marr, J. S. and Kiracofe, J. B.: 2000, 'Was the Huey Cocoliztli a haemorrhagic fever?', *Med. Hist.* **44**, 341–362.

Martin Vide, J. and Barriendos Valvé, M.: 1995, 'The use of rogation ceremony records in climatic reconstruction: A case study from Catalonia (Spain)', *Clim. Change* **30**, 201–221.

Martinez, M.: 1963, *Las Pinaceas Mexicanas*, Univ. Nacl. Auton. de Mexico, Ciudad Univ., Mexico City.

Meko, D. M. and Baisan, C. H.: 2001, 'Summer rainfall from latewood width', *Int. J. Climatol.* **21**, 697–708.

Metcalfe, S. E.: 1987, 'Historical data and climatic change in Mexico – A review', *The Geogr. J.* **153**, 211–222.

Morales, L. E.: 1995, 'Análisis de precios de los productos diezmados: El Bajio Oriental, 1665–1786', in Acosta, V. G. (ed.), *Los Precios de Alimentos y Manufacturas Novohispanicos*, Cento de investigaciones y Estudios Superiores en Antropología Social and Instituto de Investigaciones Dr. José Maria Luis Mora, pp. 122–172.

Mosiño, P. A. and García, E.: 1974, 'The Climate of Mexico', in Bryson, R. A. and Hare, F. K. (eds.), *Climates of North America*, Elsevier, New York, pp. 345–404,

O'Hara, S. L. and Metcalfe, S. E.: 1995, 'Reconstructing the climate of Mexico from historical records', *Holocene* **5**, 485–490.

Powell, L. B.: 1932, 'Tree-rings and wheat yields in Southern Saskatchewan', *Mon. Wea. Rev.* **60**, 220–221.

Quiñones Keber, E.: 1995, *Codex Telleriano-Remensis*, University of Texas Press, Austin, TX.

SAGRPA, Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion: 2002, *Sistema de Información Agropecuaria de Consulta* http://www.siea.sagarpa.gob.mx/sistemas/siacon/SIACON.html

Salvador, R. J.: 1998, 'Maize,' in Werner, M. S. (ed.), *Encyclopedia of Mexico Vol. M-Z*, Fitzroy Dearborn, Chicago, pp. 769–775.

Sanderson, S. E.: 1986, *The Transformation of Mexican Agriculture: International Structure and the Politics of Rural Change*, Princeton University Press, Princeton, NJ.

Schulman, E.: 1944, 'Dendrochronology in Mexico, I.', *Tree-Ring Bull.* **10**, 18–24.

Scott, S. D.: 1966, *Dendrochronology in Mexico*, Papers of the Laboratory of Tree-Ring Research, No. 2., University of Arizona Press, Tucson, AZ.

Senter, F. H.: 1938, 'Dendrochronology: Can we fix prehistoric dates in the Middle West by tree rings? Proceedings Nineteenth Annual Indiana History Conference', *Indiana Hist. Bull.* **15**, 118–128.

SMC, Servicio Meteorológico Nacional: 2004, http://smn.cna.gob.mx/SMN.html

Stahle, D. W., Cook, E. R., Cleaveland, M. K., Therrell, M. D., Meko, D. M., Grissino Mayer, H. D., Watson, E., and Luckman, B. H.: 2000b, 'Tree-ring data document 16th Century megadrought over North America', *Eos T. Am. Geophys. Un.* **81**, 121–125.

Stahle, D. W., Villanuava Diaz, J., Cleaveland, M. K., Therrell, M. D., Paull, G. J., Burns, B. T., Salinas, W., Suzan, H., and Fule, P. Z.: 2000a, 'Recent Tree-Ring Research in Mexico', in Roig, F. A. (ed.), *Dendrocronologia en America Latina*, EDIUNC, Mendoza, Argentina, pp. 285–306.

Stokes, M. A. and Smiley, T. L.: 1996, *An Introduction to Tree Ring Dating*, University of Arizona Press, Tucson.

Swan, S. L.: 1981, 'Mexico in the Little Ice Age', *J. Interdiscipl. Hist.* **11**, 633–648.

Texas Almanac [Galvaston]: 1861, 'The Droughts of Western Texas', *Texas Almanac* 1861:136.

Therrell, M. D., Stahle, D. W., Cleaveland, M. K., and Villanueva Diaz, J.: 2002, 'Warm season tree growth and precipitation over Mexico', *J. Geophys. Res.* **107**, 4205 doi:2001JD000851.

USDA, United States Department of Agriculture, Foreign Agricultural Service: 2003, *World Agricultural Production*, Circular Series WAP04-03 April 2003 http://www.fas.usda.gov/wap/circular/2003/03-04/wap 04-03.pdf

Van West, C. R.: 1994, *Modeling Prehistoric Agricultural Productivity in Southwestern Colorado: A GIS Approach*, Reports of Investigations 67, Department of Anthropology, Washington State University, Pullman, and Crow Canyon Archaeological Center, Cortez, Colorado.

Villanueva Diaz, J. and McPherson, G. R.: 1996, 'Reconstruction of precipitation and PDSI from tree-ring chronologies developed in the mountains of New Mexico, USA and Sonora, Mexico', in *Proceedings 1996 Meeting of the Hydrology Section, Arizona-Nevada Academy of Science* **26**, 45–54.

Wallén, C. C.: 1955, 'Some characteristics of precipitation in Mexico,' *Geogr. Ann.* **37**, 51–85.

(Received 19 May 2003; in revised form 10 November 2004)