Don't throw out the baby with the bathwater: estimating fertility from subadult skeletons

By: Gwen Robbins

This is the peer reviewed version of the following article:

Robbins, G. (2011). Don't throw out the baby with the bathwater: estimating fertility from subadult skeletons. *International Journal of Osteoarchaeology, 21(6),* 717–722. https://doi.org/10.1002/oa.1181

Abstract:

Recent research interest has focused on the bioarchaeology of children. Although paleodemography is essential for accurate reconstructions of lifestyle and health in past populations, currently there is no published technique for estimating fertility and life expectancy at birth for skeletal populations in which adults are under-enumerated. This paper provides a formula to predict Gross Reproductive Rate (GRR) from the proportion of young infants to subadults in a skeletal population. The formula was developed from 98 of Coale and Demeny's Female Model West Life Tables, which represented diverse fertility and mortality rates. The formula's accuracy was examined using independent samples from historical and archaeological cemeteries. Estimates of GRR from the subadult fertility formula were compared with estimates from Bocquet-Appel and Masset's juvenile:adult ratio. Results indicate that the subadult fertility formula predicts GRR with consistent accuracy ($R^2 = 0.98$) and precision (± 1 offspring) in the model life tables, across diverse subadult age structures and demographic characteristics. The formula is useful for subadult populations with a proportion of perinates:subadults between 0.12 and 0.45. The adult component of the sample is not included in the analysis and thus the formula is similarly useful in cases where adults are under-enumerated, or not. When applied to historical and archaeological populations, estimates for GRR are similar to previous estimates from the juvenile:adult ratio. Because crude birth rate and life expectancy at birth can be calculated from GRR using established fertility centred approaches to demography, the subadult fertility formula allows skeletal populations of diverse composition to be included in demographic research, essential for understanding of how mortality and fertility are affecting the morbidity profiles of subadult samples and for comparative bioarchaeological analyses.

Keywords: bioarchaeology | children | demography | fertility

Article:[*]

[*] Erratum included at the end of this formatted document.

Introduction

Bioarchaeologists use age and sex estimates from the human skeleton to construct demographic profiles which describe mortality and fertility rates in past populations. Paleodemography represents a particularly difficult challenge but it is a necessary component of bioarchaeology because both mortality and fertility can have significant impacts on the pathological profiles (Wood *et al*., 1992; Saunders & Hoppa, 1993; Cohen *et al*., 1994; Cohen, 1997; Wright & Yoder, 2003; Lukacs, 2008). The various techniques for paleodemography have been subject to much criticism over the years (Bocquet-Appel & Masset, 1982; Buikstra *et al*., 1986; Hoppa & Vaupel, 2002; McCaa, 2002; Bocquet-Appel, 2007). Many critiques have focused on assumptions of stability and stationarity. Others have pointed out the circularity of 'shoehorning' populations, fitting them to model life tables, which effectively eliminates the potential for recognising and studying variation. In addition, it is widely recognised that adult skeletons are problematic for demography because age estimation methods have a centrist tendency, which leads to a preponderance of individuals in the 30–45 year age bracket and an under-enumeration of older adults.

In response to the numerous critiques and difficulties of doing paleodemography, the field has evolved substantially and innovative statistical approaches to the age pyramid have been developed (Sattenspiel & Harpending, 1983; Jackes, 1986; Jackes, 1992; Konigsberg & Frankenberg, 1992; Konigsberg & Frankenberg, 1994; Paine & Harpending, 1996; Paine, 1997; Meindl & Russell, 1998; Hoppa & Vaupel, 2002) including fertility centred approaches to the age structure of skeletal populations (Sattenspiel & Harpending, 1983; Horowitz *et al*., 1988; McCaa, 1998, 2002). One area that has received less research attention in paleodemography is subadult skeletal populations, samples comprised of a large proportion of subadults in which adults are under-enumerated.

This paper provides a method (the subadult fertility formula) for estimating Gross Reproductive Rate[1] (GRR) for such skeletal populations. Once GRR has been estimated from the age pyramid, Total Fertility Rates (TFR) and life expectancy at birth (e_o) can be calculated using a published technique to derive those estimates from GRR (McCaa, 1998). In previous publications including the Health in the Western Hemisphere project (McCaa, 2002), GRR was estimated using the juvenility index (${}_{5\text{–}14}D_{20+}$), the proportion of individuals who died between the ages of 5 and 14 years to dead adults > 20 years (Bocquet-Appel & Masset, 1982). This method, like most methods for paleodemography, deliberately ignores young infants and children because they 'should be' under-represented in archaeological populations (Angel, 1969; Weiss, 1973). Despite the perception that subadults are not often preserved, McCaa found that subadults represented almost half of the assemblages (mean = 0.48; range between 0.22 and 0.56) in a meta-analysis of 51 skeletal populations (McCaa, 1998). This paper provides a technique for constructing demographic profiles for skeletal populations in which subadults are well represented and for populations in which adult skeletons are under-enumerated.

[1] GRR is defined as the average number of female offspring born to each woman, assuming she survived to the end of her childbearing years, conformed to differences in age-specific fertility rates and there was a 105:100 sex ratio at birth (Last, 2001).

Materials and methods

The subadult fertility formula was developed using Female Model West Life Tables (Coale & Demeny, 1983), data commonly used for developing methods in paleodemography (Bocquet-Appel & Masset, 1982; Buikstra *et al*., 1986; McCaa, 1998). The range of model life tables was restricted to populations that fit with the expectations for archaeological samples. The sample included 98 tables from populations with growth rates within the range of −1 to 2% and mortality levels 1–14. Growth rates were restricted because archaeological populations are not expected to grow at a rate faster than 2% (the population is doubling every generation) (Livi-Bacci, 2007). Tables with mortality rates outside the range of 1–14 were excluded because those populations had a higher proportion of individuals in the 70 + age range and that age structure is uncommon in paleopopulations (McCaa, 2002; Steckel & Rose, 2002). The tables included in this sample had diverse age structure; the proportion of perinates (0–1 years old) to subadults (2–20 years old) ranged from 0.06–0.78.

To estimate the proportion of perinates in the subadult population, the adult age categories (20 +) were excluded and only the subadult (0–19 years) age pyramid was considered. Data collected from the tables included the number of deaths in each subadult age category, population growth rate, mortality level, observed GRR, crude birth rate and crude death rate. The proportion of young infants:subadults was calculated as ${}_{0–1}D_{2–19}$, or the proportion of infant deaths in the first year of life (0–1 year) divided by the sum of subadult deaths (2–19 years). This proportion was used to develop the formula to predict GRR, based on quadratic regression analysis.

The subadult fertility formula was tested using an independent skeletal sample from St. Thomas' Anglican Church in Belleville, Ontario (Saunders *et al*., 2002). The sample for this analysis consisted of 575 individuals excavated from 579 grave shafts prior to the construction of a parish hall in 1989 (Saunders *et al*., 2002). This sample is derived from what was a large cemetery, with 1564 individuals buried between 1821 and 1874. Detailed historical records about age and sex are available (Saunders *et al*., 1995). The proportion of perinates:subadults was calculated as ${}_{0–1}D_{2–19}$. GRR was then estimated using the subadult fertility formula and the juvenile:adult ratio (${}_{5–14}D_{20+}$) and the accuracy of the two estimates was compared. Accuracy was defined as the absolute value of the difference between observed and predicted GRR.

The accuracy of estimates for GRR from the subadult fertility formula was also evaluated in 11 populations from the Health in the Western Hemisphere project (McCaa, 1998, 2002). GRR estimates from the subadult fertility formula were compared with previous estimates of GRR made using Bocquet-Appel's juvenile:adult ratio (${}_{5–14}D_{20+}$) (McCaa, 1998, 2002). The sample included populations from diverse regions and time periods (described in the Health in Western Hemisphere project (McCaa, 1998, 2002)) including a skeletal population from the Neolithic (4387–3788 B.P.) in France (Loisy en Brie), Classic Period (1200–650 B.P.) village populations from Central and North America (Chiribaya, Dickson Mound, Estaquina, Maitas, Monongahela, Pearson), an Historic era cemetery (1000 B.P.) in England (Scarborough), and Historic Era (100–400 B.P.) Native North American populations (Amelia Island and Hawikku). These populations also had diverse composition in regard to the age pyramid, with the proportion of perinates:subadults ranging from 0.24 to 0.52.

Results

The following quadratic equation was developed to estimate GRR from the proportion of perinates in the subadult population

$$\mathrm{GPR} = -2.78 + \left(7.71 \times {}_{0-1}\mathrm{D}_{2-19}\right) + \left(34.26 \times {}_{0-1}\mathrm{D}_{2-19}^{2}\right) \quad (1)$$

Results of a one-way ANOVA suggest that the proportion of perinates in the subadult component of a population is a significant predictor of GRR ($F = 81.25$, $p < 0.001$). Figure 1 demonstrates that the subadult fertility formula is a good predictor of GRR in the Coale and Demeny model life tables ($R^2 = 0.9805$, $p < 0.001$). Table 1 provides descriptive statistics on the proportion of perinates, crude birth and death rates, observed and predicted GRR, mean SE of the prediction and an estimate of accuracy. Accuracy was defined here as the absolute value of the difference between the actual value of the dependent variable (Y) and the predicted value ($\hat{Y}$), $\left(\left|Y - \hat{Y}\right|\right)$, given the proportion of perinates in the subadult sample (X). Despite the diverse age composition of the reference population, the formula performed with fairly consistent accuracy (range was 0.8–1.7 offspring).

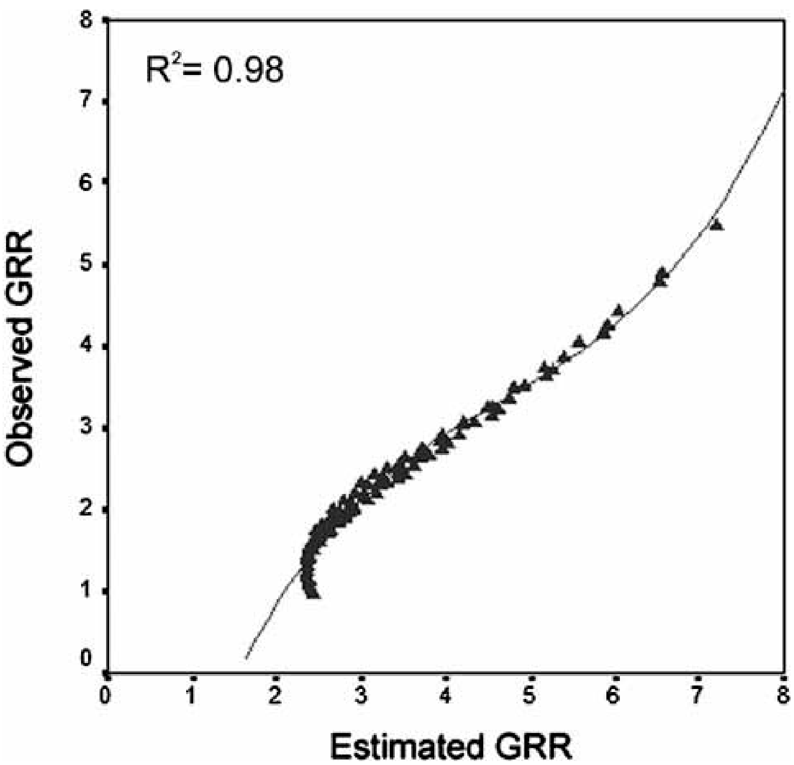

Figure 1. Observed versus estimated GRR in 98 Female Model West Life Tables (Coale & Demeny, 1983).

Using the Coale and Demeney life tables, a comparison was made of estimates of GRR from the subadult fertility formula with estimates made from Bocquet-Appel and Masset's ratio (${}_{5-14}\mathrm{D}_{20+}$) (Bocquet-Appel & Masset, 1982). The two techniques performed similarly well for model life tables with a proportion of perinates:subadults between 0.32 and 0.75 (Figure 2). The subadult fertility formula has the highest level of accuracy in populations with GRR between 2 and 4 (total fertility rates between 4 and 8 offspring). When GRR is less than 2, the subadult fertility formula tends to underestimate GRR and the Bocquet-Appel and Masset's ratio performs better. On the other hand, when GRR is greater than 2, the Bocquet-Appel ratio tends to underestimate GRR and the subadult fertility formula performs better. If the proportion of perinates:subadults is less than 0.12, the estimate for GRR from the subadult fertility formula will be less than 1.4 female offspring (total fertility = 2.7). When the proportion of perinates exceeds 0.45, the estimate of GRR will be ≥ 8.0 (total fertility ≥ 16.0 offspring). Thus the subadult fertility formula is most accurate and appropriate for estimating GRR in populations with a proportion of perinates to subadults between 0.12 and 0.45.

Table 1. Descriptive statistics for estimates of gross reproductive rate (GRR) from the subadult fertility formula.

Proportion of perinates	CBR	CDR	Observed mean GRR	Predicted mean GRR	Mean SEE	Accuracy |obs-pred|
0.13–0.14	21	24	1.42	2.36	0.005	0.95
0.15–0.19	24	25	1.61	2.45	0.014	0.84
0.20–0.24	30	26	1.94	2.73	0.027	0.79
0.25–0.29	36	28	2.33	3.21	0.040	0.88
0.30–0.34	42	34	2.72	3.81	0.057	1.08
0.35–0.39	49	36	3.25	4.54	0.077	1.30
0.40–0.44	60	45	3.98	5.55	0.123	1.56
0.45–0.49	73	55	5.1	6.76	0.214	1.71

Note: CBR, crude birth rate; CDR, crude death rate; SEE, standard error of the estimate; obs, observed; pred, predicted.

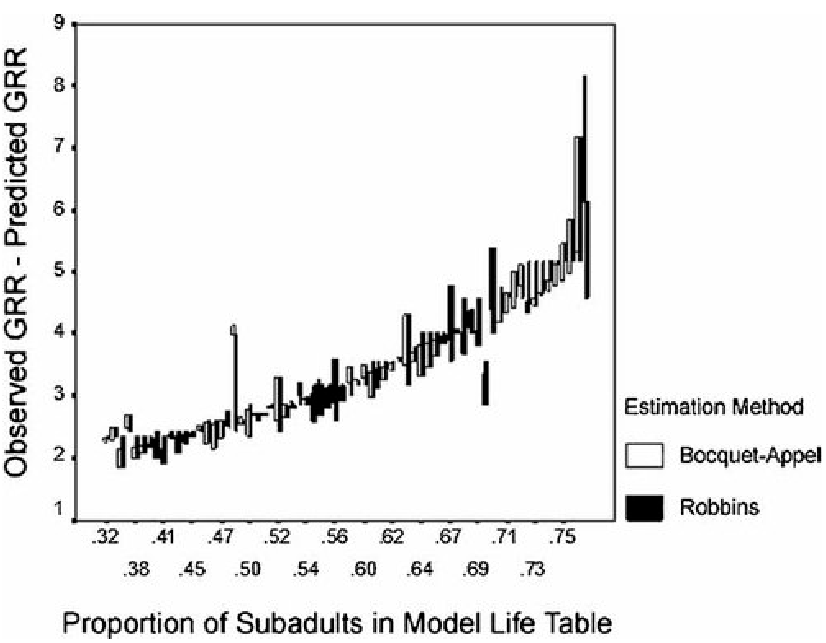

Figure 2. A comparison of the subadult fertility formula (Robbins) and another technique for estimating GRR (Bocquet-Appel). Accuracy (observed–predicted GRR) is shown here by the proportion of subadults to adults ($_{0\text{–}19\ \text{years}}D_{20\text{–}80\ \text{years}}$) in 98 Female Model West Life Tables (Coale & Demeny, 1983).

Test of the subadult fertility formula

The subadult fertility formula was applied to a skeletal population sample from Belleville, Ontario. In this sample, the proportion of perinates 0–1 year to subadults 2–19 years is 0.31. The subadult fertility formula predicts GRR is 3.6 (total fertility = 7.3) a value consistent with the GRR estimates from the Bocquet-Appel ratio (McCaa, 2002). McCaa predicted that the best fitting model for GRR was 3.5 (range = 3.0–3.5) if life expectancy at birth in this population was 20 years. If the life expectancy was higher, GRR would have been lower. The two predictions for GRR made from the subadult fertility formula and the Bocquet-Appel ratio differ by 0.1 female offspring (0.3 offspring).

The formula was also applied to 11 populations from the Health in the Western Hemisphere project and estimates for GRR were compared with previous estimates made using the Bocquet-Appel ratio (Table 2). GRR estimates from the two techniques differed on average by 1.3 offspring (range was 0–2.7). The greatest differences between the estimates for GRR made using the two techniques, was found in populations that had a high proportion of perinates (> 0.45). When the proportion of perinates exceeded the upper limit recommended for use of this formula, estimates of GRR differed by more than one female offspring.

Table 2. Comparison of estimates of GRR from the perinatal fertility formula and Bocquet-Appel's ratio using 12 populations from the Health in the Western Hemisphere project (McCaa, 1998, 2002).

Population	**Perinates 0–1 yr**	**Subadults 2–19 yrs**	**Proportion** $_{0-1}D_{2-19}$	**GRR from** $_{5-14}D_{20+}$ $e_x = 20$	$e_x = 30$	$e_x = 40$	**GRR from** $_{0-1}D_{2-19}$	**Accuracy |obs-pred|**
Amelia Island	20	83	0.24	3.1	2.8	2.8	1.1	1.7
Dickson Mound	25	56	0.45	5.0	4.4	4.3	6.2	1.2
Chiribaya	39	152	0.26	3.2	3.2	3.1	1.5	1.6
Estuquina	107	214	0.50	6.2	5.4	5.2	7.5	1.3
Hawikku	40	83	0.48	4.3	3.8	3.7	7.0	2.7
Loisy-en-Brie	19	50	0.38	3.6	3.2	3.2	4.8	1.2
Maitas	21	55	0.38	4.8	4.2	4.1	4.8	0.0
Monongahela	31	60	0.52	6.0	5.2	5.0	7.9	1.9
Pearson	23	52	0.44	.	.	6.6	6.1	0.5
Scarborough	9	37	0.24	3.6	3.2	3.1	2.9	0.2
Tlatilco 4	12	34	0.35	2.8	2.5	2.5	4.3	1.5

Conclusion

This paper provides a quadratic equation (the subadult fertility formula) for estimating GRR using the proportion of young infants to subadults, developed from the Coale and Demeney's Female Model West Life Tables. Accuracy of this formula is similar to that of a technique for estimating GRR using the juvenile:adult ratio developed previously (Bocquet-Appel & Masset, 1982). In a comparison of GRR estimates made from the subadult fertility formula and the juvenile:adult ratio, both techniques performed similarly well across a diverse range of age pyramids. The subadult fertility formula estimated GRR within ± 1 female offspring when the proportion of perinates:subadults ($_{0-1}D_{2-19}$) is within the range of 0.12–0.45. When tested on a sample from the St. Thomas Anglican Church in Belleville, Ontario, estimates for GRR made using the subadult fertility formula compared favorably with those made previously using the juvenile:adult ratio ($_{5-14}D_{20+}$), within 0.13 female offspring. In a comparison of GRR estimates made using both techniques in 11 samples from the Health in the Western Hemisphere project, the estimates were comparable (mean difference = 1.3 female offspring). Thus in populations with a proportion of perinates:subadults within the range of 0.12–0.45, the subadult fertility formula is useful for estimating GRR. In populations for which the proportion of perinates:subadults falls outside this range, or in cases where fertility is very high or very low (GRR < 2 or GRR > 8), the accuracy of the formula declines significantly and the Bocquet-Appel ratio should be preferred for estimating GRR. The subadult fertility formula can be applied to populations in which adults are under-enumerated, or not, because the formula only relies upon the subadult age pyramid. Thus, this method can be applied in cases where there is independent evidence that the adult age pyramid is not representative of the population as a whole due to burial practices, catastrophic mortality of adults, or other issues of preservation and representation.

Acknowledgements

The author thanks Jeanne Pierre Bocquet-Appel, John Lukacs, S.R. Walimbe, Clark Larsen, Mark Nathan Cohen, Michael Pietrusewsky, Stephen Frost, J. Josh Snodgrass and Frances White for comments on a previous version of this paper. She also acknowledges the anonymous reviewers for their valuable comments on the paper as well. This research was sponsored by the American institute of Indian Studies, the George Franklin Dales Foundation, Fulbright IIE and the University of Oregon Graduate School.

References

Angel JL. 1969. The bases of paleodemography. *American Journal of Physical Anthropology* **30**: 427– 437. Google Scholar

Bocquet-Appel JP. 2007. *Recent Advances in Paleodemography: Data, Techniques and Patterns*. Springer: Dordrecht. Google Scholar

Bocquet-Appel JP, Masset C. 1982. Farewell to paleodemography. *Journal of Human Evolution* **11**: 321– 333. Google Scholar

Buikstra JE, Konigsberg LW, Bullington J. 1986. Fertility and the development of agriculture in the prehistoric midwest. *American Antiquity* **51**: 528– 546. Google Scholar

Coale AJ, Demeny P. 1983. *Regional Model Life Tables and Stable Populations*. Academic Press: New York. Google Scholar

Cohen MN. 1997. Does paleopathology measure community health? A rebuttal of ‘the osteological paradox’ and its implications for world prehistory. In *Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population*, RR Paine (ed.). Southern Illinois University: Carbondale; 242– 262. Google Scholar

Cohen MN, Wood JW, Milner GR. 1994. The osteological paradox reconsidered. *Current Anthropology* **35**: 629– 637. Google Scholar

Hoppa RD, Vaupel JW. 2002. *Paleodemography: Age Distributions from Skeletal Samples*. Cambridge University Press: New York. Google Scholar

Horowitz S, Armelagos G, Wachter K. 1988. On generating birth rates from skeletal populations. *American Journal of Physical Anthropology* **76**: 189– 196. Google Scholar

Jackes M. 1986. The mortality of Ontario archaeological populations. *Canadian Journal of Anthropology* **5**: 33– 48. Google Scholar

Jackes M. 1992. Palaeodemography: problems and techniques. In *Skeletal Biology of Past Peoples: Research Methods*, SR Saunders, A Katzenberg (eds). Wiley Liss, Inc.: New York; 189– 224. Google Scholar

Konigsberg LW, Frankenberg SR. 1992. Estimation of age structure in anthropological demography. *American Journal of Physical Anthropology* **89**: 235– 256. Google Scholar

Konigsberg LW, Frankenberg SR. 1994. Paleodemography: 'Not quite dead'. *Evolutionary Anthropology* **3**: 92– 105. Google Scholar

Last JM., 2001. *A Dictionary of Epidemiology*. Oxford University Press: Oxford. Google Scholar

Livi-Bacci M. 2007. *A Concise History of World Population*. Blackwell: Oxford. Google Scholar

Lukacs JR. 2008. Fertility and agriculture accentuate sex differences in dental caries rates. *Current Anthropology* **49**: 901– 914. Google Scholar

McCaa R. 1998. Calibrating paleodemography: the uniformitarian challenge turned. *American Association of Physical Anthropology Annual Meeting*, Salt Lake City. Google Scholar

McCaa R. 2002. Paleodemography of the Americas. In *The Backbone of History: Health and Nutrition in the Western Hemisphere*, RH Steckel, JC Rose (eds). Cambridge University Press: New York; 94– 126. Google Scholar

Meindl RS, Russell KF. 1998. Recent advances in method and theory in paleodemography. *Annual review of Anthropology* **27**: 375– 399. Google Scholar

Paine RR. 1997. *Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population*. SIU: Carbondale, IL. Google Scholar

Paine RR, Harpending HC. 1996. The reliability of paleodemographic fertility estimators. *American Journal of Physical Anthropology* **101**: 151– 160. Google Scholar

Sattenspiel L, Harpending H. 1983. Stable populations and skeletal age. *American Antiquity* **48**: 489– 498. Google Scholar

Saunders SR, Hoppa RD. 1993. Growth deficit in survivors and non-survivors: biological mortality bias in subadult skeletal samples. *Yearbook of Physical Anthropology 2000.* **36**(S17): 127– 151. Google Scholar

Saunders SR, Herring DA, Boyce G. 1995. Can skeletal samples accurately represent the living population they come from? The St. Thomas Cemetery site, Belleville, Ontario. In *Bodies* *of Evidence: Reconstructing History Through Skeletal Analysis*, AL Grauer (ed.). Wiley-Liss: New York; 69– 89. Google Scholar

Saunders SR, Herring A, Sawchuk L, Boyce G, Hoppa R, Klepp S. 2002. The St. Thomas Anglican Church project. In *The Backbone of History: Health and Nutrition in the Western Hemisphere*, RH Steckel, JC Rose (eds). Cambridge University Press: New York. Google Scholar

Steckel RH, Rose JC. 2002. *The Backbone of History: Health and Nutrition in the Western Hemisphere*. Cambridge University Press: New York. Google Scholar

Weiss KM. 1973. *Demographic Models for Anthropology*. Society for American Archaeology: San Fransisco, CA. Google Scholar

Wood JW, Milner GR, Harpending H, Weiss KM. 1992. The osteological paradox: problems of inferring prehistoric health from skeletal samples. *Current Anthropology* **33**: 343– 370. Google Scholar

Wright L, Yoder C. 2003. Recent progress in bioarchaeology: approaches to the osteological paradox. *Journal of Archaeological Research* **11**: 1059– 1061. Google Scholar

Erratum

This research was sponsored by the American institute of Indian Studies, the George Franklin Dales Foundation, Fulbright IIE and the University of Oregon Graduate School.

The subadult fertility formula contains a typo. The correct formula is as follows:

$$\mathrm{GPR} = -2.78 - \left(7.71 \times {}_{0-1}\mathrm{D}_{2-19}\right) + (34.26 \times {}_{0-1}\mathrm{D}^{2}_{2-19}$$

When this formula is applied to the skeletal populations from the Health in the Western Hemisphere project, Gross Reproductive Rate (GRR) estimates differed from those made using the Bocquet–Appel (1982) ratio on average by 0.98 offspring (range was 0 to 2.7). A revised version of Table 2 is provided. Calculations of GRR in rows 1 and 3 were corrected.

Table 2. Comparison of estimates of GRR from the perinatal fertility formula and Bocquet–Appel's ratio using 12 populations from the Health in the Western Hemisphere project (McCaa, 1998, 2002)

Population	**Perinates 0–1 year**	**Subadults 2–19 years**	**Proportion** ${}_{0-1}D_{2-19}$	**GRR from** ${}_{5-14}\mathrm{D}_{20+}$			**GRR from** ${}_{0-1}D_{2-19}$	**Minimum difference**
				$e_x = 20$	$e_x = 30$	$e_x = 40$		
Amelia Island	20	83	0.24	3.1	2.8	2.8	2.9	0.1
Dickson mound H-G	25	56	0.45	5	4.4	4.3	6.2	1.2
Chiribaya	39	152	0.26	3.2	3.2	3.1	3.1	1.6
Estuquina	107	214	0.50	6.2	5.4	5.2	7.5	1.3
Hawikku, NM	40	83	0.48	4.3	3.8	3.7	7.0	2.7
Loisy-en-Brie	19	50	0.38	3.6	3.2	3.2	4.8	1.2
Maitas, Bra.	21	55	0.38	4.8	4.2	4.1	4.8	0.0
Monongahela	31	60	0.52	6	5.2	5	7.9	1.9
Pearson	23	52	0.44	–	–	6.6	6.1	0.5
Scarborough, Eng.	9	37	0.24	3.6	3.2	3.1	2.9	0.2
Tlatilco 4, Mexico	12	34	0.35	2.8	2.5	2.5	4.3	1.5