Long and spatially variable Neolithic Demographic Transition in the North American Southwest

Timothy A. Kohler[a,b,c,1] **and Kelsey M. Reese**[a]

[a]Department of Anthropology, Washington State University, Pullman, WA 99164-4910; [b]Santa Fe Institute, Santa Fe, NM 87501; and [c]Crow Canyon Archaeological Center, Cortez, CO 81321

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In many places of the world, a Neolithic Demographic Transition (NDT) is visible as a several-hundred-year period of increased birth rates coupled with stable mortality rates, resulting in dramatic population growth that is eventually curtailed by increased mortality. Similar processes can be reconstructed in particular detail for the North American Southwest, revealing an anomalously long and spatially variable NDT. Irrigation-dependent societies experienced relatively low birth rates but were quick to achieve a high degree of sociopolitical complexity, whereas societies dependent on dry or rainfed farming experienced higher birth rates but less initial sociopolitical complexity. Low birth rates after A.D. 1200 mark the beginning of the decline of the Hohokam. Overall in the Southwest, birth rates increased slowly from 1100 B.C. to A.D. 500, and remained at high levels with some fluctuation until decreasing rapidly beginning A.D. 1300. Life expectancy at 15 increased slowly from 900 B.C. to A.D. 700, and then increased rapidly for 200 y before fluctuating and then declining after A.D. 1400. Life expectancy at birth, on the other hand, generally declined from 1100 B.C. to A.D. 1100/1200, before rebounding. Farmers took two millennia (∼1100 B.C. to ∼A.D. 1000) to reach the carrying capacity of the agricultural niche in the Southwest.

archaeology | paleodemography | maize | crude birth rate

Reconstructing regional human population size and growth rates through time is a central archaeological task. Population size is affected by ecosystem productivity and technology and affects type and degree of anthropogenic impact on the environment. Regional population size limits the maximum sizes that social groups within the region can attain (1). Social group size in turn influences the capacity of groups to innovate and maintain innovations (2, 3), and changes the conditions of the contest within societies between defection and its suppression, affecting efficiency in production of public goods and therefore social organization (4–7).

Archaeologists traditionally reconstruct population sizes and growth rates through time as some function of habitation site size and date. Producing credible reconstructions using such techniques requires a finely resolved chronology and a well-known archaeological record, and as a result we have detailed reconstructions for only a few locales within the Southwest (e.g., refs. 8–10), and estimates available for the entire Southwest are either somewhat out of date (11) or restricted to larger sites relatively late in the sequence (12). Here, we demonstrate the utility of bioarchaeological data for generating subregional estimates of birth rates for intraregional comparisons, and regional estimates of birth rates and life expectancies. Together, these allow demographic overviews at spatial and temporal scales where detailed architectural-based estimates of population are not yet possible.

Population size at time $t + 1$ is a function of natality, mortality, immigration, and emigration acting on the population at time t. Previous research has shown that societies typically experience several hundred years of rapid population growth on developing or acquiring domesticated plants and animals, followed by a marked decline in growth (13, 14). According to Bocquet-Appel, this is caused by an increase in natality with only a lagged increase in mortality. Collectively, this phenomenon is called the Neolithic (or Agricultural) Demographic Transition (NDT) (15).

In a sample of preindustrial populations under the stable population model, a simple paleodemographic indicator—the number of individuals 5–19 y old, divided by all individuals 5 y or more in age—has a strong positive correlation with the crude birth rate (CBR) ($r^2 = 0.96$) and the intrinsic growth rate r ($r^2 = 0.875$) (13, 16). This indicator is called the juvenility index or ${}_{15}P_5$.

Maize cultivation is documented for the North American Southwest (Fig. 1) by ∼2100 cal. B.C. (all dates are either calibrated calendrical years from ^{14}C or calendar years derived from tree rings), with first known appearances in the United States in southern Arizona and west central New Mexico (17, 18). Despite legitimate expectations to the contrary (19)—and in contrast to the situation in Europe and the Near East—high values for the juvenility index in the Southwest greatly lagged the first appearance of cultigens, according to an earlier study calculated on 4,396 sets of human remains from 51 archaeological sites and composite samples (20).

Values for the juvenility index in that study peaked between ∼A.D. 700 and 1200. This is some 3,000 y after the first appearance of maize but is more closely coincident with cultivation of the common bean, ubiquitous after A.D. 500 following its introduction to the Southwest between 1200 and 700 B.C. (21); common use of the bow and arrow by A.D. 500 (22); the common appearance of efficient ceramic containers throughout the Southwest by A.D. 600; the development or arrival of new

Significance

Population size greatly affects the human condition but is difficult for archaeologists to estimate. For the Neolithic North American Southwest, we use indirect methods to estimate birth rate and life expectancy, two major factors determining population size. The population boom usually accompanying the introduction of cultivated plants and animals, the "Neolithic Demographic Transition," was slow to emerge here and was marked by considerable subregional variability in birth rate. This variability is likely related to differing morbidities and availability of agricultural lands in various subregions. In common with many Neolithic peoples, pre-Hispanic Puebloans experienced very high birth rates, especially between A.D. 500 and 1300 when they possibly exceeded the highest in the world today, and quite low life expectancy at birth.

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[1]To whom correspondence should be addressed. Email: tako@wsu.edu.

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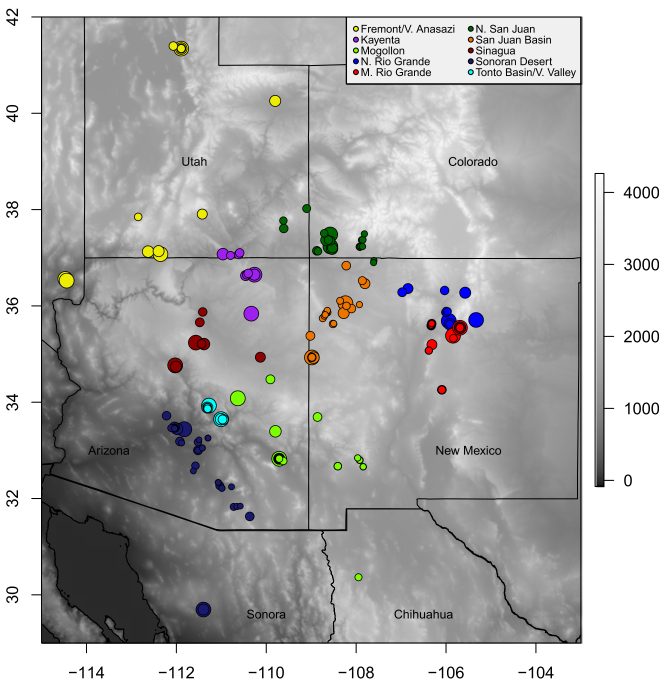

Fig. 1. Sites with assemblages contributing to $_{15}P_5$ or life expectancy estimates. Symbol size is proportional to number of individuals 5 y or older in each assemblage; symbol color indicates region. Background elevations in m.

and likely more productive races of maize [Maís Blando and Harinosa de Ocho (Maís de Ocho)] ~A.D. 600 (23); the appearance between A.D. 600 and 800 on the Colorado Plateau of villages consisting of many households together in a single site, often accompanied by public structures such as great kivas or large courtyards (24, 25); and the pithouse-to-pueblo transition between about A.D. 700 and 800, which allowed for, and signals, greatly increased storage of maize (26).

That pilot study (20) revealed considerable contemporaneous variability in the juvenility index, some of which seemed to be related to subregion. Here, we present juvenility indices from 194 sites and composite samples consisting of 10,199 sets of human remains, including those tallied in ref. 20. This larger sample allows us to partition $_{15}P_5$ values by subregion, revealing unsuspected spatial and temporal variability that affects our understanding of the causes of variability in CBR, and therefore the sources of culture change in the pre-Hispanic US Southwest. In addition, we make a preliminary calculation of regional life expectancies that reveals unsuspected temporal variability.

Results and Discussion

For the sample of human remains in Tables S1 and S2, we apply a nonparametric method for estimating local regression surfaces to fit the relationship between $_{15}P_5$ and calendar years for assemblages from 10 subregions (Fig. 1) (*SI Text, Sources of Data* and *Coding Conventions*). This method allows us to identify temporal trends in admittedly noisy data. Results are shown in Fig. 2 (*SI Text, Statistical and Graphic Conventions*).

Subregional Analysis, Southern Southwest. The earliest assemblages large enough to include in this analysis are from the Sonoran Desert. Although maize was introduced to this area from the south by ~2100 B.C. (18, 21, 27), birth rates as proxied by $_{15}P_5$ remained below what Bocquet-Appel considered zero growth ($_{15}P_5$ = 0.18; but see *SI Text, Statistical and Graphic Conventions*) until ~A.D. 1 (Fig. 2). (Contemporaneous $_{15}P_5$ values for the Kayenta area are similar but do not begin as early.) Although some researchers have argued for relatively sedentary occupations in the Sonoran Desert during the Early Agricultural period (2000 B.C. to A.D. 50) coupled with an intensive agricultural system producing most of the food (19, 28, 29), the low juvenility indices reported here favor suggestions that these occupations tended to be short-lived (30, 31) or part of a seasonal round (27), and perhaps most important, because this also affects mobility, focused on varieties of maize that were not yet very productive (32).

Values for $_{15}P_5$ plateaued in the Sonoran area between about A.D. 500 and 1000, during the late Formative and early pre-Classic (or the late Pioneer and early Colonial) periods in the Hohokam sequence. An extensive canal system allowing production of at least two maize crops per year was in place by the middle of this period (33), and not coincidentally Hohokam settlements spread far north of their core riverine zone in the Sonoran desert into the Flagstaff area, and into uplands south and west of Tucson and Phoenix during this same interval (33). A large-scale system of exchange, perhaps linked to ball court events, apparently developed into a market system from about A.D. 1000 to 1100 (34). Around that time, however, $_{15}P_5$ values began to decrease as populations reconcentrated in river valleys, especially in the Phoenix Basin, forming large platform mound communities. The very low $_{15}P_5$ values from about A.D. 1200 until the end of this sequence complement declines in population

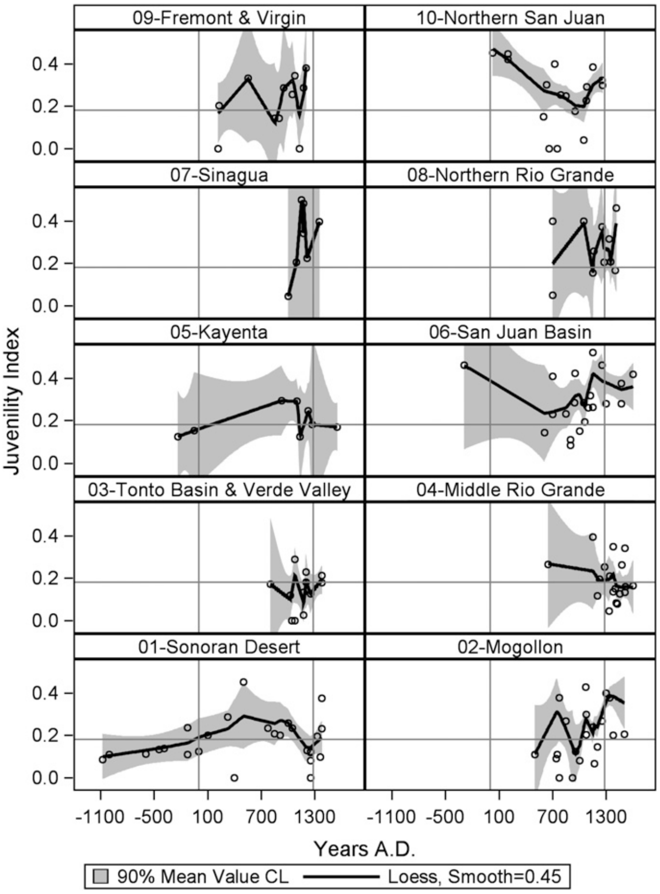

Fig. 2. Juvenility indices by region (loess fit with 90% CI). Regions are arranged from south (*Lower*) to north and west (*Left*) to east. Horizontal reference line at 0.18 represents Bocquet-Appel's estimate of the expected value of $_{15}P_5$ in a stationary population (*SI Text, Statistical and Graphic Conventions*). Vertical reference lines at A.D. 1 and 1280. Total *n* assemblages = 168.

visible in architectural data (12) and suggest a proximate cause for the "core decay" (35) long noted for this area and for the eventual disappearance of the Hohokam.

The Tonto Basin and Verde Valley areas, aggregated here, are marked by anomalously low $_{15}P_5$ values throughout their entire sequence (Fig. 2). Heavy reliance on a canal system in the Tonto Basin (as in the Sonoran Desert just to the south) may be partly responsible for these low $_{15}P_5$ values. Fink (36) has suggested that waterborne transmission of pathogens, including a variety of bacteria, viruses, protozoa, helminths, and fungi, may have elevated morbidity and mortality, particularly among infants and children. If this resulted in differentially depressing the size of 0- to 5-y-old cohorts, it would then have depressed the size of the 5- to 19-y-old cohort, ultimately reducing both the computed $_{15}P_5$ values and, of course, long-term population growth.

Cremation appears to have been more common in the Sonoran Desert and Tonto Basin/Verde Valley areas than elsewhere in the Southwest, although high proportions of cremations appear elsewhere occasionally [e.g., at Gran Quivira in the middle Rio Grande, where cremations account for 27% of all burials (37)]. Theoretically, this body treatment could affect $_{15}P_5$ values if cremations were more common for some age categories than for others, and if cremated bodies were unable to be aged more frequently than uncremated bodies. Although there is evidence for the second proposition, there is no evidence that cremation is significantly associated with age (38) (*SI Text, Cremation Analysis*).

The Mogollon subregion is large and contains both upland and lowland settings (Fig. 1), undoubtedly influencing its variability in $_{15}P_5$ values through time (Fig. 2). Juvenility indices peak somewhat later here than in most other subregions, boosted by large assemblages with high $_{15}P_5$ values (Paquimé in Chihuahua and Grasshopper Pueblo in the Mountain Mogollon area of Arizona) dating to the early A.D. 1300s. Several contemporaneous sites in the Mountain Mogollon area, including Grasshopper, apparently received influxes of women and children from the north in the late A.D. 1200s or early 1300s, possibly as refugees (39, 40). Such an influx could inflate $_{15}P_5$ values both immediately, because of the children, and over time if female immigrants were predominately of child-bearing age.

The middle Rio Grande subregion has few assemblages predating ~A.D. 1200 and was apparently lightly occupied before that time. Birth rates declined slowly and almost linearly from the A.D. 1200s through the 1500s, with the latest assemblage from Pueblo de las Humanas (Gran Quivira) late enough to have been influenced by Spanish introduction of diseases (Table S1) (37).

Subregional Analysis, Northern Southwest. Except for the northern Rio Grande (Fig. 1), the remaining six areas in Fig. 2 are completely or mostly on the Colorado Plateau, a physiographic province that in late pre-Hispanic times was associated with Pueblo societies and the Fremont of Utah. These societies relied on rainfed farming or on dry farming (21), with various water-harvesting techniques and small-scale irrigation important in the northern Rio Grande after ~A.D. 1300.

In general, these six northern sequences are marked by higher $_{15}P_5$ values than are the four southern areas, although the Kayenta and Fremont/Virgin regions are intermediate in this respect, presumably because their generally lower elevation and greater aridity relative to the San Juan Basin and the Northern San Juan limited maize production (Fig. 2 and Fig. S1). The exception to lower $_{15}P_5$ values in the western portions of the Southwest (the left-hand columns in Fig. 2) is the Sinagua area near Flagstaff, Arizona. All but the earliest site in this series postdate the eruption of nearby Sunset Crater, traditionally dated to A.D. 1065 but now believed to be closer to 1090 (41). It has long been proposed that this eruption created propitious agricultural conditions (42), and this is supported by the Sinagua's high posteruption $_{15}P_5$ values (Fig. 2).

The high $_{15}P_5$ values early in the Northern San Juan sequence are especially remarkable and unlike anything seen contemporaneously in the southern Southwest. The San Juan Basin sequence also appears to start with high values, but this is based on only one small assemblage. From ~A.D. 700 to 1100, however, the San Juan Basin rates are among the highest in the Southwest. Although $_{15}P_5$ values were declining slightly in the San Juan Basin after ~A.D. 1200, they remained relatively high there and in the northern San Juan. Whatever the causes of the depopulation of the northern Southwest during the A.D. 1200s, they seem not to have greatly affected $_{15}P_5$ values in these two growth centers.

Possible Explanations for the Plateau/Desert Valley Contrast. The contrast between the generally higher $_{15}P_5$ values for dry/rainfed farming areas in the north and the lower values for the Sonoran Desert and Tonto Basin that were more dependent on irrigation is surprising and previously unrecognized. From the intensity of Hohokam agricultural systems and their early sociopolitical complexity (25, 43), one might predict rapid population growth and therefore high $_{15}P_5$ values. However, in fact, households in the irrigation-dependent south were apparently having fewer offspring than the dry farmers to the north and east. (That these societies might have been exporting their offspring to other subregions seems implausible, although it could be explored with stable isotope analyses.) In addition to the possibility that increased pathogen loads in irrigation systems depressed $_{15}P_5$ values, we suggest that the differing distributions of potential agricultural land in the two areas contributed to this pattern.

In many portions of the Colorado Plateau, extensive tracts of productive lands became available when precipitation and temperature patterns were favorable, making it possible for families to export numerous offspring to other favorable areas. However, irrigation systems can expand only with great difficulty. In many cases, topography or vested interests make it impractical to expand or reorient irrigation networks. Theory explaining why sociopolitical complexity should develop first in circumscribed areas such as the Phoenix Basin has long been available (44), and in light of these results may be applicable to the north/south contrast in rate of political evolution in the Southwest. A possible consequence of greater social hierarchization is that opportunities for reproduction may have monopolized by fewer, richer households in irrigation-dominant societies but shared more equally in the north, with the net result at the population level being higher juvenility indices in the north, and lower indices in the south.

This expectation—consistent with reproductive skew theory (45)—could be tested by comparing burial assemblages from Classic period platform mounds advantageously located on the canal system against more peripheral contemporaneous assemblages—a task not attempted here. Regardless of such possible variability within subregions, the distribution of $_{15}P_5$ values across the Southwest (Fig. 2) suggests that pioneer southwestern archaeologist A. V. Kidder (46) was quite literally correct when he identified the San Juan (in which he included the Northern San Juan, San Juan, and Kayenta areas) as "the breeding ground for many of the basic traits of Southwestern culture and center of dissemination."

Combined Southwest: Crude Birth Rates and Life Expectancies. The $_{15}P_5$ values for all 10 subregions are combined and converted to CBR in Fig. 3 (*SI Text, Crude Birth Rates*). This reveals an almost linear trend from around 0.02 at ~1100 B.C. to a peak ~A.D. 500 at rates exceeding 0.05. Birth rates then leveled off, with some variability including a slight dip in the mid-A.D. 1100s, until about A.D. 1300. After that, CBR declined rapidly across the Southwest, to levels not experienced for the previous 1500 y.

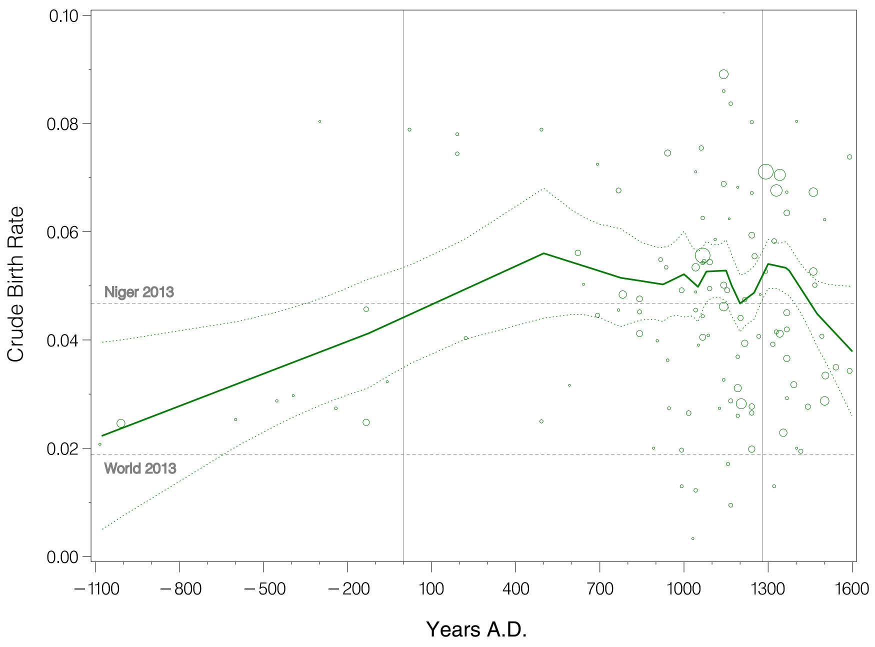

Fig. 3. Crude birth rate (green, *n* assemblages = 133) through time, entire Southwest (loess fit with 90% CI). Symbol size is proportional to number of individuals 5 y or older in each assemblage. Horizontal reference lines mark current estimated CBR for the world and for the nation with the highest current CBR, Niger. Vertical reference lines at A.D. 1 and 1280.

Overall, the birth rates for these populations appear to be very high. The mean value of the fitted CBR for all assemblages in this sequence is 0.049 ($s = 0.006$), above the highest value reported in the world today (Niger, 0.047; Fig. 3) (47).

For 36–40 assemblages that are relatively large (minimum, 24 individuals; mean, 98) and for which life tables are available or can be constructed, Fig. 4 reports life expectancies at age 15 (e_{15} + 15), and two measures for life expectancy at birth (e_0) (*SI Text, Life Expectancy Calculations*).

Total life expectancies at 15 increased very slowly from around 35 y at ~900 B.C. to about 37 y at ~A.D. 600, and then more rapidly to almost 40 y ~A.D. 1000, after which they declined markedly, bottoming out near 35 y ~A.D. 1150 (Fig. 3). Values increased again until ~A.D. 1400, and then decreased. The mean fitted value for e_{15} values is 37.2 y ($s = 1.1$).

We acknowledge a number of potential problems with the e_{15} estimate and the e_0 estimate based on life tables (e_0LT), including both underenumeration of infants and children, and underestimation of older-adult ages (48). Given the nature of the data, trends through time are more credible than are the absolute estimates. Comparisons with modern populations for which life tables are not reconstructed from death assemblages are especially problematic, and in fact the e_{15} values we estimate are much lower than some modern hunter-gatherer groups with e_{15} values between about 51 and 58 y (thus, average total life spans of six or seven decades for those surviving to 15) (49). More to the point are comparisons (below) with other ancient populations, because the biases introduced by the archaeological record and the problems inherent in building life tables from osteological samples are shared.

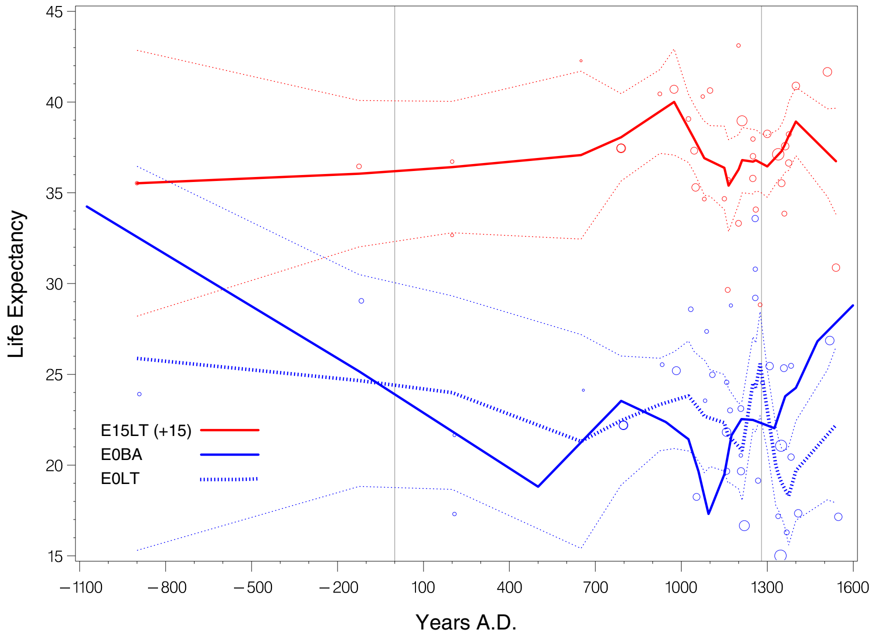

Fig. 4. Life expectancy at 15 from life tables (red, *n* assemblages = 36) through time, entire Southwest (loess fit with 90% CI); life expectancy at birth from life tables (dashed blue line, n assemblages = 40) through time, entire Southwest (loess fit with 90% CI); life expectancy at birth from juvenility indices (solid blue line, n assemblages = 120) through time, entire Southwest (loess fit, no CI). Symbol size is proportional to the number of individuals 5 y or older in each assemblage; red symbols represent assemblages used to estimate e_{15}LT; blue symbols, e_0LT. Vertical reference lines at A.D. 1 and 1280.

The two estimates of life expectancy at birth (Fig. 4) both suggest declines from ∼1100 B.C. until A.D. 500/600, followed by an increase till A.D. 700/1000, a sharp decline bottoming out A.D. 1100/1200, with post-A.D. 1300 increases. Overall, by either measure the life expectancy at birth of these southwestern populations was quite short (mean fitted value of e_0LT = 22.1, $s = 2.1$; mean fitted value of e_0BA = 22.8, $s = 3.1$).

Summary and Conclusions

Using proxies derived from excavated assemblages of human remains we have estimated juvenility indices (convertible to birth rates) for 10 subregions, and birth rates for the entire North American Southwest, for ∼2,500 y beginning ∼1000 B.C. We also used two techniques to provide preliminary estimates of life expectancies through time at birth and at age 15 for the Southwest as a whole (*SI Text, Life Expectancy Calculations*).

Table S3 assembles some comparative data for the three life expectancies estimated here. Estimates for life expectancy at birth in this southwestern series are somewhat below the mean of the other series in this table, whereas the mean fitted value for e_{15} in the Southwest is well above the average for the other series. We can tentatively conclude that in the Southwest chances of dying before age 15 were somewhat higher than was typical in the post-Pleistocene, premodern world, but those surviving to age 15 could expect somewhat longer lives than in many contemporaneous societies. The widening gap between our two measures of e_0 and e_{15} from ∼1000 B.C. to A.D. 400/500 seems to suggest an increasing proportion of mortality in prereproductive ages over this period as sedentism and reliance on maize also generally increased.

The NDT in the Southwest was less a revolution than a slowly accelerating demographic process in which birth rates increased steadily for some 1,600 y beginning no later than ∼1100 B.C. Birth rates leveled off (with some fluctuation) at high values ∼A.D. 500 and eventually declined rapidly beginning A.D. 1300. This is a long time for such high rates to be maintained (50); the mean duration of the "boom" phase of the NDT in 11 subregions of Europe is 600 y (51). This long expansion may have been possible because climates permitted Fremont farmers to intensively use large portions of the Great Basin between ∼A.D. 700 and 1200 (although colonization began earlier) (52), and farmers were also able to expand into large portions of the middle and northern Rio Grande after A.D. 900 (53). Nevertheless, the decline in e_{15} after A.D. 1000 may have been due to density-dependent compensation. By A.D. 1000, life expectancy at 15 had been increasing (slowly at first, and then more rapidly) for some 1,900 y.

Although we do not attempt to translate these indices into population sizes or growth rates, a plausible interpretation is that populations increased in size in the Southwest for ∼2,200 y, from no later than 1100 B.C. to ∼A.D. 1100, stabilizing or declining after that time. A Southwest-wide population decline beginning ∼A.D. 1100 has been suggested (11); others have reconstructed declines in the northern Southwest after A.D. 1250 and in the southern Southwest after A.D. 1350 (12). The rates reconstructed here suggest that population increases were probably most rapid between ∼A.D. 500 and 1000, the period in which values for both birth rate and e_{15} were at or near their peaks. We suggest that the close of this interval, also marked by the increasing appearance of durable masonry architecture in many subregions, signals the effective end of territorial expansion as a way of accommodating more offspring, although in some subregions population increases could still be supported via increases in sociopolitical complexity.

The CBR and all three estimates of life expectancy record a pronounced dip some time between the late 1000s and late 1100s. Given the extreme dependence on maize in nearly all of the Southwest after ∼300 B.C. (54, 55), these declines may have been partly in response to the megadrought centered on A.D. 1150 affecting large portions of the West (56). It is possible that other variability in CBR between about A.D. 900 and 1300 reflects other droughts centered on A.D. 936, 1034, and 1253 (56). In northern and upland portions of the Southwest, the progressive cooling of the northern hemisphere in the Little Ice Age (57) may also have decreased maize production after A.D. 1200 (58, 59). Although there is considerable variability in birth rates through time in specific subregions (Fig. 2), the smooth increases in CBR for the first 2000 years of this record suggest that local climatic downturns could be buffered by interregional movements until toward the end of the first millennium A.D. This in turn suggests that southwestern maize farmers took over 2,000 y to fill up their agricultural niche and become regionally susceptible to climatic variability.

Bocquet-Appel (60) suggested that initial population increases in the NDT were driven solely by increases in natality, with lagged increases in mortality eventually returning farming populations to a stable state. In the Southwest, by contrast, increasing life expectancy during reproductive years probably had a positive although minor role in initial NDT population growth, and decreased CBR contributed importantly to eventual population stabilization (or possibly decline). None of this calls into question Bocquet-Appel's conclusions concerning the centrality of the relationship between increased sedentism and increased natality—conditions that slowly coevolved in the Southwest, not resulting in relatively stable sedentism in most subregions until ∼A.D. 600.

The slow demographic processes reconstructed here hardly seem like a Childean "Neolithic Revolution" (61). We argue although that populations crossed a critical threshold in the middle of the first millennium A.D. when "more" became "different" (62). At that point, for the first time in 1,600 y, birth rates plateaued, at high levels, and even declined slightly as opportunities for colonization began to decrease. For most groups, increasing birth rates was no longer a viable strategy. Instead, groups began to exploit smaller territories more intensively, as seems to have happened in the Natufian Near East (63). Community sizes began to increase (64), plausibly in response to intergroup competition as having more members improved chances for acquiring or retaining superior territories. Larger social groups favored novel sociopolitical arrangements and investments in architectural features such as ball courts in the south and great kivas elsewhere that could coordinate large numbers of participants. Across much of the northern Southwest, this macroevolutionary transition (65) is recognized as the beginning of the Basketmaker III period. More generally, this A.D. 500–700 period marked increased internal codification and external differentiation of the Ancestral Pueblo, Mogollon, and Hohokam traditions.

Materials and Methods

Data on human remains were acquired from a number of primary and secondary sources (*SI Text, Sources of Data*) and coded following practices developed in previous NDT research (*SI Text, Coding Conventions*, and ref. 20). Figs. 2 and 3 use loess smoothing of demographic proxies against the absolute date of the assemblages from which they were developed (*SI Text, Statistical and Graphic Conventions*). We examined, and rejected, the possibility that cremations might be significantly affecting $_{15}P_5$ values (*SI Text, Cremation Analysis*). Values for $_{15}P_5$ were converted to CBR following ref. 13 (*SI Text, Crude Birth Rates*). Life expectancies at birth and at 15 were drawn from the literature or computed from life tables generated from the literature as explained in *SI Text, Life Expectancy Calculations*, where we also describe an alternative estimate for e_0 (e_0BA) derived from ref. 13.

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