



## Subsistence economics, family size, and the emergence of social complexity in hunter–gatherer systems in eastern North America

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### ABSTRACT

A consideration of ethnographic data, computational model results, and archaeological data suggest that changes in family-level economics coincident with subsistence intensification contributed to the emergence of social complexity among prehistoric hunter–gatherers in eastern North America by creating the conditions for a “rich get richer” scenario. Ethnographic data are used to construct a general computational model representing key person- and family-level behaviors, constraints, and decisions affecting the size and composition of hunter–gatherer families. Results from model experiments suggest that lowering the age at which children make a significant contribution to subsistence (e.g., through the broadening of the diet to include the kinds of mass-harvested, “low quality” foods that were increasingly exploited during the Archaic and Woodland periods) relaxes constraints on family size and makes large, polygynous families economically viable. Positive feedbacks between the productive and reproductive potentials of larger families produce right-tailed distributions of family size and “wealth” when the productive age of children is low and polygyny is incentivized. Size data from over 800 prehistoric residential structures suggest right-tailed distributions of family size were present during the Late Archaic through Middle Woodland periods. These distributions would have provided variability in family-based status that permitted the emergence of hereditary social distinctions.

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### Introduction

How, why, and under what circumstances “simple” human cultural systems transform into “more complex” ones is a topic of enduring anthropological and archaeological interest (e.g., Arnold, 1996a; Bender, 1978; Binford, 1990, 2001; Flannery, 1972; Fried, 1967; Hayden, 1994, 2001; Johnson, 1982; Morgan, 1963; Price and Brown, 1985; Service, 1962; Steward, 1963; Testart, 1982, 1988). The emergence of hereditary social differentiation is a key component of transitions from “simple” (i.e., “egalitarian”) to organizationally complex (i.e., “non-egalitarian”) human cultural systems (cf. Arnold, 1996b: p. 78; Flannery, 1972: p. 402; O’Shea and Barker, 1996: pp. 16–17). Explanations for this transformation in eastern North America have been the subject of debate for decades (e.g., see Bender, 1985; Brown, 1985; Emerson and McElrath, 2009; Ford, 1977; Morey et al., 2002; Munson, 1986). Changes in family size, composition, autonomy, and wealth often figure, implicitly or explicitly, in discussions of the emergence of social complexity in hunter–gatherers (e.g., see Bender, 1978, 1985; Binford, 2001; Brown, 1985; Brown and Vierra, 1983; Hayden,

1994, 2001; Kelly, 1995; Layton et al., 1991; Testart, 1982; Tringham, 1991).

This paper considers how changes in family-level subsistence economics might articulate with long-term, large-scale trajectories of social change in hunter–gatherer systems in eastern North America. Dual roles of production and reproduction situate the family at the intersection of subsistence, economics, and demographics (see Chayanov, 1966; Cooper, 1984; Donham, 1999; Hammel, 2005; Sahlins, 1972; Tringham, 1991; Wilk and Rathje, 1982; Yanagisako, 1979). It is at the family level that many decisions about food production, mobility, division of labor, procreation, and risk-management are made, particularly in hunter–gatherer systems where families often act as autonomous units. I focus specifically on the role that subsistence intensification may play in changing the productive and reproductive calculations of individual families and understanding how these changes may produce asymmetrical distributions of family size that provide a basis for the germination of hereditary social inequalities (i.e., the ranking of lineages).

The Archaic and Woodland periods in eastern North America encompass a broad transformation from “simple” to “complex” hunter–gatherer societies. This transformation unfolded in concert with subsistence intensification over the course of about eight millennia. Hunter–gatherer societies of the Early Archaic period

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(ca. 9500–6900 BC) are generally characterized as having a high degree of residential mobility, being completely dependent on wild foods, and having none of the organizational characteristics of social complexity (e.g., see Anderson and Sassaman, 2004). By the Middle Woodland period (ca. 200 BC–AD 500), semi-sedentary, food-producing societies were present across the east. The Hopewell “florescence” during the Middle Woodland period is generally viewed as a zenith of long-term trends of increasing ritual/ceremonial elaboration, craft specialization, and long-distance exchange. At least some degree of social ranking was probably important to how these societies operated (e.g. see Carr, 2005), and there is evidence of status differentiation among clans or lineages (Anderson and Mainfort, 2002).

While this transformation cannot be characterized as a synchronous, uniform, unilineal progression from “simple to complex” societies across eastern North America, it is clear that some process or group of processes resulted in a great deal of broadly similar change across a large area between the Early Archaic and Middle Woodland periods. Many of the archaeological hallmarks of the Middle Woodland period are first detectable during the Middle and Late Archaic periods (ca. 6900–1200 BC). The beginnings of long-distance exchange of artifacts of native copper, marine shell, and exotic lithic raw materials across the east (Brose, 1979, 1999; Cook, 1976; Goad, 1980; Hill, 2006; Jefferies, 1996; Johnson, 1994; Winters, 1968) roughly coincide with the regionalization of styles of material culture (e.g., Jefferies, 1995, 1997), a shifting emphasis from residential to logistical mobility (Brown, 1985; Emerson et al., 1986; Stafford, 1994; Stafford et al., 2000), increasing use of formalized cemetery areas (Milner et al., 2009) and increasing population (Munson, 1986). Elaboration of mortuary and other rituals during the Middle Archaic in the southeast included earthen mound construction (Gibson and Shenkel, 1988; Kidder and Sassaman, 2009; Russo, 1996; Saunders et al., 2005).

These changes in mobility, settlement, ritual, exchange, and demography occurred in the context of ongoing subsistence change. Available data on Early Archaic subsistence suggests a broad, generalized utilization of plants and animals from a variety of woodland habitats (Meltzer and Smith, 1986; Simon, 2009; Smith, 1992: p. 282; Styles and McMillan, 2009). An increased focus on foods that are seasonally available, relatively low in caloric return, and relatively simple to collect is apparent during the Middle and Late Archaic periods. Significant utilization of resources such as hickory nuts (Marquardt and Watson, 1985; Munson, 1986; Stafford, 1991), shellfish (Claassen, 1986, 1991; Styles, 1986; Waselkov, 1987), and native seed plants (Gremillion, 2004; Smith, 1992; Watson, 1989; Yarnell, 1993) is indicated by the remains of the foods themselves as well as by the presence of processing and storage features (see below), and the common occurrence of plant processing tools such as stone pestles. The use of indigenous seed plants increased through time, and reliance on these plants had increased substantially by the Middle Woodland period (Fritz, 1993; Smith, 1992, 2001).

The increased focus on seed plants was associated with domestication of native species such as sumpweed (*Iva annua*) and *Chenopodium* within the time period 2000–1000 BC (Asch and Asch, 1985; Smith, 1987, 1992, 1998). Definitive evidence of the domestication of other native seeds that were utilized in Archaic subsistence economies (such as maygrass, giant ragweed, little barley, and erect knotweed) is thus far absent (Winterhalder and Goland, 1997). While none of these indigenous domesticates assumed a role on par with that of maize in later Mississippian societies (Smith, 1992; Winterhalder and Goland, 1997), they were a significant part of the diet: over 60% of the plant foods identified in Late Archaic paleofeces from Mammoth and Salts caves, for example, were of indigenous domesticates (Marquardt, 1974; Stewart, 1974; Watson and Kennedy, 1991; see also Gremillion, 1996).

These plants were utilized for thousands of years both before and after domestication and were a significant component of “mixed” subsistence economies that included a large number of wild plants and animals (see Smith, 1992, 2001). Seeds of domesticated and non-domesticated *Chenopodium* co-occur in archaeological deposits spanning several millennia, suggesting harvests from “mixed or adjacent stands of weed and crop varieties” (Gremillion, 1993: p. 506). This pattern apparently persisted until economies associated with Mississippian period chiefdoms shifted to maize agriculture at around AD 1150 (Smith, 1992).

Storage of mass-harvested seeds and nuts post-dating the Middle Archaic period is indicated by the occurrence of food remains discovered *in situ* in storage features (e.g., Cowan et al., 1981; Fritz, 1993; Smith, 1992) as well as the co-occurrence of plant foods from different seasons in paleofecal samples (see Gremillion, 1996; Gremillion and Sobolik, 1996; Schoenwetter, 1998). Storable “surplus” plant foods collected in the summer and fall may have served as a dependable food supply to buffer shortages during late winter–early spring (Gremillion, 2004; Smith, 1992), the “lean” season in the temperate forests of eastern North America (see Walthall, 1998; Yesner, 1994).

Thus subsistence change during the Archaic and Woodland periods in eastern North America included increased use of gathered foods that were seasonally available, simple but labor-intensive to collect, and sometimes storable. Ethnographic data suggest that the collection and/or processing of these “low skill” resources was probably primarily the work of females, children, and the elderly (e.g., see Claassen, 1991; Bender, 1985; Flannery, 1969: p. 79; Waselkov, 1987). Incorporation of these kinds of resources into the diet would have potentially lowered the age at which children were able to make substantive contributions to subsistence, affecting the calculus of family-level decisions about marriage, production, and reproduction by decreasing the “cost” of raising children and, consequently, altering the developmental cycle. The broad patterns of subsistence change that are evident during the Archaic and Woodland periods, in other words, were likely coupled with economic changes at the family/household level.

Given the position of the family at the nexus of social, political, and economic life in hunter–gatherer societies, it is reasonable to suppose that family-level productive and reproductive behaviors connected to subsistence intensification may be an important component of long-term processes of change (or stasis) in the hunter–gatherer systems of eastern North America (e.g., see Bender, 1985). Investigating this supposition requires us to consider the relationship of processes operating at two different scales: the “operational” and the “historical/evolutionary” (Lyman, 2007). Operational processes at the family level play out on a day-to-day or year-to-year basis as individuals act and react within their environment. Historical/evolutionary processes play out over larger scales of time and space, underlying the transformation of one kind of system into another.

The mismatch in scale between “operational” and “historical/evolutionary” processes presents us with an analytical challenge because it is not obvious how change at the operational level is linked to evolutionary change at the level of the system. My use of “system” here refers to a social system: a socially integrated population that is organized by a characteristic pattern of relationships and behaviors among its constituent components. The behaviors and interactions of individuals and families that are the smallest units of a social system do not necessarily “scale up” in a direct fashion to the characteristics of the larger social system. Our explanations of change are weakened significantly when we cannot clearly and explicitly describe and demonstrate the linkage between these two levels (cf. van der Leeuw, 1981: p. 232).

This challenge can be addressed by employing complex systems theory and computational modeling (i.e., agent-based modeling or

ABM) to bridge the gap between the human behaviors we are focused on as a potential *cause* (the productive and reproductive decisions of individuals and families) and the systemic changes that we wish to understand and explain (the emergence of social inequalities). Computational modeling allows us to represent the human behaviors that we can document ethnographically (such as birth, marriage, reproduction, food production, and death) as operational “rules” for individual-level behavior, create a system of actors who interact according to these rules, set the system in motion, and characterize the behavior of the system in terms of aggregate patterns observable at scales comparable to those we can observe archaeologically. Through systematic experimentation, cause-effect relationships between changes in behavior at the person- and family-levels (i.e., the level of operational processes) and changes in the characteristics of the resulting systems (i.e., the level of historical/evolutionary processes) can be investigated as an empirical problem. This lets us determine whether a certain set of operational processes can produce a particular outcome from a given set of initial conditions, giving us some basis for evaluating whether a particular explanation is plausible. This is a central methodological goal of archaeological systems theory (cf. Clarke, 1968; Flannery, 1968; van der Leeuw, 1981: p. 232).

I argue that attempting to understand the role of family-level productive and reproductive behaviors in long-term processes of social change in eastern North America requires two basic kinds of information: (1) an understanding of how changes at the family level articulate with changes in patterns observable at the system level; (2) archaeological data with which to characterize changes in system-level patterns through time. For the first requirement, I use an agent-based model specifically constructed to explore how changes in two main parameters influencing family-level productive and reproductive behavior (the age at which children begin making a contribution to subsistence and the strength of the incentive for plural marriage) affect system-level characteristics (distributions of size and “wealth” among all the families in the system). Design of this model is informed by a consideration of ethnographic data.

For the second requirement, I use the distribution of sizes of prehistoric residential structures ( $n = 826$ ) from eastern North America to infer changes in the distribution of family size through time. Comparisons between model outputs, ethnographic data, and archaeological data provide a basis for interpreting the archaeological data in terms of both (1) the family-level processes that were acting to produce the distributions of house size and (2) the implications of changes in the distribution of house size in terms of large-scale processes of social change. This allows for the construction of an explanation for the emergence of social inequalities in eastern North American prehistory that is consistent with several different lines of evidence and contains an explicit linkage between “operational” and “evolutionary” processes.

The agent-based model used in this paper emphasizes change through time rather than across space. The archaeological data are also analyzed largely in terms of change through time. The broad scope of this paper is intended to be a complement, rather than a substitute, for more detailed, regional or site-level studies. The history and processes associated with the change in question played out over several millennia and involved hunter-gatherer systems across the eastern woodlands: this was a pan-eastern phenomenon. While that does not mean the particular circumstances or outcomes of change were identical everywhere, it does suggest that a dataset of matching scale is appropriate to the question. An archaeological study of one or two households, no matter how detailed, is unlikely to give us any sound insight into the underlying processes that operate over large scales of time and space. Attributing social change to large-scale ecological factors based on correlation or co-occurrence, likewise, neither identifies nor explains

the actual mechanisms of change at the level that autonomous hunter-gatherer individuals, families, and groups make decisions. As stated by Binford (1990: p. 139): correlations “are clues to the operation of systemic phenomena in the world. They are what needs explanation – they are not explanations in and of themselves.”

I first discuss productive and reproductive subsistence economics among hunter-gatherers in the ethnographic present and summarize the basic ethnographic data I use to create a “middle range” computation model. I discuss construction of the model and present the results of experiments that illuminate relationships between the variables of interest. I present and discuss data from prehistoric houses reported from eastern North America and then compare these data to the results from the model. Based on this comparison, I argue that the changes in family economics associated with subsistence intensification are a plausible explanation for right-tailed distributions of house size and the occurrence of large houses during the Late Archaic through Middle Woodland periods. I further argue that the distributions of family size produced by subsistence intensification may provide a seed for the germination of social inequality and complexity through the widening of the spread between large, “high status” families and the remainder of the population, amplified by a positive feedback that makes it easier for larger families to produce more surplus and, therefore, further increase their size.

### Hunter-gatherer family subsistence economics

Information from ethnographically-observed hunter-gatherers can be used to (1) identify the physiological constraints and cultural behaviors that affect how families form and develop; and (2) understand the range of variability in these constraints and behaviors among living hunter-gatherers. Information drawn from a wide variety of hunter-gatherer systems is useful for these purposes because it helps us identify and understand both general regularities in hunter-gatherer behaviors and the range of variability in those behaviors. The purpose of considering ethnographic data in this paper is not to identify a specific ethnographic case that can serve as an analogy for prehistoric hunter-gatherers in eastern North America, but to understand general patterns of constraints and behavior in hunter-gatherer systems that can be used to design the agent-based model and determine values of key parameters for modeling purposes.

A “family” is defined here as a co-residential group composed of a husband, one or more wives, and their unmarried children. While it is generally agreed that “family” and “household” are not necessarily the same thing (see Bender, 1967; Yanagisako, 1979), there is a lack of consensus about how to best discriminate between these two entities (e.g., see Burch, 2006; Fortes, 1958; Service, 1962; Smith, 1981; Wilk and Rathje, 1982). Generally, “household” implies co-residence while “family” implies a descent relationship. In many cases, ethnographically-documented hunter-gatherer households include both conjugal families and non-conjugal individuals: extended households, augmented households, households composed of multiple families, and households containing multiple unrelated individuals have all been documented among living hunter-gatherers (see Binford, 2001: Table 8.08; Murdock, 1967: pp. 47–48). This paper makes a simplifying assumption of analytical equivalence between “family” and “household” and considers the family to be a basic institution of domestic production and reproduction that usually centers on cooperation between males and females of reproductive age.

Among ethnographically-documented hunter-gatherers, families often represent “minimally cooperating segments” that can be more or less integrated into larger social formations depending

on seasonal or other conditions related to subsistence (e.g., Binford, 2001: p. 309; Helm, 1965: p. 379; Jarvenpa and Brumbach, 1988: p. 607; Keen, 2004). This section considers three basic, inter-related aspects of families that vary significantly and non-randomly among hunter-gatherers (see Binford, 2001): size and composition, the contributions of children to subsistence, and the dependency ratio and the developmental cycle. These affect both how a family operates in terms of day-to-day decisions about the production of food and decisions about further procreation and/or the addition of wives. I begin by discussing each of these in turn and presenting summary ethnographic data on variables related to family size and composition. I conclude this section with a graphic comparison of diachronic changes in the dependency ratio and the capacity for the production of surplus of several simple simulated families, varying the number of wives and the age at which children become producers.

#### Family size and composition

The size of a family changes as its membership changes through procreation, the addition of wives, and the subtraction of members through death, marriage, or departure for other reasons. Thus family size and composition are related attributes that are affected by a mixture of physiological, cultural, and environmental factors as well as individual choices and random variability. Summary data related to basic variables affecting family size and composition among hunter-gatherers are presented in Table 1.

Increases in the size of a conjugal family occur through procreation and the addition of wives. Perhaps the most important physiological factors affecting procreation are related to female fertility (the number of children born) and fecundity (the ability to reproduce). Available data suggest mean reproductive spans (i.e., the length of time between the first birth and the last birth of a woman's life) among hunter-gatherers ranging between 8 and 22 years with a mean of about 15 years (see Kelly, 1995: Tables 6 and 7; Pennington, 2001: Table 7.4). The pattern of age-specific changes in fertility is fairly consistent across populations (Ellison, 1994). Pennington (2001) reports a characteristic parabolic pattern of age-specific fertility among the Kutchin and the !Kung, with fertility rates increasing from the teens, peaking in the late 20s, and declining to zero by age 50. In most hunter-gatherer populations, few births occur after age 40 (Pennington, 2001: p. 175). Thus the length of the reproductive span tends to be less than the length of the total span of time during which a woman may potentially reproduce.

The total fertility rate (TFR) is the mean number of children that women bear during a complete reproductive span. TFRs from 2.6 to 8.0 have been reported for hunter-gatherers, with about 5–6 children being “typical” (Hewlett, 1991: Table 2; Kelly, 1995: p. 244; Pennington, 2001: Table 7.2). The inter-birth interval (IBI) is the average length of time between births. Available IBI data suggest mean intervals ranging from 28 to 65 months among hunter-gatherers with an IBI around 3–4 years probably most common (Kelly,

1995: Tables 6 and 7; Pennington, 2001: p. 184). A variety of factors may influence both fertility and intervals between successive births, including ovarian function, contraception and abortion, coital frequency, nutritional stress, and lactation (e.g., see Campbell and Udry, 1994; Cashdan, 1985; Cumming et al., 1994; Ellison, 1994; Handwerker, 1983; Kelly, 1995; Konner and Worthman, 1980; Lunn, 1994; Pennington, 2001).

Polygyny – the taking of multiple wives – has a multiplicative effect on the *potential* size of families in a given population, assuming each additional wife has similar reproductive potential. In contrast to the statement by Kelly (1995: p. 290) that “Polygyny is uncommon among ethnographically known hunter-gatherers,” the majority of cases considered by Binford (2001: Table 8.07) exhibited some degree of polygyny. Goody (1976: p. 51) remarked that “As far as human cultures are concerned, it is monogamy that is rare, polygyny common.”

Generally, however, the intensity of polygyny (i.e., defined as the maximum number of wives following Low [1988]) is relatively low among hunter-gatherers. Available data suggest that maximum harem size is almost always less than 10 in living hunter-gatherer groups, and is often three or less (see Betzig, 1986: pp. 92–3; Binford, 2001: Table 8.07). There are exceptions to this, however, as demonstrated by the Tiwi case (Betzig, 1986; Hart and Pilling, 1979: p. 17). In some cases, very large harem sizes are present: Keen (2006: p. 16) lists maximum harem size among the Yolngu of northern Australia as 26. Data from ethnographic cases indicate that the number of simultaneous wives has a right skew in polygynous systems, with higher numbers of wives occurring less frequently (Table 2, Fig. 1).

Deaths decrease family size. While data from several hunter-gatherer populations suggest an overall U-shaped pattern of age-specific mortality (with the highest death rates experienced among the very young and the very old), there is variation between groups (Hill et al., 2007). The sample data presented by both Kelly (1995) and Hewlett (1991) suggest rates of infant mortality (i.e., the percentage of the population that dies before reaching the age of 1 year) generally range between 10% and 30% while rates of childhood mortality (the percentage of the population that dies before reaching reproductive age) range between 20% and 50%. Infanticide may be a significant contributing factor to high infant mortality rates (e.g., see Dickeman, 1975; Hayden, 1972; Hill et al., 2007; Howell, 1979: p. 120; Smith and Smith, 1994; Yengoyan, 1981). Adult mortality ranges between about 1.1–2.3% per year among the Hiwi, Ache, Hadza, and !Kung (Hill et al., 2007). In addition to reducing the current size of a family, adult mortality may reduce the potential size of a family if the deceased was part of the “conjugal core” (i.e., a matriarch or patriarch).

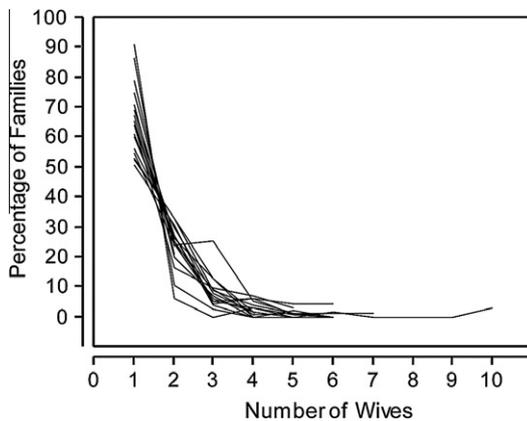
Family size also decreases when offspring depart for marriage. Male and female age at marriage varies significantly: 5–22 years for females and 12–35 years for males (Binford, 2001: Table 8.07). In the majority of cases, the mean age at marriage suggests most women are married by the time they are 16 while most males are a few years older at marriage. Obviously, age at marriage does

**Table 1**  
Approximate means and ranges of variables related to family size and composition among ethnographic hunter-gatherers.

Variable	Range	Approximate mean	Reference(s)
Reproductive span	8–22 years	15 years	Kelly (1995: Table 6.7) and Pennington (2001: Table 7.4)
Total fertility rate (TFR)	2.6–8.0 births	5.4 births	Hewlett (1991: Table 2) and Pennington (2001: Table 7.2)
Inter-birth interval (IBI)	2.5–4.0 years	–	Kelly (1995: Table 6.7) and Pennington (2001: Table 7.4)
Intensity of polygyny	0–10 wives	–	Betzig (1986) and Keen (2006)
Infant mortality	10–30%	20%	Hewlett (1991: Table 3) and Kelly (1995: Table 6.9)
Childhood mortality	20–50%	43%	Hewlett (1991: Table 3) and Kelly (1995: Table 6.9)
Female age at marriage	5–22 years	14 years	Binford (2001: Table 8.07)
Male age at marriage	12–35 years	21 years	Binford (2001: Table 8.07)
Female age at first birth	16–23 years	20 years	Kelly (1995: Tables 6 and 7) and Pennington (2001: Table 7.4)

**Table 2**  
Percentage distribution of number of wives in polygynous ethnographic cases.

Group	Families (n)	Number of wives								Reference(s)
		1	2	3	4	5	6	7	10	
Walbiri	175	65.7	24.6	5.1	2.9	0.6	1.1	–	–	Meggitt (1962: Table 9)
Walbiri (Yuendumu 1962)	79	53.2	32.9	8.9	3.8	1.3	–	–	–	Long (1970: Table 1)
Walbiri (Yuendumu 1967)	124	52.4	33.1	12.9	1.6	–	–	–	–	Long (1970: Table 2)
Inupiat	33	90.9	6.1	0.0	3.0	–	–	–	–	Burch (2006: 88) and Ray (1885: 49)
Shoshoni	38	86.8	10.5	2.6	–	–	–	–	–	Steward (1938)
Northern Arnhem Land	23	60.9	26.1	13.0	–	–	–	–	–	Hiatt (1965: Table 13)
LoDagaba	67	67.2	25.4	5.9	1.5	–	–	–	–	Goody (1958: Table 9)
Lo Wiili	?	71.0	20.0	7.0	0.0	2.0	–	–	–	Goody (1958: Table 9)
Tallensi	?	60.4	27.0	5.4	6.3	0.9	–	–	–	Goody (1958: Table 9)
Ingura (Groote Eylandt 1940)	49	51.0	30.6	4.1	6.1	4.1	4.1	–	–	Long (1970: Table 1) and Rose (1960: Table 27)
Australian Desert Groups (1955–1962)	38	60.5	26.0	10.5	3.0	–	–	–	–	Long (1970: Table 1)
Australian Desert Groups (1956–1962)	26	69.2	26.9	3.8	–	–	–	–	–	Long (1970: Table 1)
Ngalea (Ooldea 1941)	53	79.2	20.8	–	–	–	–	–	–	Long (1970: 298)
Pitjandjara (Amata 1966–67)	64	75.0	23.4	0.0	1.6	–	–	–	–	Long (1970:299)
Gunavidji (Maningrida 1966)	142	64.1	24.6	9.2	0.7	1.4	–	–	–	Long (1970: Table 4)
Djinang (Milingimbi 1966)	75	54.7	24.0	25.3	5.3	1.3	1.3	1.3	–	Long (1970: Table 4)
Murngin (Elcho Island 1966)	103	64.1	16.5	9.7	6.8	2.9	–	–	–	Long (1970: Table 4)
Murngin (Yirrkalla 1966)	64	56.2	29.6	7.8	1.6	0.0	1.6	0.0	3.1	Long (1970: Table 4)



**Fig. 1.** Number of wives plotted against percentage of families for ethnographic cases (data in Table 2).

not always correspond to the beginning of the reproductive span. Data on the mean age at first birth suggest that hunter-gatherer women may generally first give birth in their late teens or early twenties (Kelly, 1995: Tables 6 and 7; Pennington, 2001: Table 7.4). This may be several years after marriage and/or menarche (Kelly, 1995: pp. 245–246).

Understanding the relationships among variables affecting family size and composition is a complicated task (i.e., see Campbell and Wood, 1994; Ellison, 1994; Kelly, 1995; Pennington, 2001). While some of these variables are logically inter-related in a general way (e.g., if the reproductive span stays constant, then an

increase in TFR would be accompanied by a decrease in IBI), others appear to be related in ways that are not intuitively obvious. Studies have suggested, for example, relationships between variables such as female age at marriage and polygyny (see Binford, 2001: p. 300; Low, 1988), polygyny and fertility (Amey, 2002; Barber, 2004; Hern, 1992; Josephson, 2002), polygyny and child mortality (Strassman, 1997), and polygyny and sex ratio (Amey, 2002; Barber, 2004; Borgerhoff Mulder, 1994; Whiting, 1993). The general relationships between potential family size and each of the variables in Table 1 is relatively straightforward, however. The smallest mean family sizes would occur in populations with low TFRs, high IBIs, short reproductive spans, high infant and childhood mortality, late female age at marriage, late age at first birth, and no polygyny. The opposite combination has the potential to produce the largest families.

Mean family size varies from 2.9 to 7.7 among the groups considered by Binford (2001: Table 8.08). Table 3 presents data on the distributions of family size in several ethnographic cases for which information on the size and composition of individual families is available. In most of these cases, detailed membership data make it possible to determine when non-conjugal individuals (e.g., extended family members) were included in the “families” described by the ethnographer. Thus Table 3 presents data with and without these “extra” members. Histograms of family size for several of these cases are shown in Fig. 2. There are positive relationships between the percentage of polygyny and both the skewness and coefficient of variation of the distribution of family size in these cases: higher polygyny is associated with both greater variability in family size and a right-skewed distribution of family size (Fig. 3).

**Table 3**  
Statistical characteristics of distributions of family size in ethnographic cases (SD = standard deviation; Skew. = skewness; CV = coefficient of variation).

Case	n Families	Family size					Polygyny %	Intensity	Reference(s)
		Range	Mean	SD	Skew.	CV			
Inupiat (conjugal families only)	29	2–5	3.48	1.02	0.37	29.3	7	2	Burch (2006: p. 102) and Ray (1885: p. 49)
!Kung (excluding single individuals)	10	2–6	4.10	1.52	–0.20	37.2	0	1	Yellen (1977: p. 58)
!Kung (households, excluding single individuals)	165	2–9	3.10	1.37	1.26	44.1	6	2	Howell (1979: pp. 45, 234)
Paiute (conjugal families only)	14	2–6	3.79	1.48	–0.07	39.0	0	1	Steward (1938)
Shoshoni (conjugal families only)	37	2–14	5.65	2.71	0.85	48.0	14	3	Steward (1938)
Walbiri	37	2–10	3.86	2.38	1.13	61.6	38	4	Meggitt (1962: pp. 77–78)

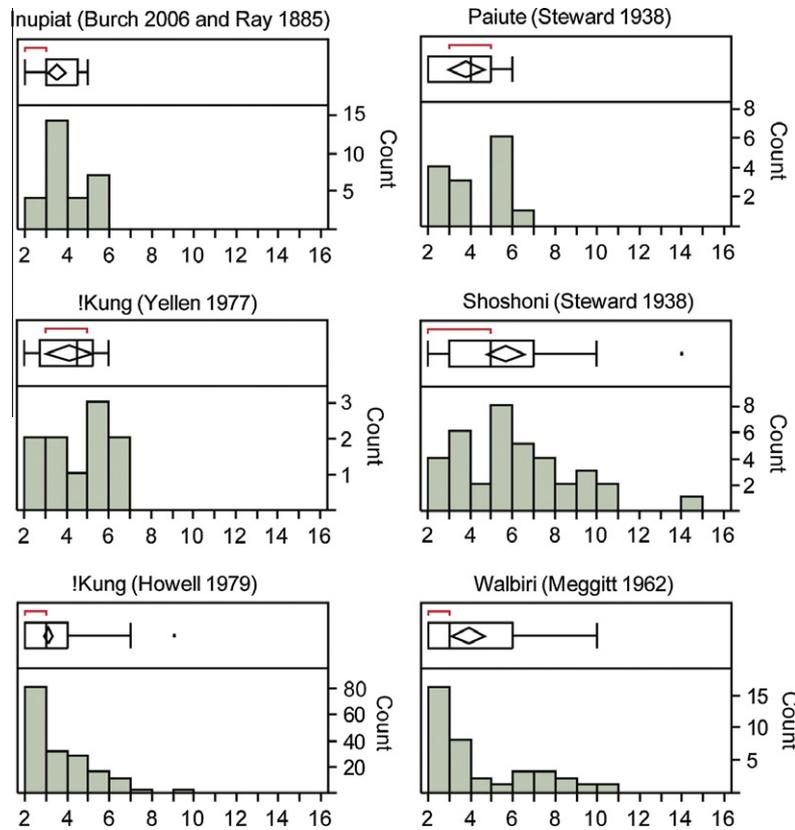


Fig. 2. Histograms of family size for ethnographic cases in Table 3.

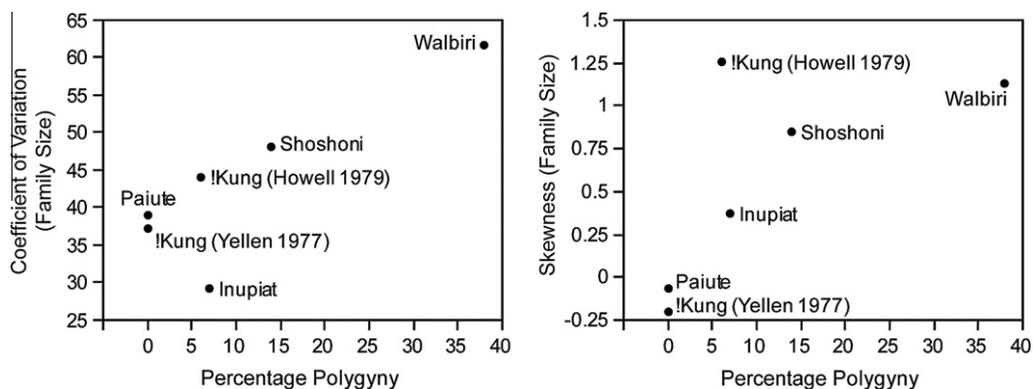


Fig. 3. Plots of coefficient of variation and skewness of family size vs. the percentage of polygyny in ethnographic cases (data in Table 3).

*The contributions of children to subsistence*

Ethnographic studies demonstrate that children’s contributions to subsistence vary among hunter–gatherer systems (e.g., Blurton Jones et al., 1994; Hawkes et al., 1995; Tucker and Young, 2005). The degree to which children contribute to their own subsistence or that of their families may be influenced by a number of factors, including the characteristics of both the resources which are included in the diet and the environment in which those resources are found (Blurton Jones et al., 1994; Hawkes et al., 1995).

Resources that are easily gathered with a minimum of skill and low processing times – such as berries, seeds, some kinds of nuts, and shellfish – are natural choices for child foragers (e.g., see Claassen, 1991; Bird and Bliege Bird, 2000; Waselkov, 1987). While these resources may not be highly ranked from the perspective a

single adult forager, if they are available in sufficient densities they may offer relatively high returns when collected by teams composed of a mixture of adults and children. Among the Hadza, where children are active foragers, women were found to choose foraging strategies based on maximizing team returns (their own returns plus the returns of their children) rather their own returns (Hawkes et al., 1995).

There are a variety of ways in which children’s foraging may be integrated into family-level subsistence economies (e.g., see Hewlett and Lamb, 2005). The Hadza case describes what might be called *integrated* child/adult foraging behavior: adults and children harvest the same resources as a team. Resource rankings may be family-specific depending on family size and composition and the way that the potential subsistence contributions of children are operationalized, which may depend on the peculiarities

of resource distribution as well as other environmental factors (safety, etc.). A resource that is efficient for one family to collect may be inefficient (and insufficient) for another family to collect.

If children are able to forage effectively for themselves (unsupervised), adults (particularly women) may be free to collect other resources (e.g., Bird and Bliege Bird, 2005). Reduced childcare demands may give women the opportunity to gather surpluses of low-ranked seasonal resources that are storable, perhaps compensating for future variability or unpredictability in some other resources. Children's foraging also appears to be positively related to fertility and negatively related to inter-birth interval (Blurton Jones, 1993; Blurton Jones et al., 1994). This is a logical relationship: children's ability to acquire food for themselves allows mothers to divert resources from the care of existing children to reproduction (Blurton Jones, 1993; Blurton Jones et al., 1994: p. 211).

Thus while the "cost" of children (in terms of efficiency of mobility, subsistence support, etc.) is often highlighted in the hunter-gatherer literature (e.g., see Kelly, 1992: p. 59, 1995: p. 241), it is clear that their foraging efforts should not be assumed to be insignificant, either from the standpoint of resource choice or return rates (Hawkes et al., 1995). When children can contribute to family subsistence, the economic "cost" of children is lowered. Hadza children provide a significant portion of their own food, making them "very cheap to raise" (Blurton Jones, 1993: p. 320). Children of different ages will not forage with uniform efficiency or returns in all environments (see Blurton Jones, 1993; Tucker and Young, 2005). When children are full participants in family-level subsistence activities, they are an asset rather than a liability.

#### *The developmental cycle, dependency ratio, and economic viability of families*

While individual families each have their own "historical" sequences of change in size and membership, the operation of common processes related to physiology (the limited duration of the female reproductive span, the inevitable growth of children) and culture (marriage and residence practices) produces a general pattern of developmental changes in family size and composition within a given system: the developmental cycle (Fortes, 1958; Goody, 1958).

First there is a phase of expansion that lasts from the marriage of two people until the completion of their family of procreation. The biological limiting factor here is the duration of the wife's (or wives') fertility. In structural terms it corresponds to the period during which all the offspring of the parents are economically, affectively and jurally dependent on them. Secondly, and often overlapping the first phase in time (hence my preference for the term 'phase' instead of 'stage') there is the phase of dispersion or fission. This begins with the marriage of the oldest child and continues until all the children are married. Where the custom by which the youngest child remains to take over the family estate is found, this commonly marks the beginning

of the final phase. This is the phase of replacement, which ends with the death of the parents and the replacement in the social structure of the family they founded by the families of their children... (Fortes, 1958: p. 5).

The phases of the developmental cycle roughly coincide with changes in the dependency ratio (Chayanov, 1966; Donham, 1999). The dependency ratio is the ratio of food consumers (the total number of persons in a family) to food producers (the number of persons who are actively procuring and/or preparing food) (Binford, 2001: p. 229).

Consider what happens as a household moves through a hypothetical developmental cycle. A new unit is established at the time of marriage. As children are born and added to the family, food requirements increase. But children, initially at least, do not add to the household work force, and that is where the pinch comes. As subsistence requirements increase, the number of workers remains constant and the dependency ratio rises... As more and more children are born, the burden on the household increases until the eldest child begins to work. At that point, the dependency ratio begins to decrease so that each household worker can begin to work fewer hours (Donham, 1999: pp. 22–23).

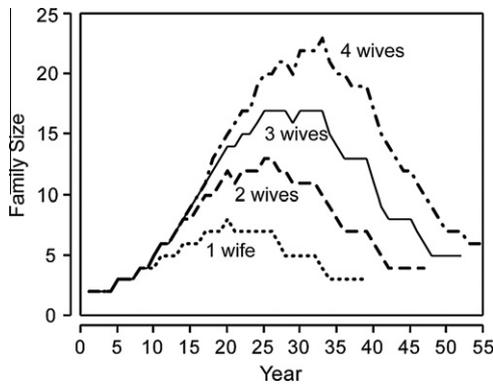
It is this relationship between the developmental cycle and changes in the dependency ratio that makes variation in family size and composition within groups potentially important to understanding hunter-gatherer economics at the operational (day-to-day) level. Greatest family sizes would generally be expected to occur at the interface of the expansion and dispersion phases. As noted by Fortes (1958: p. 5), these two phases can overlap: children may reach marriageable age and begin leaving prior to the end of the wife's fertility. The highest dependency ratios are likely to occur during the expansion phase.

For a family to be viable throughout its developmental cycle, it must be able to survive the "pinch" period where the dependency ratio is the highest. The "pinch" comes in all families with offspring: the duration and amplitude of the "pinch" is affected by the rapidity of the addition of offspring and how quickly those offspring turn from consumers into producers. The rapidity of addition of offspring will depend on factors such as fertility, infant and childhood mortality, and the number of wives. The productive potential of children will be affected by the presence and distribution of resources that can be procured by children and the foraging strategies that are employed to exploit those resources. Families within a system or population will be at different points in their developmental cycles, and the economics of family-level subsistence will vary accordingly.

To illustrate how polygynous marriage and the age at which children become producers affects the size, dependency ratio, and economic viability within single families, a spreadsheet was used to create a set of four simple simulated families (Table 4). In these simulated families, all variables except the number of wives and the age at which children become producers are held

**Table 4**  
Size, lifespan, and cumulative surplus produced over the lifespan of four simple simulated families varying the number of wives between 1 and 4 and setting the age at which children are counted as producers as either 14 or 8. In all cases the total fertility rate = 6 and the inter-birth interval = 3.

No. wives	Family size		Lifespan	Age at production = 14			Age at production = 8		
	Peak	Cumulative		Years of dependency ratio above 1.75	Surplus years	Cumulative surplus	Years of dependency ratio above 1.75	Surplus years	Cumulative surplus
1	8	8	39	16	23	3	5	34	66
2	13	15	47	24	24	-16	6	40	116
3	17	22	52	27	25	-28	7	45	161
4	23	29	55	29	26	-46	7	48	206



**Fig. 4.** Change in family size through time for four simulated families (summary data in Table 4). Each family is represented by a line. The Y axis is the size of the family (number of members); the X axis measures time in years.

constant: total fertility rate = 6; inter-birth interval = 3; female age at marriage = 16; male age at marriage = 20; female age at first birth = 20. Each wife bears her first child at age 20 and an additional child every 3 years thereafter until age 35 (6 children total per wife) in a deterministic fashion. Children leave the family when they reach marriage age. Offspring alternate in sex. There is no mortality. For polygynous marriages, the second marriage occurs at year 10, the third marriage at year 15, and the fourth marriage at year 18. Anecdotal data indicate that wives are typically added incrementally during the developmental cycle of the polygynous family (see Hiatt, 1965: p. 77; Meggitt, 1962).

Fig. 4 shows change in the size of these simulated families through time as wives are added and offspring are produced. Family sizes are similar through the first 10 years, but diverge dramatically during the period between 10 and 20 years. This is due to the parallel reproductive capacities of polygynous families and the longer duration of the expansion phase in polygynous families. The peak size of the polygynous family with four wives is nearly thrice that of the monogamous family and its developmental cycle lasts 16 years longer.

The graphs at the top of Fig. 5 illustrate how the dependency ratio changes through time in each of the four families as composition changes through the addition/subtraction of wives and offspring. Dependency ratio is calculated as the number of consumers divided by the number of producers. The dotted line marks a dependency ratio of 1.75, considered “typical” of hunter-gatherers (Binford, 2001: p. 230). When children are counted as “producers” at age 14 (top left), all four families experience dependency ratios above 1.75 for a sustained period of years in the central portion of the developmental cycle, rising during the expansion phase as the family adds children (consistent with the analysis of Chayanov [1966]). The duration of this period of high dependency ratios is positively related to the number of wives. When children are counted as producers at age 8 (top right), dependency ratios in all four families are below 1.75 for all but 5–7 years in the first half of the developmental cycle.

The dependency ratio is a relative measure: the actual amount of surplus that can be produced is dependent on family size. Assuming again that a dependency ratio of 1.75 represents a “break even” point, we can use a simple calculation to characterize the productive capacity of each family on both a year-to-year basis and over the family’s lifespan. For each year, the number of producers is multiplied by 1.75. This represents the total productive capacity of the family for that year (each producer can provide for 1.75 consumers). When the total number of consumers in the family is subtracted from this number (i.e., each person consumes 1 “unit” of production), the result is an estimate of the productive

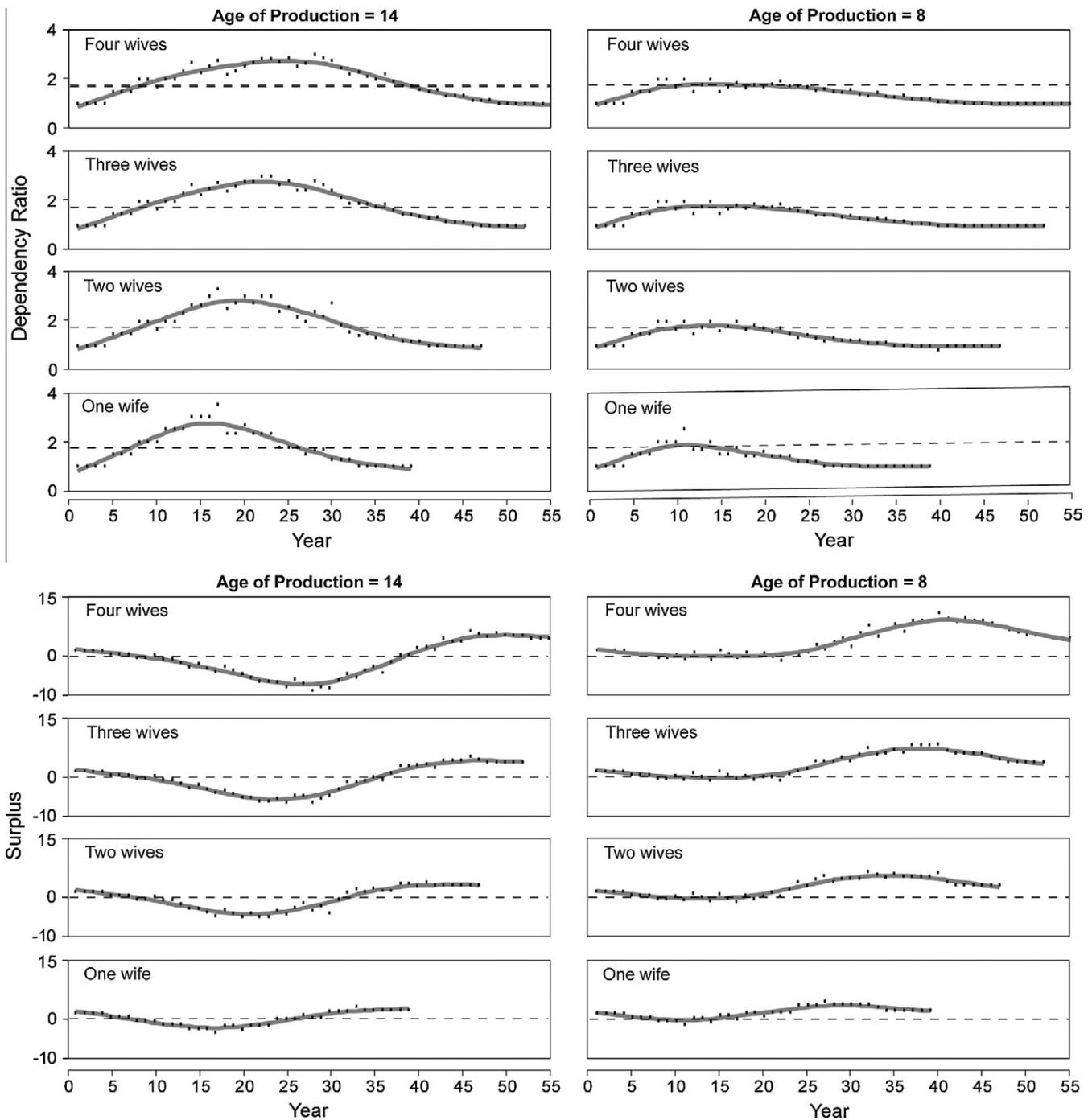
capacity in terms of person-units. A result of 3, for example, means that, for that year, a family could produce resources for itself plus three more individuals. A result of  $-3$  indicates a production deficit of 3 person-units. The sum of these yearly calculations represents the total cumulative production capacity of a family during its lifespan.

The graph at the bottom left of Fig. 5 illustrates how differences in the dependency ratio might translate into capacities for surplus production in the four families when children become producers at age 14. In all four families, the high dependency ratios of the expansion phase are associated with production deficits. The deficit period is shorter and shallower in smaller families. The monogamous family is the only family to produce a cumulative surplus over its lifetime, and cumulative lifetime surplus levels are negatively related to family size (see Table 4).

The graph at the bottom right of Fig. 5 shows the productive capacities of the same families calculated assuming that children become producers at age 8. In this situation, the deficits associated with the expansion phase are shallow and families have the capacity to produce surplus during most of their lifespans. In this case, surplus productive capacity is positively associated with family size: the largest families have the greatest capacities for producing surplus both on a yearly basis and over the course of the family’s lifespan (see Table 4). If all other factors remain equal, lowering the productive age from 14 to 8 effectively makes large, polygynous families economically viable (i.e., it brings them near or above the “break even” point on a year-to-year basis) and significantly increases their lifetime capacity to produce surplus.

These results illustrate that changes in the age at which children make a contribution to subsistence may have a significant effect on the viability and productive capacity of families of different sizes and compositions. The length of the period of time during which a child will be a non-producer affects the “cost” of the child and, consequently, the economic calculations of a family. In subsistence systems where children do not become producers until their teens, a large, polygynous family may not be economically viable on an operational (i.e., day-to-day or year-to-year) level because much of the expansion phase of its developmental cycle will be characterized by high dependency ratios and production deficits. Smaller, monogamous families may be more viable under these conditions. In subsistence systems where children become producers at a younger age, larger families are not only economically viable at an operational level, but have a much greater capacity to produce surplus over the lifespan of the family. Smaller families are also viable when the age at production is low, but have less productive capacity than larger ones.

This simple example explores the basic economic effects of altering the age at which children become producers *within families*. A number of other factors must be considered to understand the implications of changes in productive age at the level of a cultural system. If there are equal numbers of males and females in a polygynous system, not all men can have the same number of wives, and, therefore, not all families will be the same size. Each family will make decisions about procreation and the addition of more wives with knowledge of their current economic situation and the costs or benefits of adding more children. Calculations about the incorporation of additional wives into a family will include factors of both operational economics and the availability of suitable brides. Brides may be scarce and costly in systems where the intensity of polygyny is high, leading to a high differential in male and female ages at marriage (Goody, 1976: p. 64). Mortality, fertility, and sex have random components which must also be taken into account. A more sophisticated approach is required to understand how changes in the age at which children become producers affects patterns of change at the system level.



**Fig. 5.** Change in dependency ratio and capacity for surplus production in four simulated families, varying the number of wives and the age at which children become producers (summary data in Table 4). The X axis in these charts shows time in terms of the number of years since the family was initiated. The Y axis shows dependency ratio (top) and level of surplus production (bottom). All variables remain stay constant except for the number of wives and the age at which children become producers.

### A computational model of family production and reproduction

The ethnographic data discussed above outline (1) the general physiological constraints and cultural behaviors that affect how families form and develop and (2) the range of variability in these constraints and behaviors among living hunter-gatherers. These data are not suitable for directly evaluating hypotheses about the kind of systemic change with which this paper is concerned, however, for two primary reasons. First, there is a fundamental mismatch between the scales of the ethnographic data and the system-level change we are trying to understand. Ethnographic

cases, while potentially rich in the kind of specific, synchronic detail that is impossible to recover archaeologically, comprise a collection of disconnected “snapshots” of operational processes. These snapshots may let us identify general regularities in how hunter-gatherer systems work and suggest possible “evolutionary” sequences between different kinds of systems, but ultimately tell us nothing directly about diachronic processes associated with change over long spans of time.

Second, the nature of the ethnographic record precludes the use of any kind of experimental framework: it is impossible to identify causes of change or evaluate the plausibility of

explanations of change by altering one variable while holding all others constant.

Computational modeling and complex systems theory offer remedies to both of these issues (see Gilbert, 2008; Kohler and van der Leeuw, 2007; Miller and Page, 2007). The family-based systems of production and reproduction considered here possess the characteristics of complex systems (Boccaro, 2004: p. 3): (1) they consist of a relatively large number of interacting agents; (2) they exhibit emergent behavior (self-organizing, collective behavior difficult to anticipate from knowledge of the individual agents' behavior); and (3) this emergent behavior does not result from central control. (Note that the term “complex system” here refers to any system with the particular suite of characteristics where system-level behavior can be understood as emerging “bottom up” from the interactions of individual agents, rather than to a hierarchically-organized “complex” social system.) In this case, we are trying to understand the relationship between the “rules” affecting family-level productive and reproductive behaviors at the operational level and the patterns of family size and “wealth” distribution that emerge at the system level. We can use a computational model to systematically explore how changes at the lower (i.e., family) level affect patterns that emerge at the system level.

The ethnographic data discussed in the previous section were used to construct an agent-based model (named FamilyNet2) with representations of key person- and family-level behaviors and constraints affecting the size and composition of hunter-gatherer families: marriage, reproduction, mortality, and family-level economic production. The goal of this section is to describe the FamilyNet2 model in sufficient detail to enable the reader to understand how the phenomena of interest are represented and how the model operates. Additional details of the design and operation of the FamilyNet2 model are provided in Appendix A. The raw code for the FamilyNet2 model is provided online in a supplementary file.

#### General description of the model

The FamilyNet2 model was written in the Java programming language and built using Repast J. Repast (Recursive Porous Agent Simulation Toolkit) is a free, open-source agent-based modeling and simulation toolkit that was created at the University of Chicago in collaboration with Argonne National Laboratory (North et al., 2006). It is one of several available agent-based modeling toolkits (e.g., see Gilbert and Bankes, 2002; North et al., 2006; Tobias and Hofmann, 2004). It was chosen for this work because of its suitability for representing the system under consideration and because it is supported by the Center for the Study of Complex Systems at the University of Michigan. Documentation of Repast can be found at [www.repast.sourceforge.net](http://www.repast.sourceforge.net).

The FamilyNet2 model was constructed as part of the development of the ForagerNet2 model, a more complicated model that includes representations of space, social learning, and social networks (see White, 2012). Many of the representations in the FamilyNet2 model are essentially very similar to those embedded in the ForagerNet2 model. The FamilyNet2 model is not intended to represent all aspects of hunter-gatherer systems or the details of any particular hunter-gatherer society. The simple design of the model and the exclusion of extraneous detail was a purposeful strategy to produce a “middle range model” that describes “the characteristics of a particular social phenomenon, but in a sufficiently general way” that it can be applied to many hunter-gatherer systems (Gilbert, 2008: p. 42). This use of the term “middle range” in this context should not be confused with Binford (1977, 1981) “middle-range theory”.

Description of the structure and operation of a model such as this one is challenging because of the nature of articulations between various components of the model. The first part of this

section describes the representations that constitute the “building blocks” of the model: the persons and families that are the building blocks of the social system that inhabits the “world” of the model. The second section describes the methods (marriage, reproduction, and mortality) that determine how persons and families in the model behave and interact with each other within the parameters of the model world. The third section discusses how the model operates during a run and how data are collected from model experiments. The fourth section discusses some basic aspects of the model's behavior that suggest the model is a valid representation of the systems it is intended to represent.

#### Representations of persons, families, and the world

The FamilyNet2 model has three main “levels:” person, family, and the system. A schematic illustration of the inter-relationships of basic parts and operations of the model is shown in Fig. 6. Persons and families exist in the world of the model as discrete entities. In other words, each person and each family in the model has a unique identity and can be different from all other persons and families. Persons are fundamental, indivisible units. Families are groupings of persons that can change in composition. The social system of the model at any given point in time is composed of all persons and families that are currently in existence. The behavior of these persons and families is affected by model-level rules and parameters.

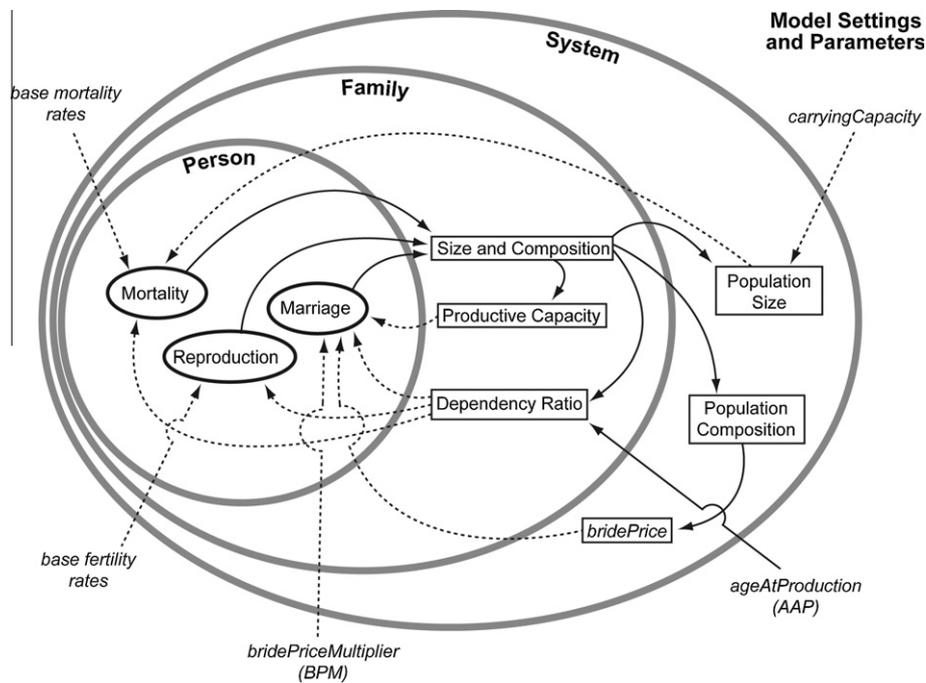
#### Persons

Each agent in the model represents an individual person. Each person has variables to store the characteristics of the person (age, sex, marriage status, the family of which the person is a member, etc.) and lists to store the identities of persons related by descent (parents, children), persons related through co-residence in a family/household unit (husbands and wives, co-wives, stepchildren, etc.), and persons with whom marriage is prohibited. A list of variables associated with persons is provided in Appendix A.

Persons in the model have a lifespan that begins with birth and ends with death. The age at which persons become eligible for marriage and are able to reproduce is set by the value of the model-level parameter *ageAtReproduction*. For the experiments discussed here, *ageAtReproduction* was set to 16 for both males and females. Note that this is the age at which persons become eligible to marry: the actual age of marriage for individual persons will depend on interactions and conditions during a model run. The age of 16 was chosen so that the ages of reproductive viability and marriage eligibility could reasonably be combined into a single variable to simplify modeling.

The female reproductive span extends from age 16 through 35 in the experiments discussed here. While at the high end of the range documented for ethnographic hunter-gatherers, a 20-year reproductive span was chosen because it would allow the highest ethnographic total fertility (8.0 births) with the shortest inter-birth interval (2.5 years). A reproductive span shorter than 20 years would preclude the emergence of model systems with combinations of high fertility and low inter-birth interval like those observed among ethnographic hunter-gatherers (see Table 1).

Based on age, each person is either a producer or a non-producer. The value of the model-level parameter *ageAtProduction* (*AAP*) specifies the age at which children are counted as producers. As discussed above, there is significant variability in the age at which hunter-gatherer children make a substantial contribution to subsistence. Understanding the effects of changes in *AAP* is one of the main goals of the model experiments discussed below.



**Fig. 6.** Schematic illustration of the levels and mechanisms of the FamilyNet2 model. Feedbacks and effects between person-, family, and system-level variables (in rectangles), model parameters (in italics), and person-level methods are represented by arrowed lines. Solid lines represent arithmetic effects (e.g., reproduction directly changes family size and composition by adding an individual) and dashed lines represent effects on probabilities (e.g., the dependency ratio affects the probability of reproduction).

### Families

Families are co-residential groupings of persons that form through marriage and change in size and composition through marriage, reproduction, and mortality. Families are the basic units of production and reproduction in the model. Mostly commonly, persons in families are related through biological descent, marriage, or marriage to a common partner. Less commonly, families can form that include members that are not related by descent or marriage (e.g., when both parents in a family die and their “orphan” children are re-housed in a different family). A list of variables associated with families is provided in Appendix A. Note that the term “household” used in model code is synonymous with “family” as used here.

The dependency ratio of a family (ratio of the number of consumers to the number of producers, *aka* the CP ratio) is a key factor in probability-based, family-level decisions about marriage and reproduction. A dependency ratio of 1.75, considered “typical” of hunter-gatherers (Binford, 2001: 230), was used to perform economic calculations.

A measure of the productive capacity (surplus or deficit) of each family is converted to “assets” each year by multiplying the number of producers by 1.75 and then subtracting the number of consumers. This calculation assumes that each producer in the family is capable of producing 1.75 “units” and each member of the family (producers and consumers) consumes 1.00 “units.” In a family of 4 with 2 producers, for example, 3.5 units are produced and 4.0 units are consumed, resulting in a deficit of 0.5 units. In a family of 5 with 3 producers, 5.25 units are produced and 5.0 units are consumed, resulting in a surplus of 0.25 units. These units are an abstract currency created to allow operation of feedbacks related to family-level productive capacities.

The assets created through production each year are added to the cumulative assets of the family (or subtracted in a deficit year). In this model, family-level assets are relevant to marriage in situations where marriage entails exchange of assets between the families of the bride and groom (see below).

### The system and the world

Together, the persons and families interacting in the “world” of the model comprise a social system. Model-level parameters set conditions for all persons or all families in the world and define aspects of the system: all persons have the same *ageAtProduction* and *ageAtReproduction*, for example. The values of these parameters do not change as a result of the dynamics of the model, but can be changed during an experiment to observe the effects of a change. Table 5 presents a summary of model-level parameters and the default values of those parameters used in the experiments discussed here.

The “world” of the model has no spatial component. Time passes in the model in the form of discrete steps, each step representing 1 year.

### Methods

Methods are named sections or “chunks” of Java code that perform operations when called under specific circumstances. When the marriage methods are called for a particular person, for example, a series of operations is initiated which results in a determination of whether or not that person will marry during that particular step. Marriage methods are person-level methods because marriage is a person-level behavior. The operations performed by the methods are affected by person-level variables (e.g., the marital status of a particular male), family-level variables (the dependency ratios of the current families of the male and female, which are affected by marriage, reproduction, mortality, fertility, etc.), and system-level variables (e.g., the current “cost” of marriage) and parameters (e.g., what constitutes a “sustainable” dependency ratio). Each of these variables in turn, can be affected by other methods in the model.

### Marriage methods

Marriage is the mechanism of family formation and one of the mechanisms (along with mortality and reproduction) for changing

**Table 5**  
Key model-level parameters and variables in the FamilyNet2 model.

Parameter/Variable	Type	Description	Default Value
<i>numberOfPersons</i>	Integer	Parameter: size of initial population	500
<i>ageAtProduction (AAP)</i>	Integer	Parameter: age at which children become producers	NA (varied for experiments)
<i>ageAtReproduction</i>	Integer	Parameter: age at which persons may marry and begin reproducing	16
<i>reproductiveMax</i>	Integer	Parameter: maximum age at which females may reproduce	35
<i>maxFertility</i>	Double	Parameter: mean lifetime fertility rate used to calculate yearly base probabilities of reproduction	10
<i>childMortality</i>	Double	Parameter: total probability of death between birth and <i>ageAtReproduction</i>	0.40
<i>adultMortality</i>	Double	Parameter: yearly probability of death of persons older than <i>ageAtReproduction</i>	0.02
<i>maxAge</i>	Integer	Parameter: maximum allowable age	70
<i>sustainableCP</i>	Double	Parameter: ratio of consumers: producers in household(family) that is considered “sustainable”	1.75
<i>carryingCapacity</i>	Integer	Parameter: population above which there is an increase in mortality rates	500
<i>upperBPLimit</i>	Double	Parameter: upper limit placed on value of <i>bridePrice</i>	10
<i>lowerBPLimit</i>	Double	Parameter: lower limit placed on value of <i>bridePrice</i>	–10
<i>bridePriceMultiplier(BPM)</i>	Double	Parameter: adjusts influence of <i>bridePrice</i> on marriage decisions	NA (varied for experiments)
<i>bridePrice</i>	Double	Variable: the “cost” of getting married in terms of the assets that must be transferred from one household to another at the time of marriage	–

the size and composition of a family. In the FamilyNet2 model, females may have only a single husband while males can have multiple wives. This structural asymmetry is meant to allow the forms of marriage that are most commonly found in hunter-gatherer societies (i.e., monogamy and polygyny) (see Binford, 2001).

Marriage methods are affected by a variety of factors, including probabilistic economic calculations performed by both males and females and the availability of productive “assets” (see above) that must be transferred between families at the time of marriage. All males and all unmarried females of reproductive age (16) are eligible to marry each step. The model includes a basic incest prohibition preventing marriage between individuals that have a close biological relationship or that have been part of the same family. The operations of the basic methods associated with marriage are summarized as a flow chart in Fig. 7.

If a male is already independent of his parents (i.e., he is already married), the probability he will seek to add a wife is conditioned by a calculation expressing the difference between the dependency ratio in his current family (*curCPR*) and the dependency ratio if he adds a wife (*condCPR*) as a percentage of his current dependency ratio:  $(curCPR - condCPR)/curCPR$ . The addition of a single adult to a family will always lower the dependency ratio. The results of this formula are illustrated in Fig. 8. This simple calculation captures two key aspects of the economics of polygyny: (1) wives are more likely to be added when the addition is of greater economic benefit; and (2) as family size increases, each additional wife has progressively less impact on the dependency ratio, all other things being equal. If a male of reproductive age is currently unmarried, he will always attempt to marry.

When a male attempts to marry, a potential bride is randomly chosen from the pool of unmarried females of reproductive age. The model then checks to confirm that the marriage pairing would not violate basic incest prohibitions (no marriages within a person's biological family, no marriages to a spouse's parents, grandparents, or children, no marriages between any two individuals that have ever been part of the same co-residential family) nor create an economically unviable family (e.g., if the female has many dependents from a previous marriage where the husband has died).

If these conditions are met, the probability that the female will accept the marriage is calculated by comparing the dependency ratio within the potential bride's current family (*brideCurrCPR*) with the dependency ratio of the family she would join (e.g., as a second wife) or form with the male (*condCPR*). The probability of her accepting the marriage is calculated as  $1/(condCPR/brideCurrCPR)$ . The results of this formula are illustrated in Fig. 8. Thus there is a

50% chance that a female will enter into a marriage that will put her in a situation where the dependency ratio is twice as high as in her current situation.

Marriage is linked to production through the exchange of assets at the time of marriage. A model-level variable *bridePrice* is adjusted each step by comparing the current ratio of available males to available females with the same ratio during the previous step. If the ratio has increased (i.e., potential brides have become more scarce), the value of *bridePrice* increases by a randomly generated number between 0 and 1. If the ratio has decreased, the value of *bridePrice* decreases by a randomly generated number between 0 and –1. When the value of *bridePrice* is positive, marriage entails a cost to the male side. When the value of *bridePrice* is negative, the bride's family bears the cost of marriage.

If sufficient assets are not available, a marriage will not take place. If *bridePrice* is at +2, for example, and the male's family (his parents' family if unmarried, his own conjugal family if married) has cumulative assets of only 1.5 units, the marriage will not be allowed. For the runs considered here, the value of *bridePrice* is capped at limits of  $\pm 10$ . Without these limits, populations can go extinct when the price moves too high or too low and the system cannot compensate in a timely fashion.

The *bridePriceAdjustment (BPA)* affects the probabilities produced by the economic calculations performed by males and females during the marriage methods. Each step, the model calculates the value of *BPA* as the current *bridePrice* divided by the maximum possible *bridePrice*. If *bridePrice* is  $>0$  (i.e., potential brides are relatively scarce), the male calculation is affected: when *bridePrice* is at its maximum positive value, the probability of the male searching for an additional wife will be doubled. If *bridePrice* is  $<0$  (i.e., potential brides are relatively common), the female calculation is affected: when *bridePrice* is at its maximum negative value, the probability of a female accepting a plural marriage offer will be doubled. The *bridePriceMultiplier (BPM)* is used to adjust the strength of these scarcity-based adjustments by multiplying the effects of the bride price adjustment. When *BPM* is set at zero, *bridePrice* does not affect individual calculations affecting decisions to search for or accept marriage partners. Note that *bridePrice* still affects marriage, however, because a transfer of assets equal to *bridePrice* is required for marriage.

#### Reproduction methods

Each married female of reproductive age goes through the reproduction methods (Fig. 9) each step. At the core of these methods is a probability of reproduction (*pReproduce*) calculated by dividing a model-level parameter specifying the maximum fertility

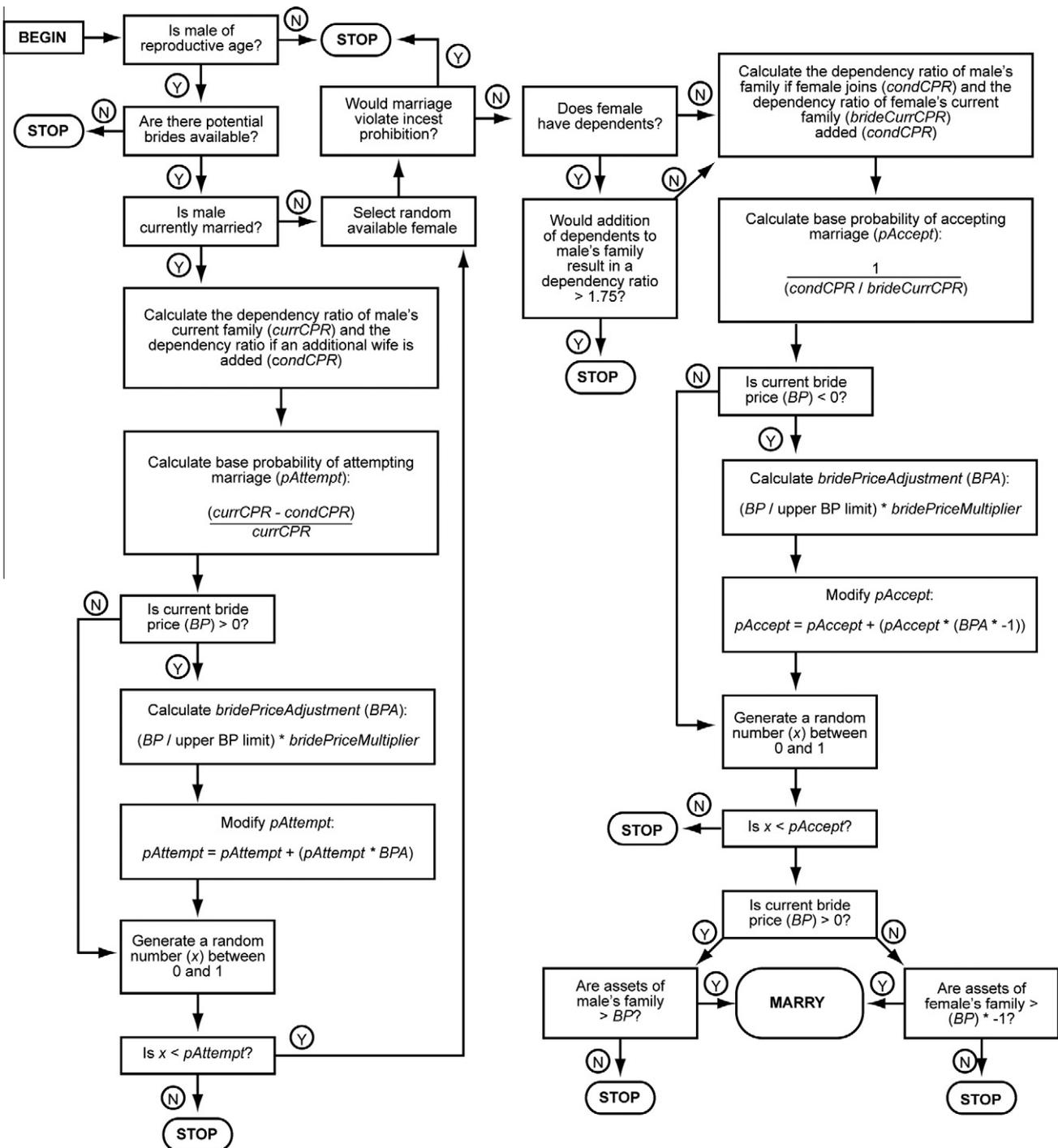


Fig. 7. Flow chart of marriage methods in by the FamilyNet2 model.

rate (*maximumFertility*) by the number of years in the female reproductive span (*reproductiveSpan*). In the experiments discussed here, the value of *maximumFertility* was always set to 10 and the value of *reproductiveSpan* was always set to 20 years, resulting in a *pReproduce* of 0.5. Note that the year-to-year base probability of reproduction is constant, rather than variable as in actual human populations. This is a simplification for the purposes of modeling.

Reproduction methods include mechanisms for both avoiding procreation and terminating the life of a newborn infant (i.e., committing infanticide). Both of these are probabilistic mechanisms that consider how the addition of a child would affect the current

dependency ratio of the family. The chance of avoiding procreation is determined by calculating how much above 1.75 the dependency ratio would rise if another child were to be added and taking this amount as a percentage of 1.75 (e.g., the chance of avoidance is 100% if another child would raise the dependency ratio to 3.5).

Successful reproduction results in the creation of a child of random sex who is then added to the family, the “world,” and all applicable lists. Post-birth, the chance of infanticide is calculated the same way as avoidance: the difference is that the birth and death of a child figure into infant mortality rates where avoidance of procreation does not. The sex of a child does not affect the probability of infanticide. Note that there are explicit linkages between

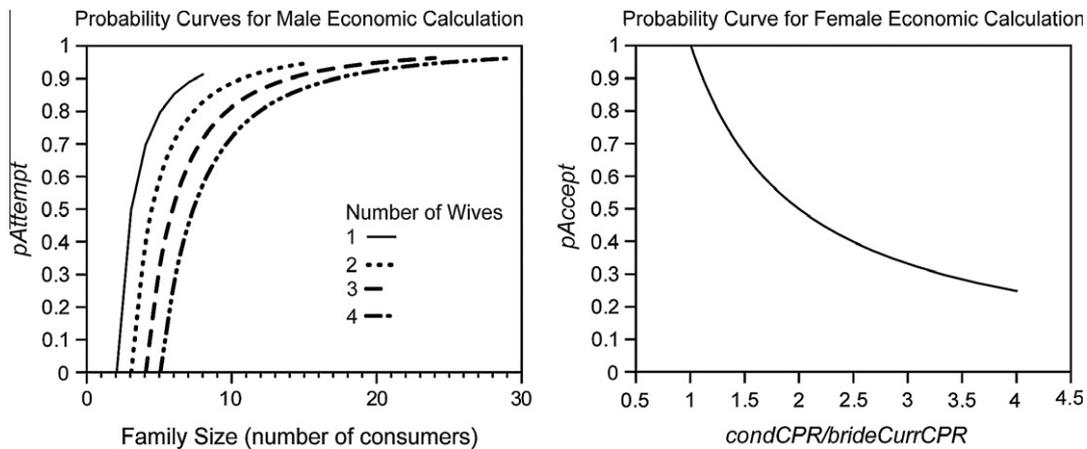


Fig. 8. Probability curves for marriage-related economic calculations made by males and females in the FamilyNet2 model.

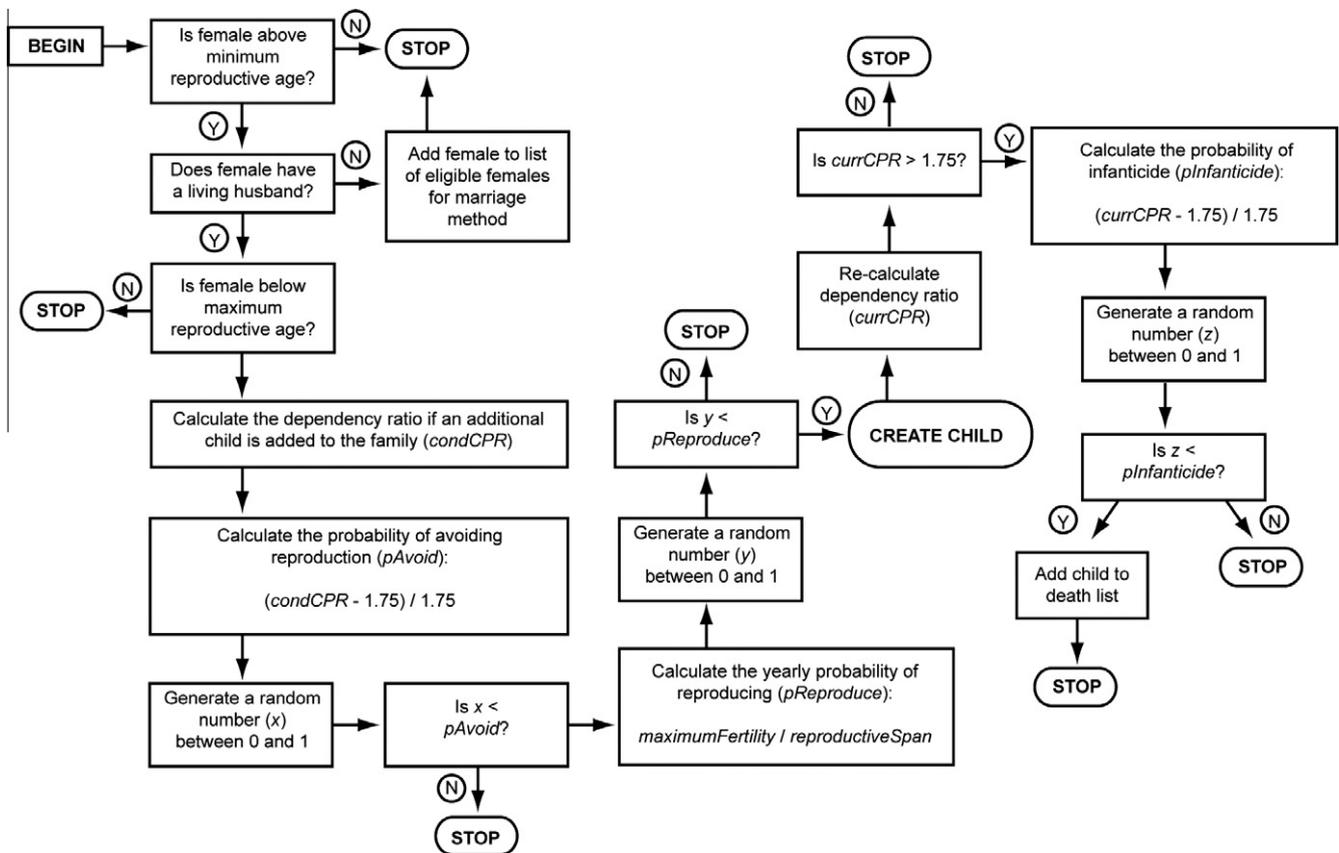


Fig. 9. Flow chart of reproduction methods in the FamilyNet2 model.

avoidance/infanticide and the dependency ratio of the family in this model: it is consideration of family composition (rather than a desire to regulate birth interval) that influences decisions to avoid pregnancy or terminate a newborn infant.

The total fertility rate (the mean number of births that occur over the course of a female's reproductive span) is a behavior-related variable that can be viewed as a result of a model run. Note the difference between the value of the parameter *maximumFertility* and the actual number of births that is measured by the total fertility rate. While the base probability of reproduction every year (i.e.,  $p_{Reproduce}$ ) is 0.5 when *maximumFertility* is 10 and *reproductiveSpan* is 20, the actual mean number of births will be reduced

through avoidance and other factors (such as a high female age at marriage) that are affected by family economics. In other words, the behavior of the agents in the model during a particular run will produce a mean total fertility rate that is not directly programmed into the model and can be analyzed as a system-level behavioral result.

#### Mortality methods

Each person is exposed to a risk of death at each step during a model run (Fig. 10). If a person reaches the maximum age of 70 (set by the value of the model-level parameter *maxAge*), death is automatic. Below this maximum age, the probability of an adult

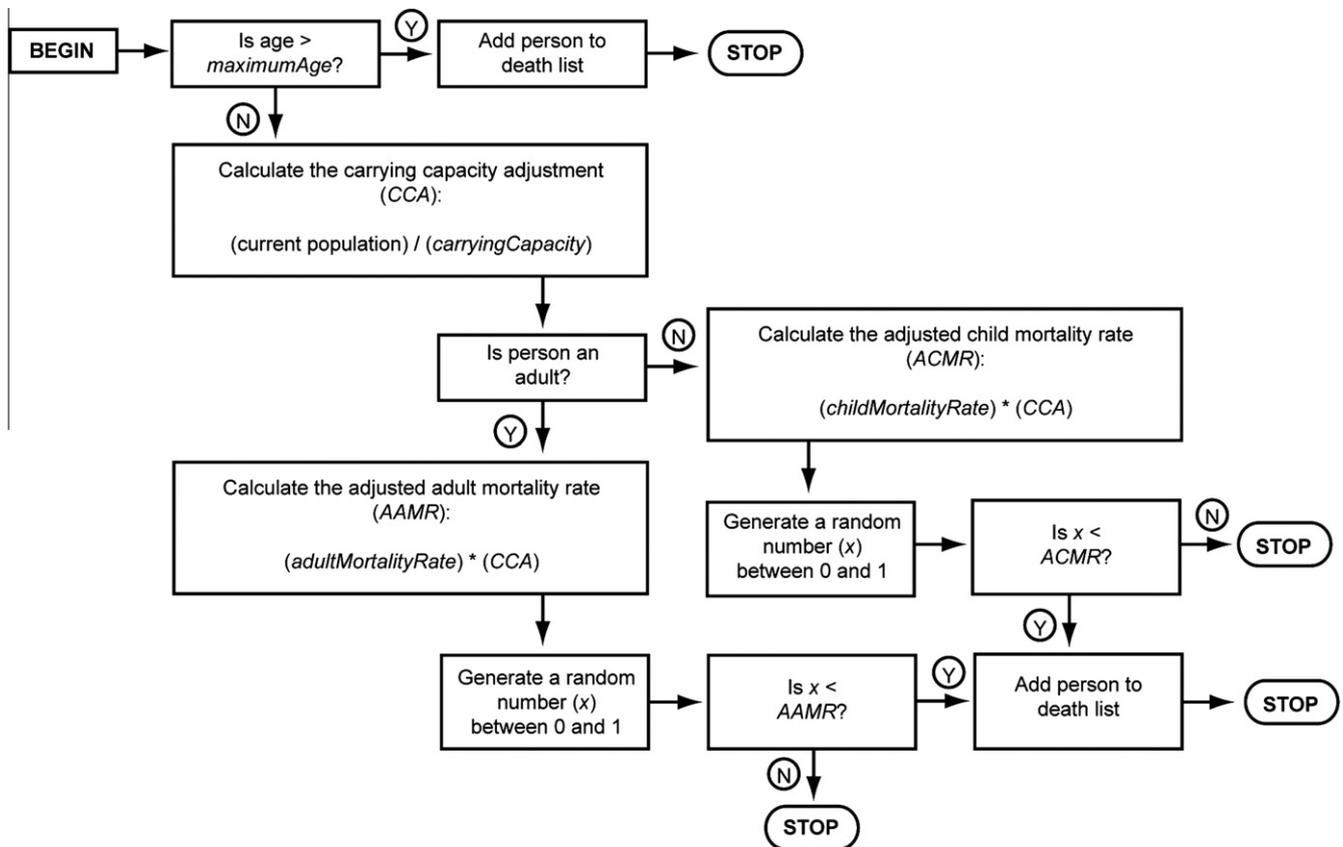


Fig. 10. Flow chart of mortality methods in the FamilyNet2 model.

Table 6

Summary of operations of the step method in the FamilyNet2 model.

Operation	Description
Check step count	Check to see if it is time to change time period, values of parameters, etc.
Clear lists	Clear lists that are re-generated each step (list of adult males, list of females eligible for marriage, etc.)
Calculate the carrying capacity adjustment	Calculate adjustment to mortality rates based on comparison of current size of population with population size specified by the value of the parameter <i>carryingCapacity</i>
Shuffle the person list	Shuffle the order of the lists of all living persons in order to randomize the order in which persons execute person-level methods
Initiate male and female step methods	Go through person list: call male step method for male persons, female step method for female persons. The male step method checks the male's age to see if it is > the value of the parameter <i>ageAtProduction</i> ; if so, the male is added to a list of adult males eligible for marriage. The female step method check's the female's age to see if it is > the value of the parameter <i>ageAtProduction</i> ; if so and if the female has no living husband, the female is added to the list of females eligible for marriage. If the female is already married and within her reproductive span, the reproduction methods are called
Calculate bride price	Calculate the ratio of males and females eligible for marriage and compare the ratio to that of the previous step. If ratio is higher than in previous step, increase <i>bridePrice</i> by random amount between 0 and 1. If ratio is lower than in previous step, decrease <i>bridePrice</i> by random amount between 0 and 1
Determine marriage order	Randomize order in which eligible males perform marriage methods
Marriage methods	Each eligible male initiates execution of the marriage methods.
Add new persons	Add newly created people (i.e., newborns) to the list of persons; collect data on the number of newborn persons if within a data collection period (T1 or T2)
Collect data on marriage/polygyny	If within data collection period, collect data on numbers of wives and numbers of marriages
Mortality methods	Each person initiates mortality methods to determine if he/she will die in current step
Remove dead people	Persons who have died in current step are removed from households and list of living persons; person's age at death is recorded. If within data recording period, data are collected for statistics on infant mortality, fertility, marriage, etc.
Age persons	Each person is aged 1 year
Locate and rehouse orphans	Check for "orphans" (persons below <i>ageAtProduction</i> who are not living with a person who is above <i>ageAtProduction</i> ); orphans are rehoused in viable families
Purge dead households	Households with a size of 0 (no members) are removed
Perform yearly household economic calculations	Calculate dependency ratio of each household; increment age of household; if in data collection period, collect data on household size
Report aggregate data	If at the end of a data collection period, calculate and report aggregate statistics from the data collection period: infant mortality rate, mean household size, maximum household size, mean fertility, mean male age at marriage, mean female age at marriage, percentage of polygynous marriage, mean intensity of polygyny, mean surplus of households over their lifespans

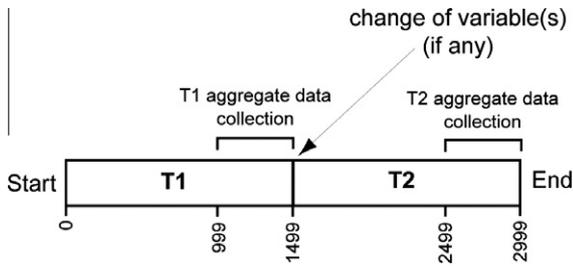


Fig. 11. Basic structure of model experiments.

dying is determined by a yearly adult mortality rate. Children are exposed to a risk of death through a yearly child mortality rate. For the experiments discussed here, the child mortality rate was set at 2.67% yearly and the adult mortality rate was set at 2.0% yearly.

The “base” adult and child mortality rates are adjusted each step based on the difference between the current population size and the specified “carrying capacity” of the world (set by the model-level parameter *carryingCapacity*). Populations in excess of the carrying capacity are subject to higher mortality rates while those below carrying capacity are subject to lower mortality rates. This is a feedback mechanism to provide some degree of population size stability during runs. A “carrying capacity” of 500 does not mean the population will always be 500: it simply means that mortality rates are positively or negatively adjusted based on whether population size is above or below 500.

Note that there is no distinct parameter for infant mortality: infants are exposed to the same yearly risk of death as all other sub-adults. Infants can experience higher mortality rates, however, through the economically-sensitive infanticide mechanism that is represented in the model. Thus infant mortality, like total fertility, is a behavior-related variable that can be viewed as a result in model experiments.

Model operation and data collection

At startup, the model produces an initial population of a specified number of persons of random sex and random age between the age of reproduction (16) and 25. Initial population size was

set to 500 for all the experiments discussed here. Initial families are created through random marriages between eligible males and females.

Following the creation of initial persons and families, the model takes a “step” and initiates a sequence of operations: calculation of bride price and carrying capacity adjustments, person- and family-level methods related to marriage, reproduction, and mortality, and any collection and storage of data for analysis (Table 6). This same sequence of operations is repeated in every subsequent step until the model has completed a specified number of steps.

Model experiment runs lasted 3000 steps (i.e., 3000 “years”). Aggregate data were recorded during two 500 step periods (T1 and T2) (Fig. 11). Changes in value of a parameter, if any, were made at step 1500. The 1000 step periods before each data collection period allow the behavior of the system to stabilize following startup and any changes implemented at step 1500.

Model experiment runs could be configured to collect several different kinds of data outputs: aggregate data on population-level means during T1 and T2; cross-sectional data on the attributes of individual people and families; and longitudinal data on the characteristics of individual families. At the end of each 500-year data collection period (i.e., T1 and T2), aggregate data on mean and maximum family size, infant mortality rate, mean fertility, mean male and female ages at marriage, percentage and intensity of polygyny, and the mean amount of surplus produced over the lifespan of a family were reported. For analytical clarity, the “family” unit of analysis only included co-residential groups with both a husband a wife (i.e., conjugal groups with both productive and reproductive capacity).

Validity of model behavior

The validity of a model (how well the model represents what it is intended to represent) can be evaluated by comparing the behaviors of the model with the known behaviors of the real world systems it purports to represent (see Gilbert, 2008). For obvious reasons, the behaviors that are the subject of this comparison can be neither those behaviors that are directly programmed into the model nor those behaviors that constitute the emergent phenomena we are trying to investigate. We can, however, make comparisons between data from real world hunter-gatherer systems and corresponding aspects of the model system that are the result

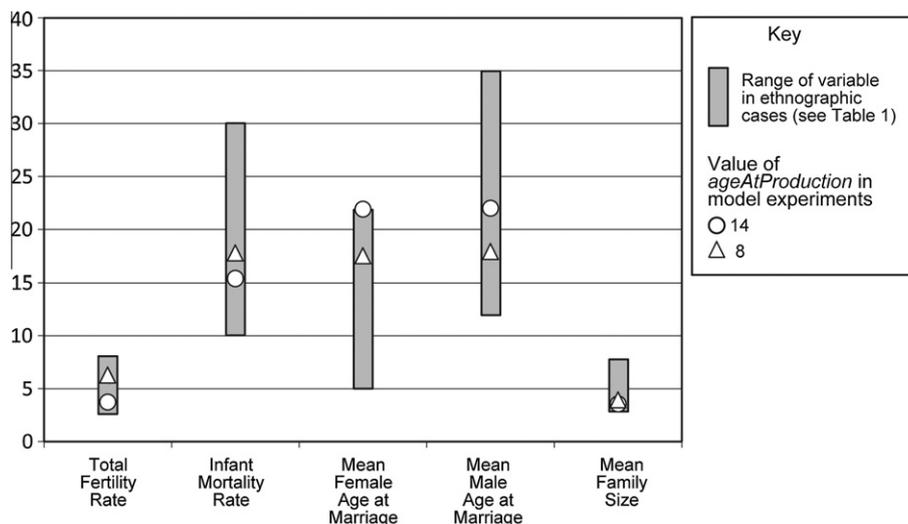


Fig. 12. Comparison of results from model runs with range of variables among ethnographically-documented hunter-gatherers. Means of total fertility rate, infant mortality rate, male and female ages at marriage, and family size fall within ethnographic hunter-gatherer range whether the value of *ageAtProduction* is set to 14 (circles) or 8 (triangles).

of the dynamics of the model. These comparisons allow us to assess the degree to which the internal dynamics of the model match those of the system it represents.

The specifics of validation experiments and results are discussed in Appendix A. Experimental results suggest the systems in the model produce rates of fertility, infant mortality, mean family size, and mean male and female ages at first marriage within the ranges documented among ethnographic hunter-gatherer systems (Fig. 12). All of these are system-level characteristics that are the result of family- and person-level “rules” and constraints that influence productive and reproductive behavior. An examination of individual families produced by the model suggests that the “rules” produce realistic results at that level, also. Along with age profiles similar to those of real populations, these results suggest that the model reasonably captures the basic dynamics and economic aspects of family size and composition that are of interest here, and is therefore a useful tool for investigating cause-effect relationships between the family-level behaviors and system-level patterns we are interested in.

### Model experimentation and results

A series of experiments was performed to evaluate how the age at which children become producers (*ageAtProduction*, hereafter *AAP*) and the strength of the incentive for polygynous marriage (*bridePriceMultiplier*, hereafter *BPM*) were related to a number of other variables, including mean family size, distributions of family size, the degree and intensity of polygyny, infant mortality rates, and mean age at marriage. These experiments were undertaken in order to understand both: (1) how variables related to family-level production and reproduction are inter-related in the model; and (2) how changes in family-level economics might “scale up” to changes that are discernible at the system level.

Because the goal of these experiments was to isolate the effects of changes in one or two variables, the values for most parameters used by the model (i.e., basic parameters related to mortality, fertility, population size, and what constitutes a sustainable dependency ratio) remained constant (see Table 5). The values for these parameters were chosen to fall within the ranges documented among ethnographic hunter-gatherers. Basic information about the settings and characteristics of each set of model experiments is provided in Table 7.

Experiments A1 and A2 were designed to evaluate the gross effects of a significant reduction in *AAP*. Both experiments began

with *AAP* set at 14. In A1, *AAP* was reduced to 8 at step 1500, while in A2 it remained at 14 for the entire run. Mean family size increased significantly during T2 of A1 following a decrease in *AAP* from 14 to 8 (Fig. 13). This increase was associated with increases in the percentage of polygynous marriage, increases in mean fertility, and decreases in the mean female age at marriage (Fig. 14). The suite of changes triggered by a decrease in *AAP* is consistent with general expectations derived from ethnographic data: constraints on reproduction and family size are relaxed because larger families are economically viable when children make a contribution to subsistence. None of these changes occurs when *AAP* remains unchanged (i.e., in Experiment A2).

Experiment B examined the effects of the direction and magnitude of a change in *AAP* between T1 and T2. In each run, *AAP* during T1 and T2 was a randomly chosen integer between 5 and 16, allowing *AAP* to change between T1 and T2 by  $\pm 11$ . Comparisons of the change in *AAP* vs. change in mean family size, mean fertility, percentage of polygyny, and mean male and female ages at marriage indicate linear relationships between these variables: the direction and degree of change in *AAP* produces a relatively straightforward change in these variables related to family size and composition (Fig. 15). A decrease in *AAP* results in proportional increases in mean family size, fertility, infant mortality, and polygyny, and proportional decreases in the mean male and female ages at marriage.

In all runs discussed thus far, the value of *BPM* was set to 0, meaning that *bridePrice* plays no role in the economic calculations performed by males contemplating the addition of a wife or females contemplating the acceptance of a marriage proposal. These runs produced degrees of polygyny between 1% and 10%. As discussed above, setting *BPM* to be  $>0$  alters the probabilities associated with either male or female marriage calculations: a scarcity of potential brides (i.e., a current *bridePrice*  $> 0$ ) increases the probability that a male will seek additional wives, while a glut of potential brides (i.e., a current *bridePrice*  $< 0$ ) increases the probability that a female will accept a marriage.

Results from Experiment C show the relationship between the value of *BPM* and the mean and maximum levels of polygyny produced. These runs produced levels of polygyny between 1% and 27% (Fig. 16). While the range of levels of polygyny is similar in runs where the T2 *AAP* was set at 8 and 14, consistently higher mean percentages and intensities of polygyny were produced when the T2 *AAP* was set at 8. Greater mean family sizes and infant mortality rates were also associated with the lower *AAP*. The relationships between these variables and *BPM* are curvilinear: mean percentages of polygyny, intensities of polygyny, family size, and

**Table 7**  
Basic settings and characteristics of model experiments.

Experiment	n Runs	T1		T2		Data outputs
		<i>AAP</i>	<i>BPM</i>	<i>AAP</i>	<i>BPM</i>	
A1	1000	14	0	8	0	Summary data from T1 and T2, each run
A2	1000	14	0	14	0	Summary data from T1 and T2, each run
B	1000	5–16 (random)	0	5–16 (random)	0	Summary data from T1 and T2, each run
C1	1000	14	0	8	0–100 (random)	Summary data from T1 and T2, each run
C2	1000	14	0	14	0–100 (random)	Summary data from T1 and T2, each run
D	100	14	0	8	0	Data on live persons at the beginning of T1 and T2
E1	100	14	0	8	0	Data on population size and <i>bridePrice</i> at each step
E2	100	14	0	14	0	Data on population size and <i>bridePrice</i> at each step
E3	100	14	0	8	1	Data on population size and <i>bridePrice</i> at each step
E4	100	14	0	14	1	Data on population size and <i>bridePrice</i> at each step
F	1	14	0	8	0	Data on each live family at each step from beginning of T1 $\rightarrow$ T1 + 100, beginning of T2 $\rightarrow$ T2 + 100
G	1000	14	0	5–16 (random)	0–100 (random)	Data on each live family at the beginning of T1 and T2
H	50	14	0	14	0	Data on each dead family during T1 and T2
I	50	14	0	8	0	Data on each dead family during T1 and T2
J	50	14	0	14	50	Data on each dead family during T1 and T2
K	50	14	0	8	50	Data on each dead family during T1 and T2

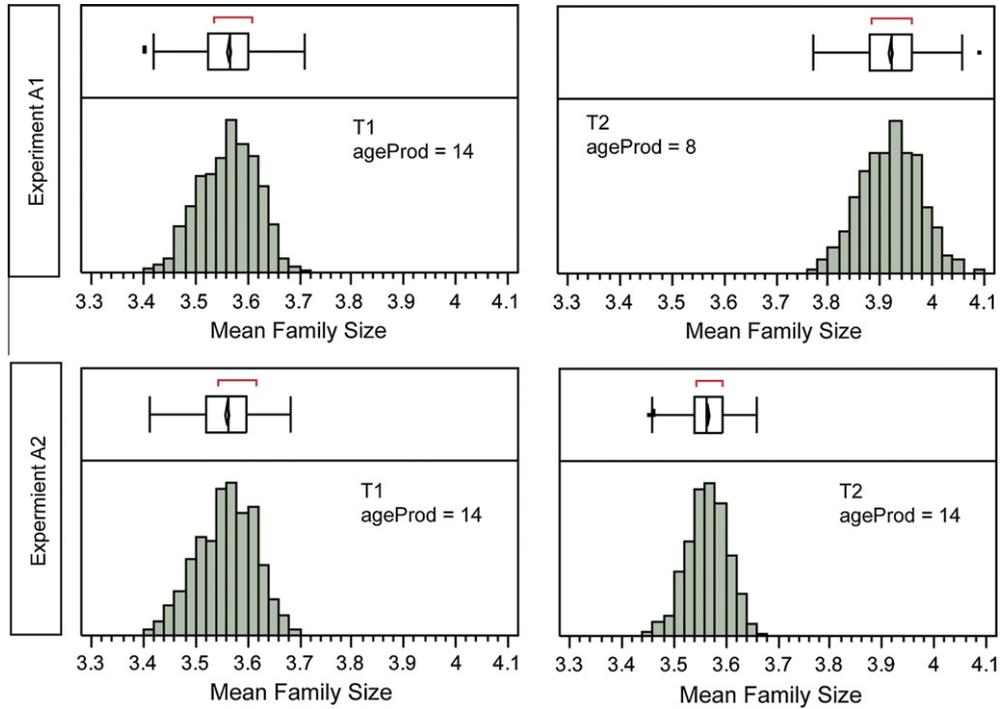


Fig. 13. Histograms of mean family size produced during 2000 runs in Experiments A1 and A2.

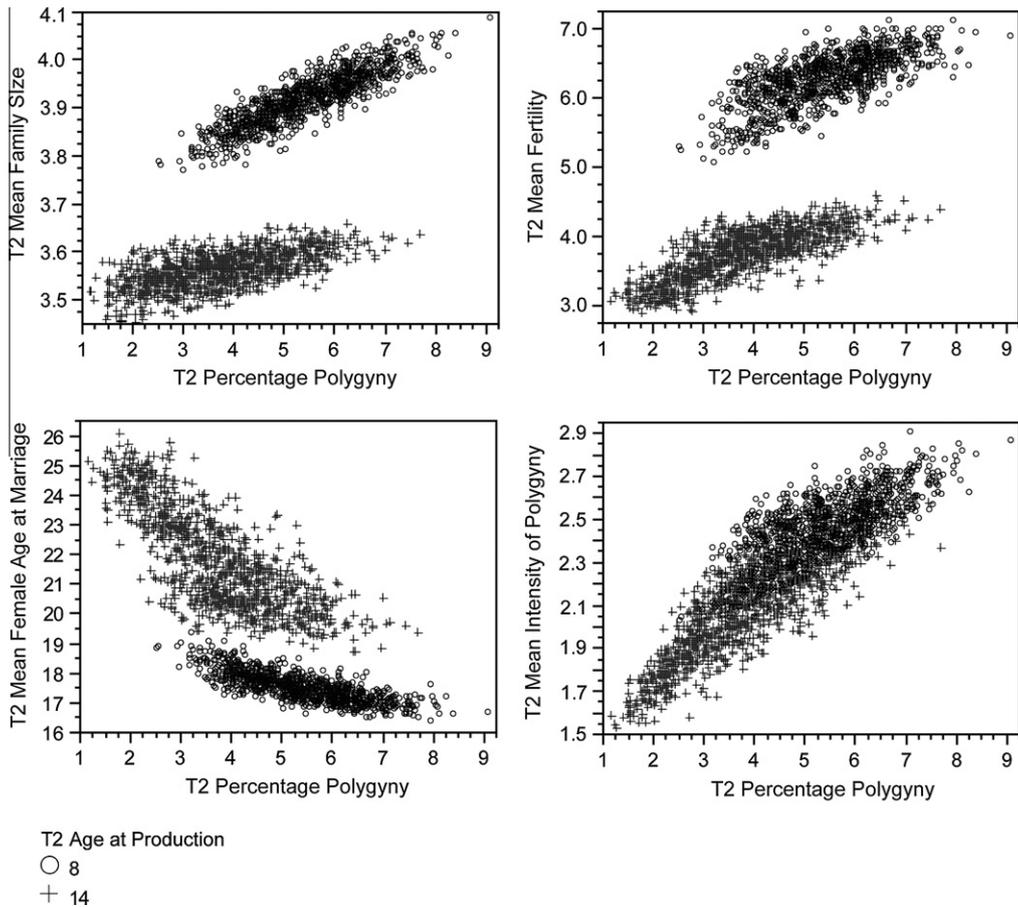
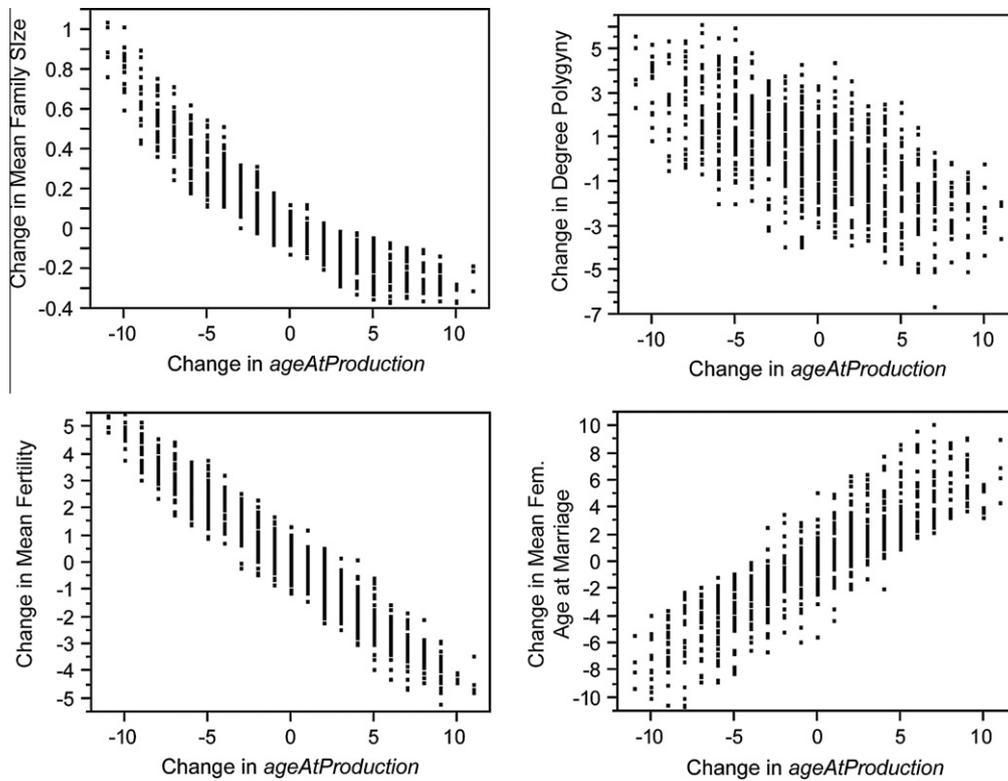


Fig. 14. Mean family size, mean fertility, mean female age at marriage, and mean intensity of polygyny plotted against the percentage of polygyny (Experiments A1 and A2).



**Fig. 15.** Relationships between changes in *ageAtProduction* from T1 to T2 and changes in mean family size, the degree of polygyny, mean fertility, and mean female age at marriage (Experiment B).

infant mortality increase relatively rapidly when *BPM* is increased between 0 and 20. As is clear from the scatterplots, however, the value of *BPM* demarcates the maximum percentage of polygyny that is produced but does not have a large effect on the minimum percentage of polygyny. Within the model, it is necessary to incentivize plural marriage through an increase in the *BPM* in order to produce ranges of the degree of polygyny consistent with those seen in the ethnographic record (i.e., including cases over 10%).

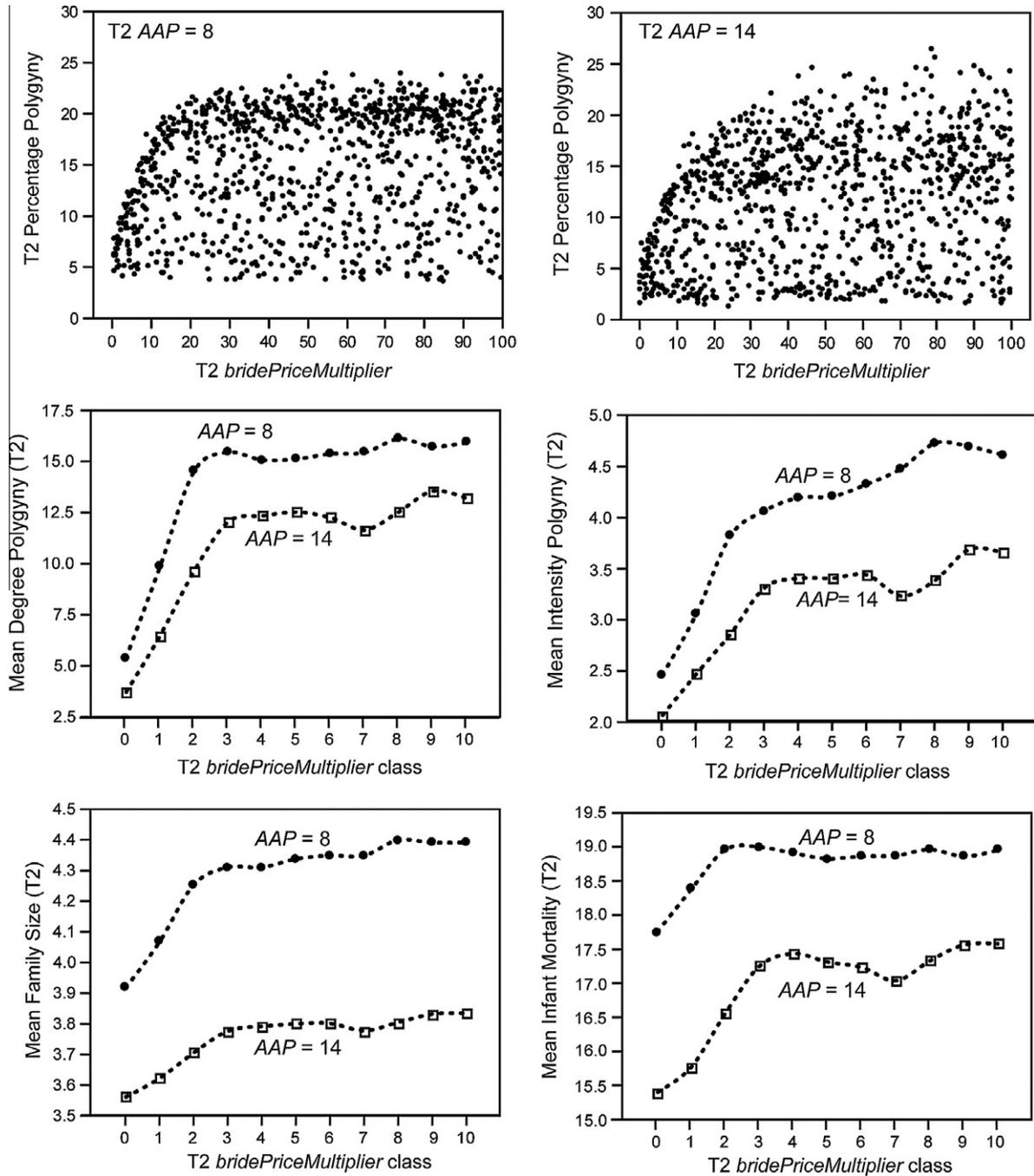
Relationships between the degree of polygyny and the statistical characteristics of the distribution of family size were investigated in Experiment G. All runs started with *AAP* set at 14 and *BPM* set to 0. At step 1500, change in the values of these parameters was randomized (5–16 for *AAP*, 0–100 for *BPM*). Cross-sectional data were recorded on the size of each “live” family during a single step at the start of T2. These data were used to calculate the percentage of polygyny and the statistical characteristics of the distribution of family size (mean, standard deviation, skewness, coefficient of variation) in each run (Fig. 17). The model produced the expected positive relationships between the degree of polygyny and the mean, standard deviation, and coefficient of variation of family size. Examples of family size distributions from a run producing low polygyny (Run 748) and high polygyny (Run 780) are also shown in Fig. 17.

Most of the values from the ethnographic examples considered above (see Table 3) plot within the cloud of values produced by the model (see Fig. 17). There are several obvious exceptions. The mean family size of the Walbiri example is lower than that produced by model runs with a comparable degree of polygyny. Meggitt (1962: p. 80) states that girls typically marry and leave family unit by the age of 10 or 12, decreasing the size of residential families. The model, in contrast, contains no provision for marriage below the age of reproductive maturity (set at 16). This difference could account for the low mean family size of the Walbiri relative to the model results.

In the Inupiat example, measures of variability (standard deviation and coefficient of variation) are lower than those produced by model runs with a comparable degree of polygyny. Burch (2006: pp. 82–84) speculated that a combination of low fertility and high infant mortality rates resulted in relatively few living children among the Inupiat, and relatively small family sizes (see also Smith and Smith, 1994). The largest conjugal family in the sample considered here was 5 persons: thus the range of family size is only 2–5 persons. Mean fertility in the model runs plotted in Fig. 17 ranged from 2.6 to 8.8 while infant mortality ranged from 10.2% to 21.2%. Fertility below this range and/or infant mortality above this range could account for the low variability in family size among the Inupiat relative to the model results.

Finally, the model was used to explore the relationship between the peak size of a family over the course of its lifespan and its cumulative productive capacity. Data on peak size and lifespan surplus were collected at the “death” of each family during T2 in Experiments H, I, J, and K, varying *AAP* (14 and 8) and *BPM* (0 and 50). The 200 runs in these experiments produced data on over 640,000 families. Histograms in Fig. 18 show the distribution of lifespan surplus in each of the four cases. It is clear that both lowering *AAP* from 14 to 8 and increasing *BPM* from 0 to 50 result in more skewed distributions of lifespan surplus. The combination of a low *AAP* and high *BPM* produces the most skewed distribution of lifespan surplus (Fig. 18, bottom left).

The scatterplots on the right side of Fig. 18 show peak family size (the largest size reached by a family) plotted against lifespan surplus for each experiment. These diagrams graphically depict the “possibility space” of relationships between peak family size and productive capacity that is produced by each set of model variables. In the top three diagrams, the possibility space takes the shape of an ovoid cloud of points, the right edge of which is the least well-defined. In these diagrams, the families with the greatest capacity for surplus production are not necessarily the largest. In the diagram associated with the most skewed distribution of life-



**Fig. 16.** Relationships between the value of *bridePriceMultiplier* and polygyny, mean family size, and infant mortality. The top charts show a nonlinear relationship between the value of *bridePriceMultiplier* and the maximum percentage of polygyny that can be produced during a model run. The four bottom charts show the differences in how the value *bridePriceMultiplier* (collapsed into classes) is related to the mean degree of polygyny, the mean intensity of polygyny, mean family size, and mean infant mortality. Higher values of all of these variables are produced in runs where *ageAtProduction* is 8 rather than 14.

span surplus (Fig. 18, bottom right), however, there is an association between high peak size and high lifespan surplus in the right side of the cloud: while much of the population occupies approximately the same possibility space as in the other experiments, the highest levels of surplus production are associated with large families. These large families, comprising a relatively small component of the population, occupy the long right tail of the distribution of lifespan surplus.

In summary, experiments performed using the FamilyNet2 model have demonstrated that a change in the age at which children become producers (*AAP*) causes patterned changes in mean

family size, the degree and intensity of polygyny, mean fertility, infant mortality, and male and female ages at marriage in the model systems. Values produced for all of these variables are within the range of those reported for ethnographically-documented hunter-gather systems. Changes are caused by adjustments in the family-level economic calculus affecting decisions related to reproduction and marriage. When the incentive for plural marriage is increased by adjusting the probability of taking additional wives based upon the relative scarcity of potential brides (increasing *BPM*), high polygyny systems can emerge. Model systems produced under conditions of both incentivized polygyny and a low age at

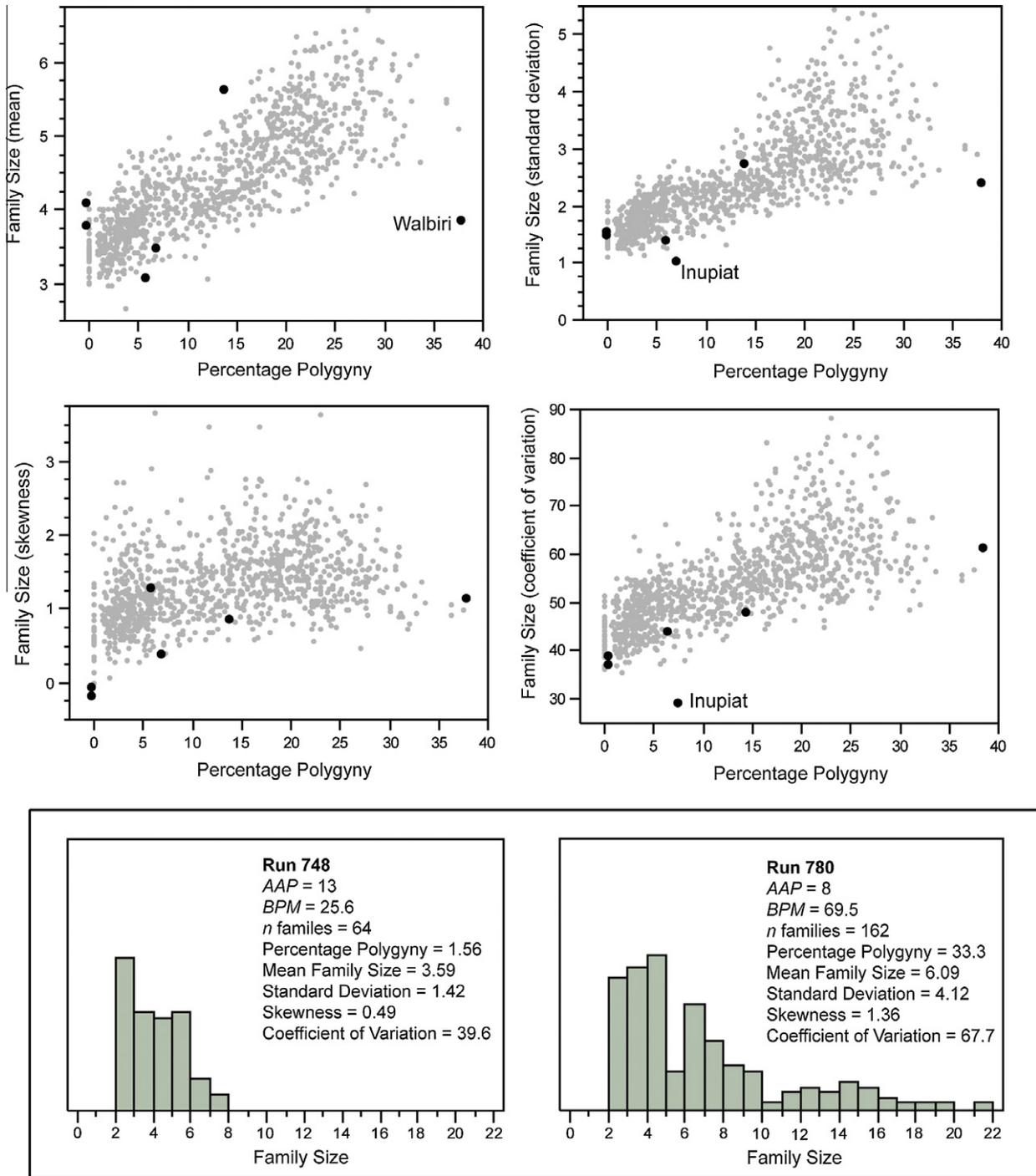


Fig. 17. Mean, standard deviation, skewness, and coefficient of variation of family size plotted against the degree of polygyny (Experiment G, 1000 runs) with values from ethnographic cases plotted (black dots). The histograms at the bottom show differences in the distribution of family size from two example runs.

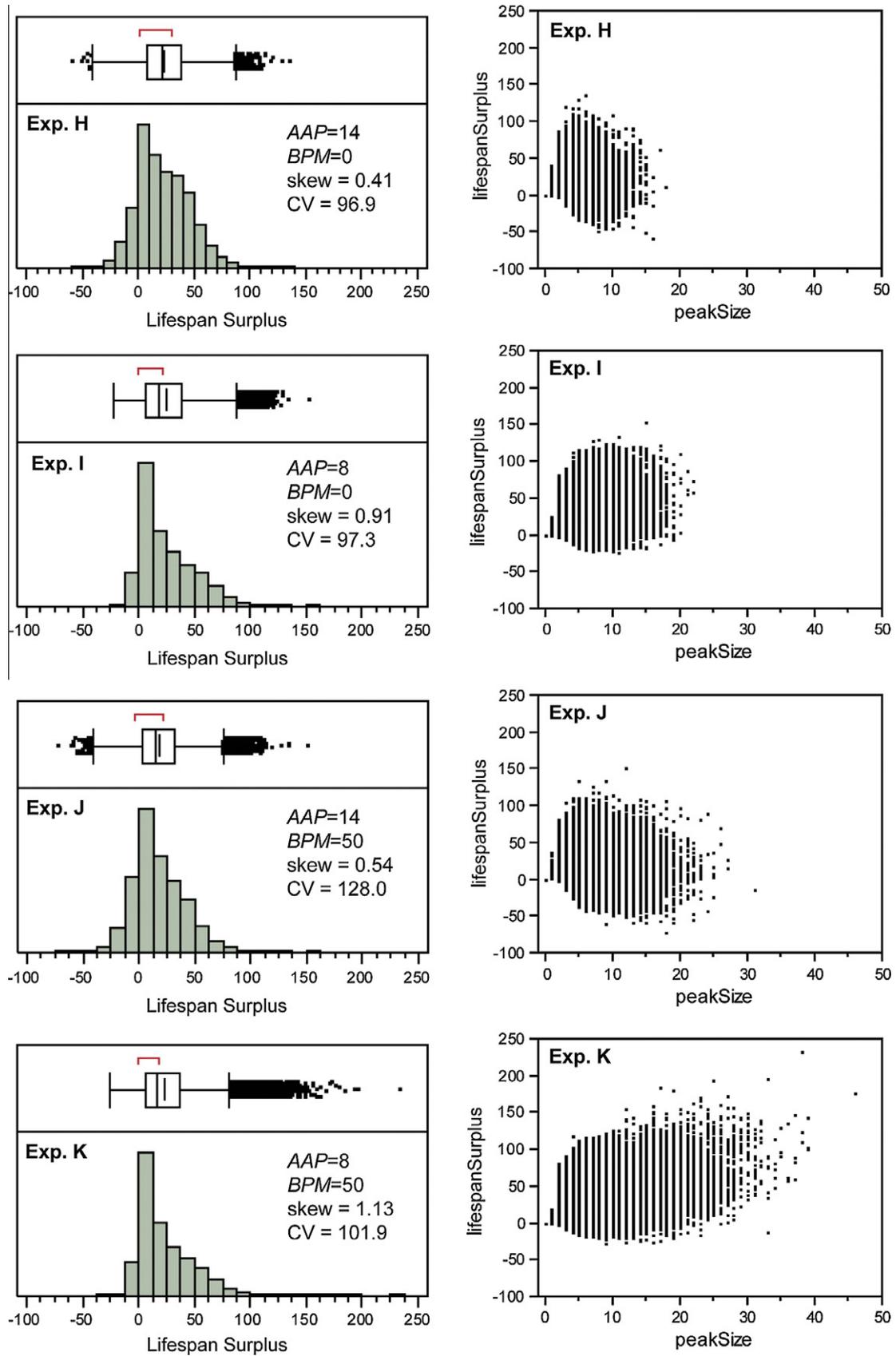
production have a highly skewed, right-tailed distribution of productive capacity. In these cases, large family size is associated with high levels of cumulative surplus production relative to the rest of the population.

**Archaeological data**

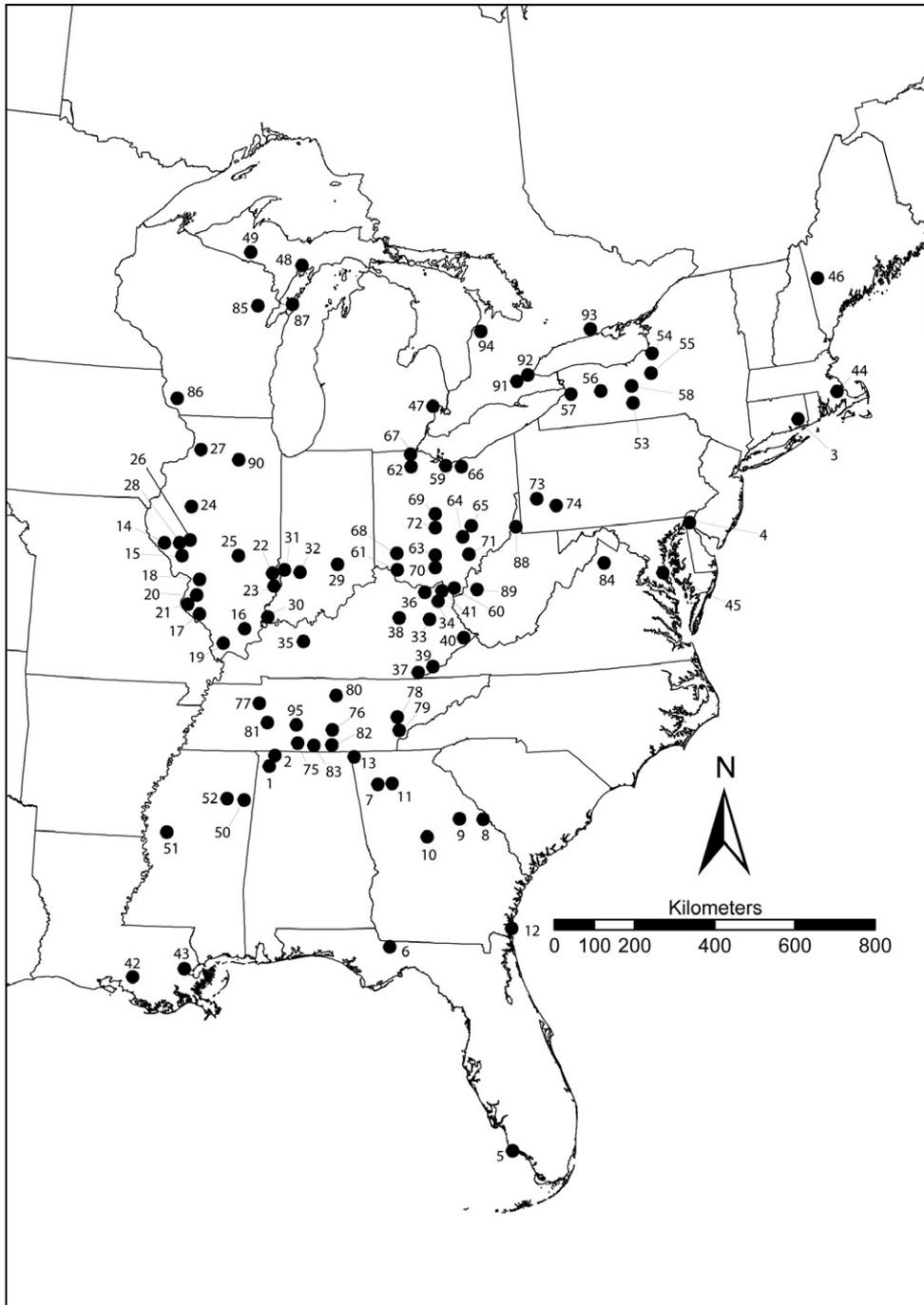
Archaeological data from eastern North America can be used to make inferences about changes through time in the distribution of family size. These data can be compared to data produced by the

computational model and ethnographic data in order to make an interpretation about their meaning.

The best archaeological data pertaining to family size come from the remains of residential structures. The existence of some degree of positive relationship between the size of a residential structure and the number of occupants is warranted by studies using ethnographic data (e.g., Cook, 1972; Cook and Heizer, 1968; LeBlanc, 1971; Naroll, 1962; Whiting and Ayres, 1968). Size data from dated assemblages of residential structures has the potential to inform us about changes through time in mean family size, maximum family size, and the distribution of family size.



**Fig. 18.** Histograms of the amount of surplus produced over the lifespans of families during four experiments (Experiments H, I, J, and K) with different combinations of *ageAtProduction* and *bridePriceMultiplier* (left). The charts at the right plot *lifespanSurplus* of each family against its *peakSize*.



**Fig. 19.** Locations of archaeological sites with domestic structure data used in the analysis (Paleoindian through Middle Woodland periods). Information on individual sites and structures and associated bibliographic references can be found in the supplementary data file provided online.

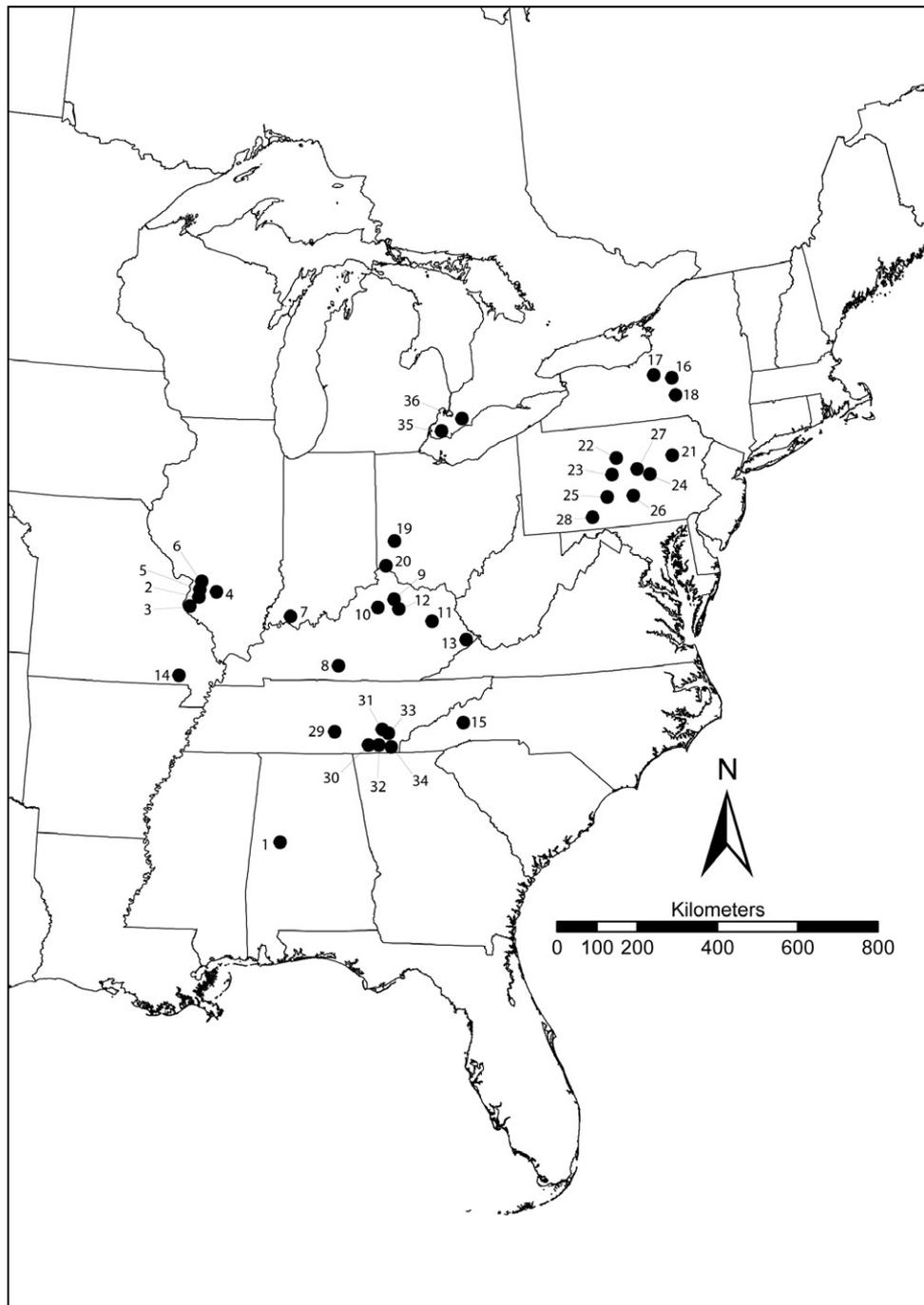
Conventions of chronology and nomenclature used to subdivide prehistoric time vary somewhat across eastern North America. The framework employed here is a general one that is intended to serve as a simple organizational tool. Because this study is concerned with long-term, large-scale patterns of change, age estimates more precise than gross chronological period are not required. General date ranges are given in terms of calendar years.

#### *Prehistoric domestic structures in eastern North America*

The locations of sites with reported prehistoric residential structures from eastern North America are presented in Figs. 19

and 20. Basic data on individual structures from these sites are provided online in a supplementary file. The locations of sites dating to Paleoindian period through Middle Woodland/Late Woodland transitional period are shown in Fig. 19. The locations of sites that are clearly post-Middle Woodland (i.e., Late Woodland, Late Prehistoric, Fort Ancient, Emergent Mississippian, and Mississippian periods) are shown in Fig. 20.

The data discussed here were compiled from a variety of published sources, are of uneven quality, and are not intended to be exhaustive. Use of this kind of extant data requires one to place some level of confidence in the conclusions and interpretations of the original researchers. Some purported dwellings are excluded



**Fig. 20.** Locations of archaeological sites with domestic structure data used in the analysis (post-Middle Woodland period). Information on individual sites and structures and associated bibliographic references can be found in the supplementary data file provided online.

from the analysis because published information relevant to the size and/or age of the structure is unconvincing or insufficient to confidently include the structure. Sites or structures that were excluded from the analysis for any reason are indicated by an “X” in the “Exc.” column in the supplementary data file.

The area enclosed by a structure was estimated based on the linear dimensions and shape of the structure. The areas of circular structures were estimated by calculating the area of a circle with a given diameter. The areas of ovoid structures were estimated by calculating the area of circle with a diameter equal to the mean of the “long” and “short” axes of the structure. The areas of rectangular and subrectangular structures were estimated by multiplying

the length and width dimensions of the structure. Published floor area estimates were utilized when it was judged that these estimates were probably more accurate than those generated by the methods described above.

A variety of criteria were used to assign structures to chronological periods, including radiocarbon dates pertaining to individual structures or other deposits at a site, associated diagnostic artifacts, stratigraphic associations, etc. Structures which could not be confidently assigned to a time period based on the available data were excluded from further analysis.

Residential structures dating to the Middle/Late Archaic through Middle Woodland periods appear to include two main

classes: “closed” and “open.” Closed post structures varied in shape from circular to rectangular and were sometimes constructed around a pit or basin. Basins or depressions without associated posts have also been identified as the remains of residential structures, generally with the assumption that the postmolds have been destroyed in the plowzone. It is not clear in some cases if these basins/depressions are the remains of purposeful semi-subterranean construction or if they mark the locations of floor areas depressed through use and subsequently filled with refuse. In either case, the dimensions of these depressions would tend to underestimate the original size of the structure, especially when truncated by plowing. In many cases, basins/depressions (especially those that are irregular in shape) without posts are excluded from the analysis for this reason.

Open structures, identified by curvilinear arcs of postmolds or widely-spaced posts supporting arbors, are often interpreted as warm weather dwellings (e.g., see Milanich and Fairbanks, 1980: pp. 74–75). These structures are typically interpreted as temporary shelters erected and used during mild weather (e.g., see Bentz, 1988: p. 8; Bowen, 1977: pp. 109, 113; Keener and Nye, 2007: p. 287; Smith, 1992; Vickery, 1976: p. 219). While these shelters may have served a family-level, residential purpose, their openness precludes a meaningful estimation of “floor” area. These structures are not included in the statistical analysis.

The use of multiple kinds of dwellings during the Middle/Late Archaic through Middle Woodland periods is consistent with the operation of “semi-nomadic” systems where mobility, group size, and activities vary on a seasonal basis (see Binford, 1990). Domestic structures pre-dating the Late Archaic period are not numerous. The low number of domestic structures identified from these early periods certainly reflects the nature of the architecture in use rather than the lack of architecture. While all known modern hunter-gatherers construct shelters at residential sites “regardless of the expected occupational duration,” there is “a very general inverse relationship between mobility and investment in housing” (Binford, 1990: pp. 120–122). Late Pleistocene and Early Holocene (i.e., Paleoindian and Early/Middle Archaic) hunter-gatherers in eastern North America with a high degree of residential mobility would have likely constructed numerous expedient shelters, very few of which would be detectable archaeologically. Materials for structural supports and wall/roof coverings would have been readily available in the temperate woodlands of eastern North America, suggesting that (generally) few components of houses would be transported from one residential site to another (see Binford, 1990: p. 128).

#### *Paleoindian (ca. 11,500–9500 BC)*

Paleoindian houses are exceedingly rare in eastern North America. While several eastern Paleoindian sites have produced clustered distributions of artifacts that have been interpreted as the remains of camps of individual families or larger social units (e.g., see Deller and Ellis, 1992a, 1992b; Fitting et al., 1966; Storck, 1997), the remains of discrete domestic structures are largely unknown. Gramly (1988) describes one possible dwelling area at the Adkins site, perhaps the result of a tent structure enclosing approximately 13 m<sup>2</sup>. An oval/rectangular scatter of postmolds at the Thunderbird site was interpreted as the remains of one or more Paleoindian structures enclosing a maximum area of approximately 21 m<sup>2</sup>.

#### *Early Archaic (ca. 9500–6900 BC)*

Only a small number of possible structures dating to the Early Archaic period have been identified in eastern North America. The earliest of these is what appears to be a small (ca. 4.9 m<sup>2</sup>), ovoid, open-sided, post shelter associated with the Thebes component at the Twin Ditch site (Morrow, 1996: pp. 347–348). Abel

(1994) attributed a small (ca. 7.8 m<sup>2</sup>), circular, basin/post feature at the Weilnau site to the Early Archaic period based on the presence of bifurcate and Stanley cluster projectile points in the fill. Both of these structures are included in the analysis because both appear to enclose a definable area.

Ledbetter et al. (2004) described the remains of a possible tent structure defined by debris concentrations and a few possible anchor stones at the Vulcan site. Perino (1970: p. 119) described two “house sites or living areas” defined by dark soil or midden at the Stilwell II site. The site was dated to the Early Archaic period based on the presence of Kirk and bifurcate projectile point forms. Based on the published information, it is unclear whether the stained areas (measuring about 6.1 m long and of an unknown width) represent house basins or surface midden accumulations. Neither of these sites is included in the analysis.

#### *Middle Archaic (ca. 6900–3800 BC)*

Structures reported from the Middle Archaic period include both post and basin “houses” as well as arcs of postmolds that may be the remains of open shelters or windscreens. Only three reported structures (from Barton-Milner, Nochta, and Oconto) fit the criteria for inclusion in the analysis.

The Middle Archaic structure from the Nochta site is a rectangular basin with no associated posts (Higgins, 1990: p. 100; McElrath et al., 2009: p. 363). It was interpreted as a possible structure based on its size (about 7.8 m<sup>2</sup>) and configuration. It is included here despite the lack of posts because the sample of Middle Archaic houses is so small.

Wittry and Ritzenthaler (1956: p. 245) report a possible Middle Archaic oval structure about 4 m in width in addition to arcs of postholes at the Oconto site (see also Pleger, 2000). The structure reported from Barton-Milner was a post structure encompassing about 16 m<sup>2</sup> (Ahler, 2000).

Multiple rectangular structures interpreted as houses were present in Middle Archaic deposits at the Koster site, built on terraces or platforms that were cut into the slope of the occupational surface (Brown and Vierra, 1983; Carlson, 1979; Wolyneec, 1977). The boundaries of individual structures could generally not be determined, however, making area estimates impossible (Brown and Vierra, 1983: 184; Wolyneec, 1977: p. 275). Brown and Vierra (1983: 184) suggest that the post houses in Horizon 8C might have been around 4.5 × 5.0 m (22.5 m<sup>2</sup>). Wall trenches associated with structures in Horizon 6A2 varied in length from 2.3 to 3.0 m (Wolyneec, 1977: p. 275).

Open arcs and ovoid patterns of postmolds in the Middle Archaic deposits at Modoc Rock Shelter have been interpreted by Ahler (2000) as the possible remains of domestic shelters. Clusters of posts at the base of the midden at the Black Earth site may also be the remains of Middle Archaic domestic structures (Jefferies, 1982: pp. 82, 89).

#### *Late Archaic (ca. 3800–1200 BC)*

Structures dating to the Late Archaic are considerably more numerous than those of earlier periods. Domestic structures can be roughly divided into three main classes: closed basin and/or post structures; open arcs of postmolds; and constructed platforms of clay, sand, or rock that may have been used as dwelling floors. Published descriptions of “closed” post and/or basin structures include structures ranging in size from less than 5 m<sup>2</sup> to over 100 m<sup>2</sup>, with the majority enclosing less than 25 m<sup>2</sup>.

Most of the shallow basins that are interpreted as possible Late Archaic domestic structures (e.g., at the Labras Lake, Range, Cherry, Delaware Park, and Spring Creek sites) are excluded from the analysis for the reasons discussed above. The literature on the Labras Lake features is inconsistent. While Phillips and Gladfelter (1983: p. 201) seem to make a distinction between “shelters” with inter-

nal pits and hearths and “domestic areas” with no internal features, other authors (Fortier, 1993: p. 260; Yerkes, 1987) do not seem to make this distinction. Only Features 171 and 1172 from Labras Lake are included in the analysis.

Several other purported Late Archaic structures were excluded from the analysis for a variety of reasons. Three of the hypothesized structures from Wapanucket No. 6 (Lodge Floors #1, #4, and #7) are excluded from the statistical analysis based on maps and descriptions in the report (Robbins, 1959) that suggest that the excavators did not have confidence that they had delineated the boundaries of the structures accurately. Structure 2 from the Grayson site (Ledbetter and O’Steen, 1992) is excluded because the dimensions of the structure could not be determined. The number of structures represented by the multitude of postmolds from the Robeson Hills site is not clear: Winters (1969: p. 92) simply states that post alignments suggest “circular or oval houses ranging in size from 7 to 30 ft” as well as “small rectangular structures.” An arc of postholes is present along only one side of the structure from the Robinson site (Morse, 1967), suggesting the structure may have not have been a closed house. The large structure (Feature 903) from the Missouri Pacific #2 site was interpreted as a communal arbor (McElrath and Fortier, 1983: p. 59) and is not considered a “closed,” single family structure for the purposes of this analysis. Pfeiffer (1984: pp. 76–77) describes post molds outlining “three oblong structures with compact living floors, storage pits, refuse pits, hearths, and workshops” about 50–55 m<sup>2</sup> in size associated with a Brewerton component at the Bliss-Howard site, but does not provide drawings or individual dimensions. While one or both of the structures at the Cady site may date to the Late Archaic period (Strachan, 1974), the multicomponent nature of the site makes confident attribution difficult in the absence of direct dating.

Platforms constructed of clay, sand, or rock, some of which are associated with postholes, have been interpreted as the floors of residential structures (e.g., see Lewis and Lewis, 1961: p. 15; McCollough, 1973: p. 65; Ritchie, 1940: p. 54; Sassaman and Ledbetter, 1996: p. 78; Webb and DeJarnette, 1942: pp. 61, 238; Winters, 1969: p. 98). The sizes of individual platforms from the Riverton site are assumed to reflect the sizes of individual structures and are included in the statistical analysis. Data on platforms from other sites are usually generalized descriptions and are not sufficient for inclusion.

Arcs of postmolds have been reported from many Late Archaic sites. Clusters of pit and hearth features and/or concentrations of debris at some Late Archaic sites have been interpreted as “domestic areas” that probably centered around residential structures (e.g., Lennox, 1986; Sassaman et al., 2006: p. 556). No attempt was made to include these in the analysis.

#### *Early Woodland (ca. 1200–200 BC)*

Structures dating to the Early Woodland period in eastern North America include both residential structures and monumental and/or ceremonial structures. The latter category includes sub-mound, circular post structures that were originally interpreted as houses (see Clay, 1986, 1987; Seaman, 1986; Webb and Snow, 1945). None of these ceremonial structures is considered here.

Reported Early Woodland domestic structures utilized both post and basin architecture. Compacted floors were noted in some of the Early Woodland post houses reported by Stothers and Abel (1993) as well as in the Tchefuncte “house” described by Shenkel and Holley (1975: p. 232). Circular to ovoid post structures range in size from about 5 m<sup>2</sup> to nearly 80 m<sup>2</sup>, with the majority enclosing less than 25 m<sup>2</sup>. The Meadowood structure from the Sinking Pond site (Granger, 1978) is included in the analysis because the compacted floor appears to define a bounded area even though postholes were only discerned along a portion of the edge. Shallow

depressions at the Larson and Carbon Monoxide sites have been interpreted as the remains of domestic structures. Only Feature 6 from Carbon Monoxide and Feature 17 from Larson, the best preserved structures from the sites, are included in the analysis. A shallow pit feature at the Clyde Farm site was interpreted as the remains of a pit house (Custer et al., 1987).

As at Late Archaic sites, arcs of postmolds may define the edges of open shelters (e.g., Blank, 1977; Bowen, 1989: pp. 46, 62, 212; Carskadden and Gregg, 1974; Railey, 1991: p. 61; Schweikart, 2008: p. 189; Shane, 1967: p. 104). The large Cogswell phase structure reported from the Grayson site appears to have been open on one or more sides (Ledbetter and O’Steen, 1992: p. 32). The Deptford structure from Stafford North also may have been open (Milanich and Fairbanks, 1980: p. 74). Shenkel and Holley (1975: p. 232) interpreted the scatter of postmolds at the Little Oak Island site as the possible remains of a linear (open?) shed-like structure.

Circumscribed scatters of material at the Carbon Monoxide site were interpreted as possibly marking the locations of domestic structures (Fortier, 1985: p. 61). Clusters of features at the Mayview Depot site were also interpreted as marking possible house locations that could no longer be defined based on intact postholes (Robertson et al., 2008: p. 120). Circular shell middens 6–9 m in diameter were interpreted as refuse deposits associated with individual households at Deptford sites (Milanich and Fairbanks, 1980: p. 72). None of these are included in the analysis.

#### *Middle Woodland (ca. 200 BC–AD 500)*

Structures dating to the Middle Woodland period have been identified at numerous sites in eastern North America. As during the Early Woodland period, both residential and monumental/ceremonial structures are present. Structures are generally identified as habitation structures based on their smaller size relative to large, sub-mound structures, the presence of a suite of food storage and processing features (Smith, 1992), and their location not beneath earthen burial mounds. Structures have been identified clustered in “villages” and small groups as well as apparently isolated. House remains marked by basins and/or post outlines vary in shape from circular to oval to rectanguloid. Many of the structures included in this analysis were also used by Smith (1992) in his study of Hopewell farming settlements.

Published descriptions of “closed” post and/or basin structures suggest floor areas ranging from less than 5 m<sup>2</sup> to nearly 190 m<sup>2</sup>, with just over half enclosing less than 30 m<sup>2</sup>. The structure from Brown’s Bottom #1, interpreted by Pacheco et al. (2006) as a habitation structure, is similar in size to the corporate/ceremonial structures from Mound City. With the exception of this structure, the size range of the structures considered here is similar to that of those in Smith’s (1992) study.

Postholes arranged in arcs, rectilinear lines, and “C” shapes suggest the remains of open-sided structures, typically interpreted as warm weather shelters (e.g., Smith, 1992).

#### *Middle Woodland–Late Woodland Transitional (ca. AD 500–650)*

This category is composed of a small number of structures attributed to cultural phases that are variously described as either “late Middle Woodland” or “early Late Woodland,” such as Allison-LaMotte (Indiana-Illinois), Newtown (Kentucky-Ohio), and Mund (Illinois). These regional expressions, all associated with Lowe Cluster hafted bifaces (Justice, 1987), immediately post-date Hopewell but are distinct from later Late Woodland, Late Prehistoric, Mississippian, and Fort Ancient. Because it was unclear if structures from these sites should be included with the Middle Woodland or post-Middle Woodland samples, a separate category was created.

### Post-Middle Woodland (ca. AD 650–contact)

As defined here, the post-Middle Woodland includes more-or-less distinctive Late Woodland, Late Prehistoric, Emergent Mississippian, Mississippian, and Fort Ancient archaeological cultures that clearly post-date the Middle Woodland period but cannot always be differentiated from one another on the basis of chronology. Houses post-dating the Middle Woodland period are numerous compared to earlier periods. While no effort was made to include data from every post-Middle Woodland house in eastern North America, a relatively large sample ( $n = 651$ ) was compiled using published data from both large and small sites.

Post-Middle Woodland residential architecture includes a variety of basin, basin/post, post, and wall trench structures. So-called “keyhole” structures dating to the Late Woodland/Late Prehistoric period in Illinois and Pennsylvania are included under the assumption that these are indeed residential structures rather than special purpose structures (such as sweat lodges) (see MacDonald, 2008; Smith, 1976). As in the earlier samples, structures associated with mounds (i.e., either sub-mound structures or structures built on platform mounds) have been excluded under the assumption that these structures are likely not remains of single-family dwellings. This assumption may not be warranted, however, in the case of at least some structures built atop Mississippian platform mounds: a variety of purposes has been suggested for these structures, including the habitations of “elite” families (e.g., Muller, 1986; Pauketat, 1997). It does seem likely, however, that the sizes of these platform mound structures may have been influenced by factors other than simply the number of occupants.

Large structures that are known to be multi-family dwellings (e.g., Late Prehistoric longhouses found in the northeast) are not considered in this study.

### Structure size and family size

For the purposes of this study, interpretation of the archaeological data on structure size requires accepting three assumptions: (1) these structures are residential structures; (2) the occupants of each structure primarily constitute a single, functionally-integrated “family” unit; and (3) the size of each structure is positively related to the number of occupants.

Identification of these structures as residential structures is, in most cases, a fairly straightforward proposition. While some of the larger structures (e.g., the Brown’s Bottom #1 “house”) could be interpreted as having a corporate or ritual function, most of structures considered here were interpreted as dwellings by the original excavators and later analysts.

With regard to the second assumption, it perhaps bears repeating that “houses” are neither “households” nor “families.” Houses constitute a physical space within which members of a family and/or household unit live and interact. We may infer the characteristics of the occupants of a structure, however, from the characteristics of a structure and its associated remains. Ethnographic reports suggest that the “household” is a meaningful spatial unit in the organization of many (but not all) hunter-gatherer camps (see Cook and Heizer, 1968; O’Connell, 1987; Wiessner, 1974). The assumption that each structure represents the living area of a single, functionally-integrated family unit, while analytically necessary, is a potential source of error: the co-residential groups that built and used these structures doubtless sometimes included individuals outside of the “nuclear” family (i.e., members of the extended family or unrelated individuals). I assume that, despite this potential source of error, the conjugal family probably forms the modal core of the co-residential groups that inhabited the structures considered here.

The third assumption is warranted by studies using ethnographic data (e.g., Cook, 1972; Cook and Heizer, 1968; LeBlanc, 1971; Naroll, 1962; Whiting and Ayres, 1968), and is generally accepted by researchers both in eastern North America (e.g., see Binford et al., 1966; Fortier, 1993; Gardner, 1983; McGregor, 1958; Milanich and Fairbanks, 1980; Sassaman and Ledbetter, 1996: p. 94; Winters, 1969) and elsewhere around the world (e.g., Flannery, 2002; Soffer, 1985). “Closed” structures with identifiable boundaries are the basic archaeological unit of analysis for this study because the sizes of these structures can be used to generate estimates of the number of occupants. The number of occupants of a structure was estimated using Cook’s (1972: p. 16) “rule of thumb formula”: 25 ft<sup>2</sup> (2.3 m<sup>2</sup>) for each of the first six people, 100 ft<sup>2</sup> (9.3 m<sup>2</sup>) for each additional person. This general formula has been used commonly in eastern North America (e.g., Custer et al., 1996; Henderson, 1992; Smith, 1992).

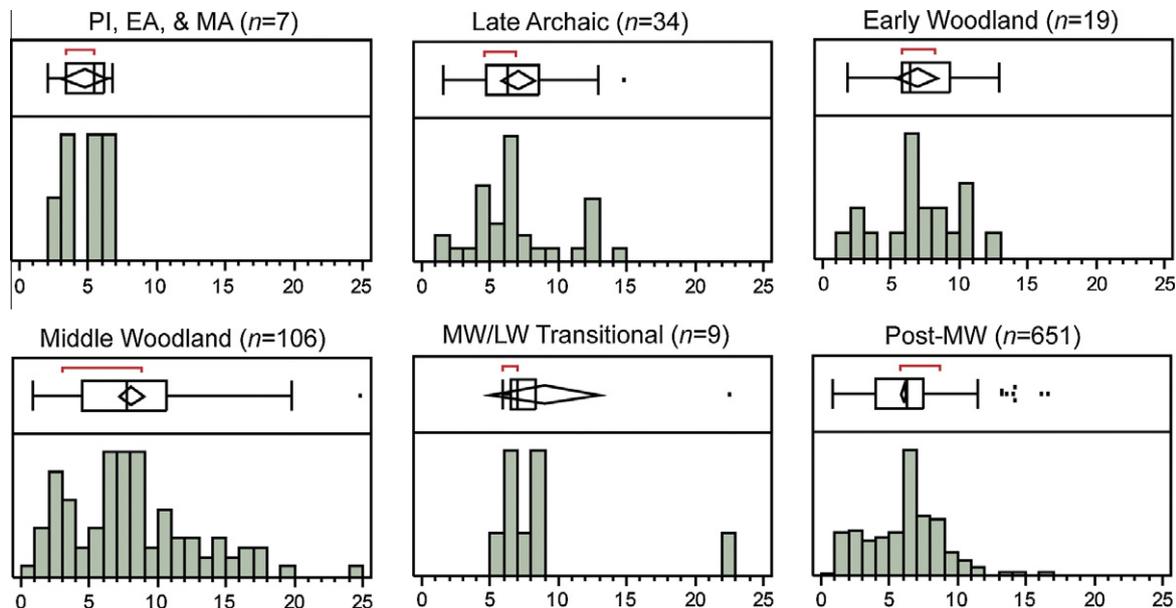


Fig. 21. Histograms of the estimated number of occupants (family size) for archaeological structures by time period (Paleoindian, Early Archaic, and Middle Archaic samples combined).

Based on these assumptions, I consider the size distributions of assemblages of structures from different time periods to be a reasonably accurate index of the distribution of family size during various periods of North American prehistory. Histograms of the estimated number of occupants for eight divisions of prehistoric time are shown in Fig. 21 (the Late Woodland/Late Prehistoric, Emergent Mississippian/Mississippian, and Fort Ancient categories are combined into a single “post-Middle Woodland” category for these histograms). Individual data and the coefficients of variation for each distribution are depicted in Fig. 22. Summary statistical data are given in Table 8.

Several things are notable about the characteristics of these distributions. First, the highest coefficients of variation in the estimated number of occupants are associated with the Middle Woodland sample. The distribution of family size suggested by houses from this period is clearly right-tailed, with structures of a size suggesting up to 25 occupants.

The Late Archaic and Early Woodland samples, while smaller than the Middle Woodland sample in terms of both sample size and mean, also have relatively high coefficients of variation. While examples of houses with 10–5 estimated occupants are present during both periods, houses suggesting more than 15 occupants are absent. Small sample sizes make the shape of distributions unclear.

Variability in family size appears to decrease following the Middle Woodland period. Only a few houses suggesting more than 15

occupants are present in the combined post-Middle Woodland sample, despite the large sample size. The different means and distributions of size within each sub-group of the post-Middle Woodland sample are consistent with the presence of several distinct architectural classes in these groups (e.g., Late Woodland keyhole structures, rectangular wall trench structures associated with Mississippian settlements, and the relatively large post houses associated with Fort Ancient villages in the Ohio Valley).

The data from houses pre-dating the Late Archaic are equivocal given the small sample size (i.e., calculating a coefficient of variation from samples of two or three is not particularly meaningful). It is worth noting, however, that none of the reported Paleoindian, Early Archaic, and Middle Archaic residential structures in eastern North America are of a size suggesting more than about eight occupants. The small size of these structures is consistent with the small size of Late Pleistocene and Early Holocene residential structures from western North America and Beringia. The 37 semi-subterranean and surface structures from Ushki-I range in size from 8 to 100 m<sup>2</sup>, with two of the three structures over 50 m<sup>2</sup> constructed with two distinct rooms (see Goebel and Slobodin, 1999). Assuming the two-chambered structures were built to house two families, this suggests a mean family size of around 6.5 (coefficient of variation 38.9). The incompletely-excavated structure at the Upward Sun River site suggests a size of less than 10 m<sup>2</sup> (see Potter et al., 2011). Purported western Paleoindian post structures from the Hell Gap and Agate Basin sites are also less than 10 m<sup>2</sup> (see Fri-

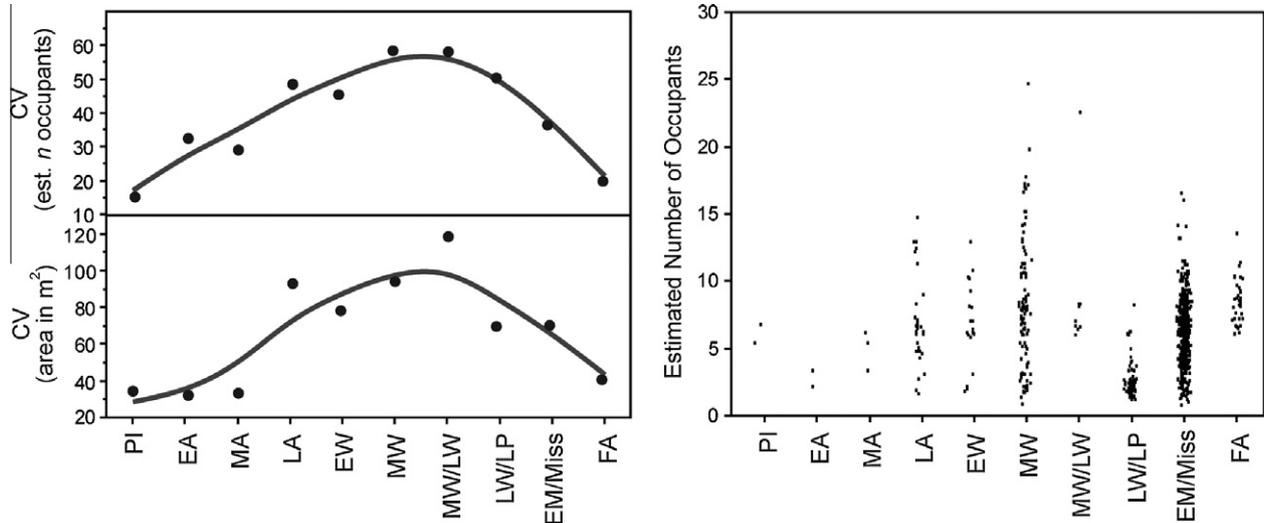


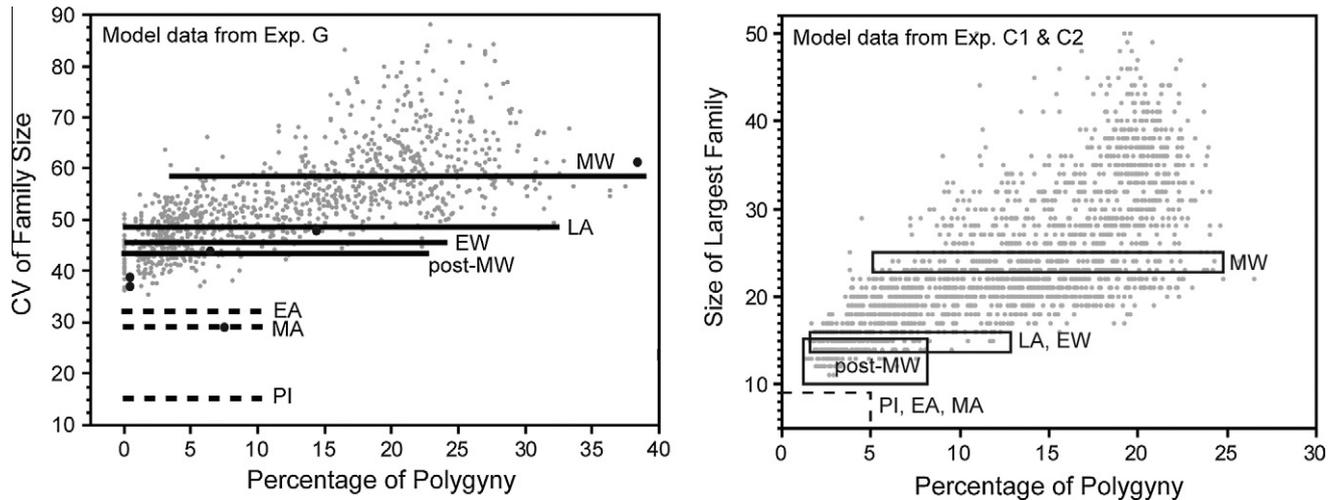
Fig. 22. Coefficients of variation for estimated number of occupants (family size) and structure area (m<sup>2</sup>) by time period (left). The smoothed line (calculated by statistical software) is a representation of the general trend of the data points. The figure on the right plots the estimated number of occupants of each structure by time period.

Table 8  
Statistical characteristics of house and family size estimates from archaeological data by time period.

Period	n Structures	Est. number occupants			Size (m <sup>2</sup> )		
		Mean	SD	CV	Mean	SD	CV
Paleoindian	2	6.1	0.93	15.2	16.7	5.82	34.8
Early Archaic	2	2.7	0.88	32.2	6.3	2.04	32.2
Middle Archaic	3	5.0	1.46	29.2	12.1	3.99	33.1
Late Archaic	34	7.0	3.4	48.5	28.5	26.58	93.4
Early Woodland	19	6.8	3.11	45.6	27.1	21.29	78.4
Middle Woodland	106	8.0	4.69	58.5	39.1	36.79	94.2
MW/LW Transitional	9	8.9	5.19	58.3	40.8	48.16	118.1
Late Woodland/Late Prehistoric	81	2.5	1.28	50.5	6.1	4.26	69.4
Emergent Mississippian/Mississippian	536	6.3	2.33	36.7	22.1	15.49	69.9
Fort Ancient	34	8.6	1.67	19.5	37.7	15.47	41.1
Post-Middle Woodland Combined	651	6.0	2.60	43.4	21.0	15.97	76.1

**Table 9**  
Comparisons between distributions of estimated number of occupants (Kolmogorov–Smirnov tests,  $p$  = probability of being sampled from the same distribution, results statistically significant at the  $p < 0.05$  level in bold).

	E. Woodland	Mid. Woodland	Post-MW combined	LW/LP	EM/Miss	Fort Ancient
Late Archaic	0.83	0.05	0.19	<b>0.00</b>	0.20	<b>0.00</b>
E. Woodland	X	0.57	0.54	<b>0.00</b>	0.54	<b>0.01</b>
Mid. Woodland	X	X	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.01</b>
LW/LP	X	X	X	X	<b>0.00</b>	<b>0.00</b>
EM/Miss	X	X	X	X	X	<b>0.00</b>



**Fig. 23.** Comparison between model, ethnographic, and archaeological data. Values of coefficients of variation of family size estimated from archaeological data are plotted across the distribution of data points produced by Experiment G (left). Values of maximum family size estimated from archaeological data are plotted across the distribution of data points produced by Experiments C1 and C2 (right).

son, 1982; Irwin-Williams et al., 1973; Knudson, 2009). As they stand, the extant data give us no reason to suspect that Late Pleistocene and Early Holocene foragers in eastern North America were building large structures to accommodate large families. The estimated size (about 22.5 m<sup>2</sup>) of the Middle Archaic structures from Koster (Brown and Vierra, 1983: 184) suggests those structures may have held about seven people.

Results from pairwise Kolmogorov–Smirnov tests are presented in Table 9. The Kolmogorov–Smirnov is a non-parametric test that compares the distributions of two samples and calculates the probability that the two samples were derived from the same population. The Middle Woodland sample differs significantly (at the  $p = 0.05$  level) from all the post-Middle Woodland samples, but does not differ significantly from the Late Archaic and Early Woodland samples. All of the post-MW groups are significantly different from one another. The Emergent Mississippian/Mississippian sample is not significantly different from the Late Archaic and Early Woodland samples. The Kolmogorov–Smirnov tests also indicate that most of these distributions do not appear likely to be normal or lognormal.

#### Comparison with model and ethnographic data

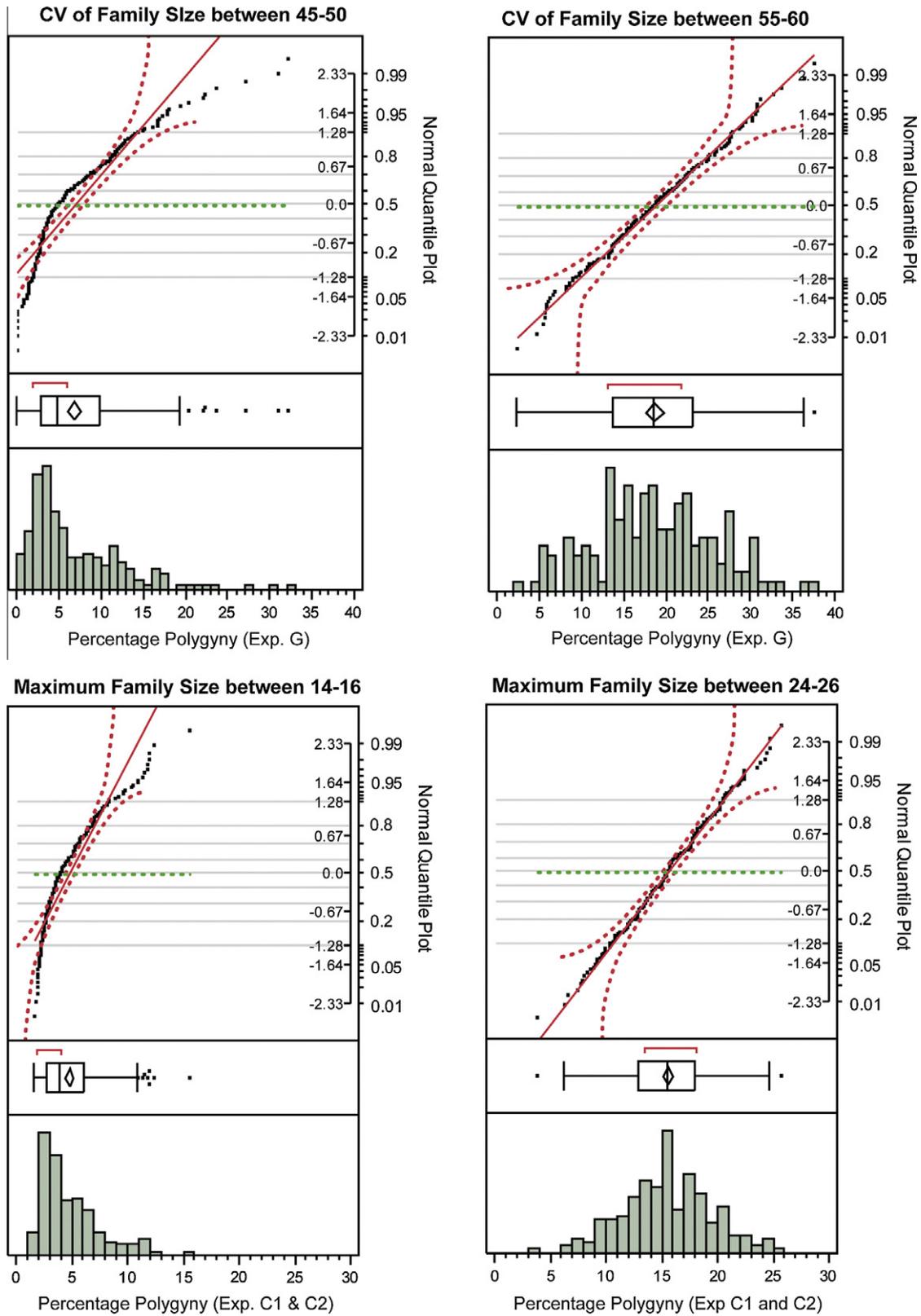
The archaeological data on the distribution of family size can be compared to data produced by the computational model and ethnographic data. Fig. 23 shows two such comparisons using data from Experiments C1 and C2 (2000 runs). The left graph plots the coefficients of variation in family size from the archaeological samples plotted along with the model and ethnographic data previously shown in Fig. 17. The spread of the model data suggests that a given coefficient of variation in family size can be produced by systems with a range of degrees of polygyny. The right graph in

Fig. 23 compares the maximum estimated family size from the archaeological samples against a plot of the maximum family size from model data. Again, the relationship between the variables is positive but relatively loose, indicating similar maximum family sizes can be produced by systems with different degrees of polygyny.

Fig. 24 shows the distributions of the degree of polygyny from the model associated with two ranges of maximum family size and coefficients of variation of family size estimated from the archaeological data. Coefficients of variation in family size between 45 and 50 (i.e., in the range suggested by the Late Archaic, Early Woodland, and post-Middle Woodland structures) are associated with degrees of polygyny between 0% and 32%, with 95% of values falling between 0% and 18% (Fig. 24, top left). Coefficients of variation between 55 and 60 (i.e., in the range suggested by the Middle Woodland sample) are associated with degrees of polygyny between 2% and 38%, with 95% of values falling between 5% and 32% (Fig. 24, top right). While there is overlap between the ranges of polygyny associated with these two different ranges of the coefficient of variation, the probability distributions suggest that the higher coefficients of variation of the Middle Woodland period were probably associated with a higher degree of polygyny.

Data on maximum family size suggest a similar interpretation (Fig. 24, bottom). There is little overlap in the distributions of degrees of polygyny associated with maximum family sizes in the 14–16 range (Late Archaic, Early Woodland, post-Middle Woodland) and those in the 24–26 range (Middle Woodland). The former suggest degrees of polygyny between 0% and 10% (95% confidence interval), while the latter suggest degrees of polygyny between 8% and 23% (95% confidence interval).

The relationships between the coefficient of variation of family size, maximum family size, and the degree of polygyny in the mod-



**Fig. 24.** Histograms of the degree of polygyny associated with coefficients of variation (family size) between 45–50 (top left) and 55–60 (top right) from model data (Experiment G). Histograms of the degree of polygyny associated with maximum family sizes of 14–16 (bottom left) and 24–26 (bottom right) (Experiment C).

el suggest the archaeological data represents the following basic sequence: (1) a beginning state characterized by small family size during the Paleoindian and Early Archaic periods; (2) increasing variability in family size (and an increase in mean family size) dur-

ing the Late Archaic through Middle Woodland periods; and (3) a decrease in mean family size and variability in family size following the Middle Woodland period. Comparison of model and archaeological data suggests that the degree of polygyny in Late

Archaic and Early Woodland systems was probably less than 10%, while polygyny during the Middle Woodland period was probably greater than 10% and perhaps as high as 20–30%. Polygyny probably declined to less than 10% in post-Middle Woodland systems. Available data suggest that polygyny was likely relatively low prior to the Late Archaic period.

In summary, the lack of statistical difference in distributions among the Late Archaic, Early Woodland, and Middle Woodland is consistent with the idea that a common process was operating to produce these distributions. The high degree of variability in family size and the relatively high maximum family sizes inferred from the house data from the Late Archaic through Middle Woodland periods suggest that polygyny probably played a role in the creation of these distributions. Differences in the estimates of maximum family size and the coefficient of variation of family size suggest that polygyny (both the degree and the intensity) and mean family size increased during the Late Archaic through Middle Woodland periods, peaking during the Middle Woodland period. Polygyny and mean family size decreased following the Middle Woodland period.

### Discussion and conclusions

A comparison of archaeological data with results from the model suggests that changes in the family-level productive and reproductive calculus associated with subsistence intensification are a plausible explanation for the distributions of house size that are present during the Late Archaic through Middle Woodland periods. Model runs combining a lowering in the age of production with a strong incentive for multiple marriage produced right-tailed distributions of “wealth” where the productive capacities of some of the largest few families are unmatched by the remainder of the population. These results suggest that, in the presence of a strong impetus for multiple marriage (spurred by a scarcity of available brides), changes in family-level home economics may produce a positive

feedback that provides a seed for the germination of social inequality by widening the spread between large, “high status” families and the remainder of the population.

The coupling of these factors is a path to breaking the social symmetry of “simple” hunter–gatherer systems through the emergence of social strata based on family size. This is the result of positive feedbacks operating on variability in family size that is affected by random processes (such as mortality and fertility), multiplicative processes (the addition of wives), and the “zero sum” availability of females for additional wives. Arthur (1989, 1999) has described how positive feedbacks can, over time, magnify small, random variations in initial states into large differences. This is also described as “increasing returns” or the “rich get richer” phenomenon (Arthur, 1989, 1999; Bentley, 2003).

The right-tailed distributions of family size and productive capacity in the highly polygynous systems produced by the model are similar to the right-tailed wealth distributions associated with the unequal distribution of wealth evident in many different kinds of economies (see Angle, 1986): “most people possess relatively little wealth while a very small minority are extremely wealthy” (Watts, 2003: p. 105). In industrial economies, these wealth curves follow a power law, plotting as a straight line on a log-log scale (Watts, 2003). In these kinds of systems, there is no intrinsic limit on how much wealth can be accumulated: the distribution is said to be “scale-free” because its right tail stretches to infinity. The accumulation of wealth in the systems modeled here is limited, however, as wealth based on family size and family-level productive capacity is constrained by factors such as the finite duration of the human lifespan and the finite number of potential available marriage partners. In real hunter–gatherer systems, maximum family size might also be constrained by ecological factors: the size of autonomous families could not exceed the maximum foraging group size that could be supported during the most dispersed season of the year.

The limits on wealth that are present in the model are clearly visible when data from the top and bottom distributions shown

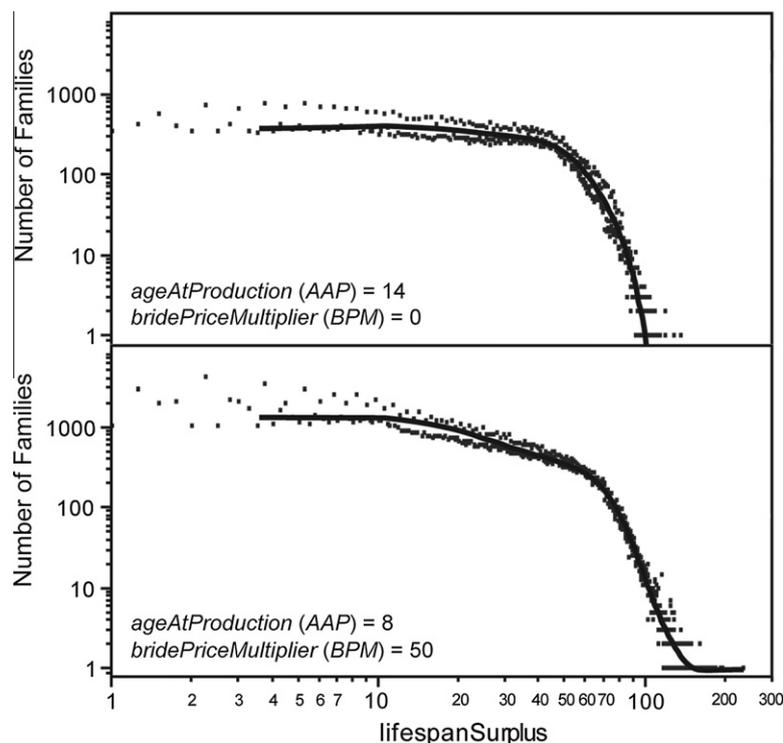


Fig. 25. Log-log plot of the number of families vs. lifespan surplus. Data in the top chart are from Experiment H (see Fig. 18 top). Data in the bottom chart are from Experiment K (see Fig. 18 bottom).

in Fig. 18 are plotted on log–log axes (Fig. 25). There is a steep drop-off at productive capacities above 50 in both illustrations. Note, however, the difference between the two distributions: while the plot of the upper distribution (produced under conditions of no “extra” incentive for plural marriage and a high age at production) plunges into the horizontal axis, there is a small tail present where the plot of the lower distribution (produced under conditions of a strong incentive for plural marriage and a low age at production) meets the horizontal axis. This tail is formed by the largest, “wealthiest” families in the distribution. It creates a slightly sigmoid shape, suggesting the existence of two incipient strata of wealth in the population.

The constraints on building and maintaining wealth solely through marriage and family-level production may encourage the development of mechanisms for storing wealth in material goods, the accumulation and transfer of which may have fewer intrinsic limitations. In contexts where there are mechanisms for transferring wealth from person-to-person and generation-to-generation, a family’s wealth would not necessarily disappear at the end of its developmental cycle. In the absence of some social mechanism for periodically dissipating accumulated wealth, inequalities initially based on variation in family size could ossify into inequalities based on heredity. Wealth could be preserved within lineages and passed on from one generation to the next, perpetuating inequalities in the distribution of wealth and fostering the development of a permanent upper stratum.

This is a plausible scenario for the emergence of social inequality in prehistoric eastern North America that is consistent with several lines of data: (1) results from the model (where process is known and understood); (2) the particular archaeological data on house size discussed above; (3) the timing and characteristics of subsistence intensification in eastern North America; (4) studies of skeletal remains that suggest an increase in fertility associated with a shifting emphasis on horticulture (see Bocquet-Appel and Naji, 2006); (5) ethnographic data that suggest a general, positive relationship between levels of polygyny and the contribution of plant foods to the diet (Binford, 2001: 280; Korotayev, 2003; Marlowe, 2003); and (6) ethnographic data that suggest positive relationships between polygyny, family size, and social status (e.g., Hartung, 1982; Keen, 2006; Kolig, 1989; Layton, 1986; Netting, 1982; Rose, 1968; Whiting and Ayres, 1968: 124).

The explanation for the emergence of social inequality presented here contrasts somewhat with that presented by Hayden (2001) in his discussion of “transegalitarian” societies. In his model, the wealth distribution which provides the grist for the emergence of social inequalities takes the form of an upside-down pyramid. A histogram of wealth in this case would be left-tailed rather than right-tailed. While many of the wealth-increasing strategies that Hayden (2001) discusses might apply in some form to the case presented here, none other than those involving family-level productive and reproductive decisions are required to produce a right-tailed wealth distribution and the emergence of an incipient upper stratum.

Further work on the case in eastern North America could include both augmentation of the computational model and further consideration of archaeological data. In terms of the model, adding a spatial dimension to the interactions that take place would allow us to investigate the role that space plays in these processes. In real hunter–gatherer systems, transfer of information about potential brides, rather than being universal and instantaneous, occurs through person–person interactions that are structured by spatial proximity. Social interactions are also structured by social networks: characteristics of the social networks of individuals are likely to vary considerably when the formation and maintenance of these networks are connected to marriage (i.e., the social networks of individuals in the emergent “upper” wealth stratum are

likely to be larger and more widespread than those of individuals in the lower stratum because the head of a large household would acquire more kin connections each time he adds a wife and each time he marries off a son or daughter). The model could also be augmented by including representation of mechanisms for transforming and transferring wealth, “leveling mechanisms” that prevent, discourage, or dissipate accumulations of wealth, some mechanism for allowing females to marry before reproductive age, representation of divorce or other cultural mechanisms for terminating marriage, and the representation of individual productive capabilities as a continuous, age-based variable (rather than a nominal variable).

One potentially useful class of archaeological data not considered here is the size and location of storage features. Storage allows a seasonally abundant resource to be fully exploited by extending its availability (Redding, 1988; Testart, 1982). This strategy could certainly be used in an effort to mitigate the “pinch” by evening out seasonal fluctuations and/or buffering unpredictability (Halstead and O’Shea, 1989). According to Wiessner (1982), privatized storage (i.e., storage within households) is the hallmark of privatized risk: societies that have communal storage facilities have accepted risk at the level of the group, while societies that practice individual household storage have accepted risk at the level of the household. Diversification is likely to include plant species that are low-ranked, abundant, reliable, high-yield annuals – classic candidates for storage and (sometimes) domestication (Flannery, 1973; O’Shea, 1989). If the emergence of social inequalities is based in part on differences in family-level production, one would expect that the storage of resources contributing to this emergence would be privatized.

The identification of a set of processes that accounts for the patterns of change that we see in the archaeological house size data does not, of course, mean that other sets of processes could not have produced a similar pattern. One could argue that large structures could also have been built to accommodate groups of families, perhaps on a seasonally-specific basis. In other words, perhaps a fission-fusion process operating at the family level produced assemblages of houses with a large amount of variation in size. This possibility could be addressed both with modeling (i.e., creating a model representing this process to see if distributions of family size matching those suggested by the archaeological data could be produced) and by an examination of archaeological data bearing on seasonality of occupation, numbers of hearths, etc. The most common interpretation of the house data, however, is that the classes of structures that have been identified (i.e., closed post structures, closed basin/post structures, open cabanas or windbreaks) correspond to seasonally-specific dwelling types. If this is the case, we would not expect size variation *within* these classes to be related to seasonal fission-fusion of families.

In conclusion, I have proposed a scenario for the emergence of heredity social inequality in prehistoric eastern North America that is consistent with several independent lines of evidence. I have proposed that subsistence intensification entailed changes in family-level productive and reproductive calculus, relaxing constraints on family size and making large, polygynous families economically viable. Under these conditions, positive feedbacks between production and reproduction favored the development of high polygyny systems with large families and a right-tailed distribution of family size and wealth. This distribution would have provided the variability in family-based status that permitted the emergence and entrenchment of hereditary social distinctions. I have supported my argument with a computational model that allows system-level distributions of family size to emerge from numerous person- and family-level interactions and behaviors, specifying an initial condition and demonstrating that relatively simple changes in the “rules” governing family-level behavior produce significant,

patterned changes at the system level. Comparison of model outputs with archaeological data suggest that the right-tailed distribution of house size evident during the Late Archaic through Middle Woodland periods could have resulted from a positive feedback favoring large families through polygyny and increased fertility associated with a widened resource base.

This explanation contains elements of both culture process and culture history and is intended to apply to eastern North America. While the general processes and mechanisms that affect family size and composition in hunter-gatherer systems may be universal, the historical trajectories of change (or stasis) in those systems vary significantly across time and space. This is the expected result of variability in both the natural and cultural environments of these systems as well as in the details of their individual histories: the same processes may produce different outcomes with different initial conditions and/or different parameters (cf. Flannery, 1972: p. 409). Thus the particular scenario presented here may be more-or-less applicable to other societies in other parts of the world depending on context. In cases where family-level behaviors are of central concern, the model (or some derived version of it) could be used to represent the particulars of the system, explore the linkages between levels of process, and develop archaeological test expectations based on whatever specific circumstances or details are of interest. This approach utilizes the capabilities of agent-based modeling as a “third way” of doing science, incorporating elements of both induction and deduction, experiment and theory (Axelrod, 1997). It also requires a level of specificity about

variables and conditions that renders “black box” causal explanations impossible.

### Acknowledgments

This paper has been a long time in the making. I first presented a subset of the ideas and data in this paper in an informal presentation at IPFW in 2004. Other portions of the paper were developed and presented during courses at the University of Michigan in 2007. The computational model was constructed as part of my dissertation work. I am indebted to many people for their efforts in helping me clarify my thinking and giving me the tools and perspective that I have used to attempt to approach an old problem in a new way. Bob Whallon, John Speth, and Carla Sinopoli provided constructive advice on a previous, less-developed version of this paper. Henry Wright and Rick Riolo provided encouragement and technical advice at various stages. I also benefited from conversations and interactions with Khori Newlander and Sarah Striker at various points in the development of these ideas. Brad Koldehoff, Heather Lapham, Charles Niquette (and staff at Cultural Resource Analysts, Inc.), Nancy O'Malley, and Alice Wright provided me or pointed me to archaeological data which I would have been otherwise hard-pressed to obtain. The inter-library loan departments at IPFW and the University Michigan also deserve thanks for their efforts in helping me acquire access to many of the publications that provided fragments of the archaeological data assembled and used here. My daughter Hazel and my wife Liz put

**Table A1**  
Variables of the person class in the FamilyNet2 model.

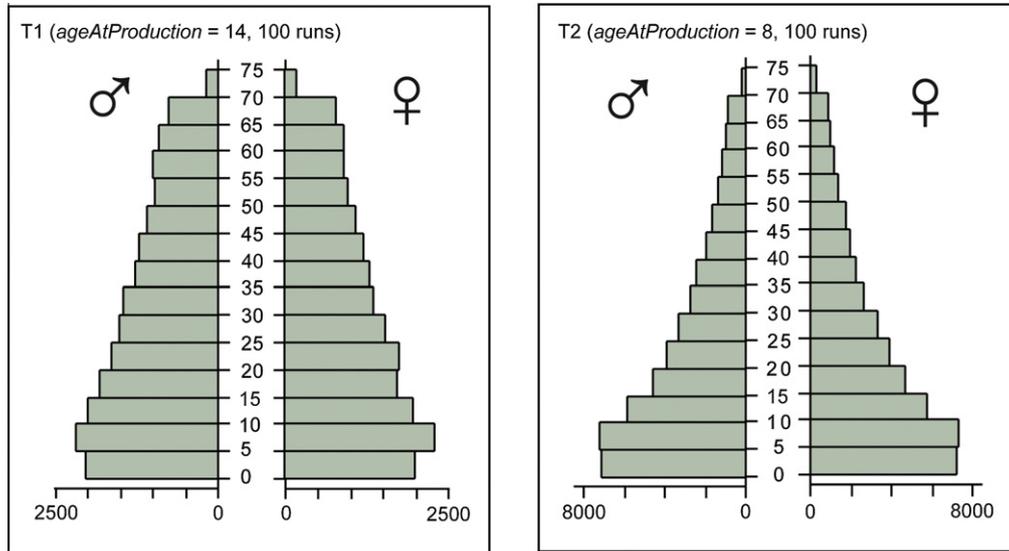
Variable	Type	M	F	Description
<i>id</i>	Integer	X	X	Unique identifier for each person
<i>currentHousehold</i>	Household	X	X	Current Household to which person belongs
<i>father</i>	Person	X	X	Biological father of person
<i>mother</i>	Person	X	X	Biological mother of person
<i>age</i>	Integers	X	X	Age of person (in years)
<i>sex</i>	Integer	X	X	Sex of person (0 = male, 1 = female)
<i>live</i>	Boolean	X	X	Life/death status (true = alive, false = dead)
<i>previouslyMarried</i>	Boolean	X	X	Marriage status (true = person has been previously married)
<i>ageAtMarriage</i>	Integer	X	X	Stores age at which person was first married
<i>ageAtDeath</i>	Integer	X	X	Stores age at which person died
<i>wifeList</i>	List (Person)	X		List of wives (including deceased) of an adult male
<i>husbandList</i>	List (Person)		X	List of husbands (including deceased) of an adult female
<i>childList</i>	List (Person)	X	X	List of biological offspring
<i>familyList</i>	List (Person)	X	X	List of individuals related by descent
<i>coResidentList</i>	List (Person)	X	X	List of individuals residing in same household but not related by descent (e.g., step-parents, co-wives)
<i>incestList</i>	List (Person)	X	X	List of all persons with whom marriage is prohibited (includes all family and co-residents)

**Table A2**  
Variables of the Household class in the FamilyNet2 model.

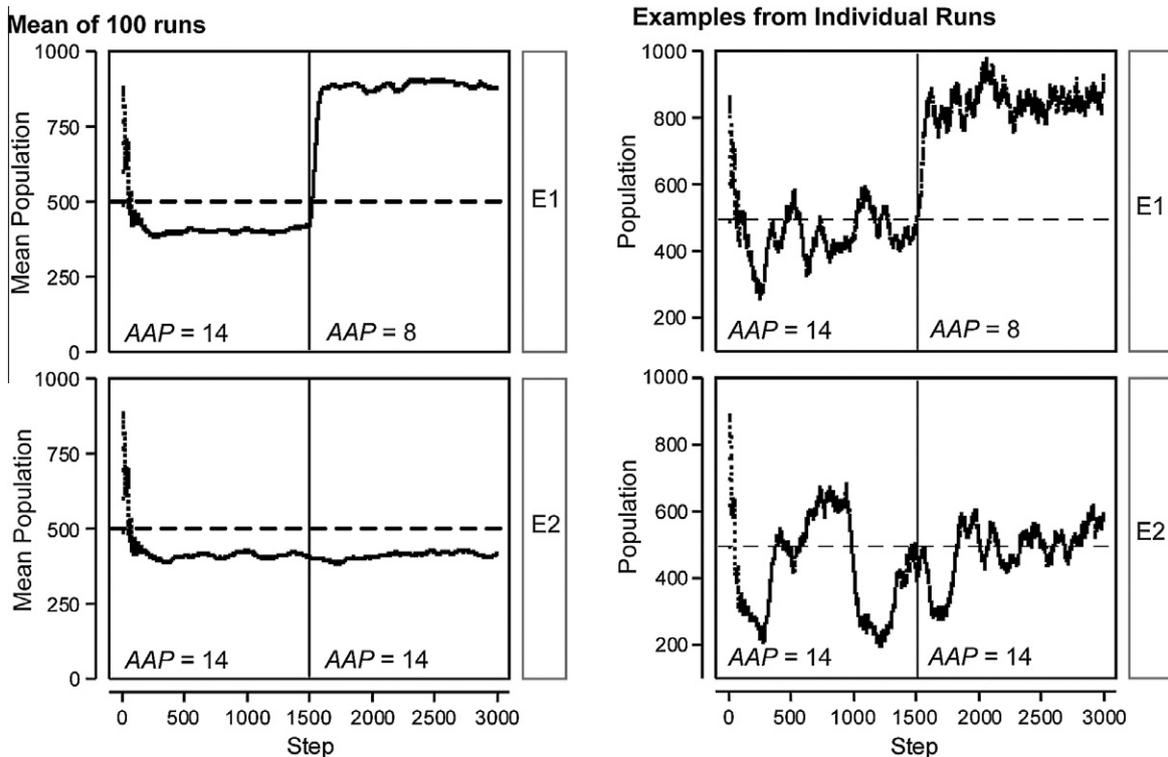
Variable	Type	Description
<i>id</i>	Integer	Unique identifier for each household
<i>head</i>	Person	Person that is the “head” of the household (adult male founder)
<i>year</i>	Integer	Year of the household's existence (first year is “year 1”)
<i>size</i>	Integer	Current number of members of household
<i>cPRatio</i>	Double	Current dependency ratio (ratio of consumers to producers)
<i>currentSurplus</i>	Double	Amount of surplus (or deficit) production for the most recent year
<i>householdAssets</i>	Double	Assets in the “bank” of the household
<i>lifespan</i>	Integer	Total length in years of a household's existence
<i>peakSize</i>	Integer	Greatest size of the household during its existence
<i>peakCPRatio</i>	Double	Highest dependency ratio during the household's existence
<i>peakWives</i>	Integer	Greatest number of simultaneous wives during the household's existence
<i>peakProducers</i>	Integer	Greatest number of simultaneous producers during the household's existence
<i>peakDependents</i>	Integer	Greatest number of simultaneous dependents during the household's existence
<i>lifespanSurplus</i>	Double	Cumulative surplus (or deficit) during the household's existence
<i>surplusYears</i>	Integer	Cumulative number of years of surplus production
<i>deficitYears</i>	Integer	Cumulative number of years of deficit production
<i>memberList</i>	List (Person)	List of all current members of household

**Table A3**  
Summary results from Experiments A1 and A2 (1000 runs each).

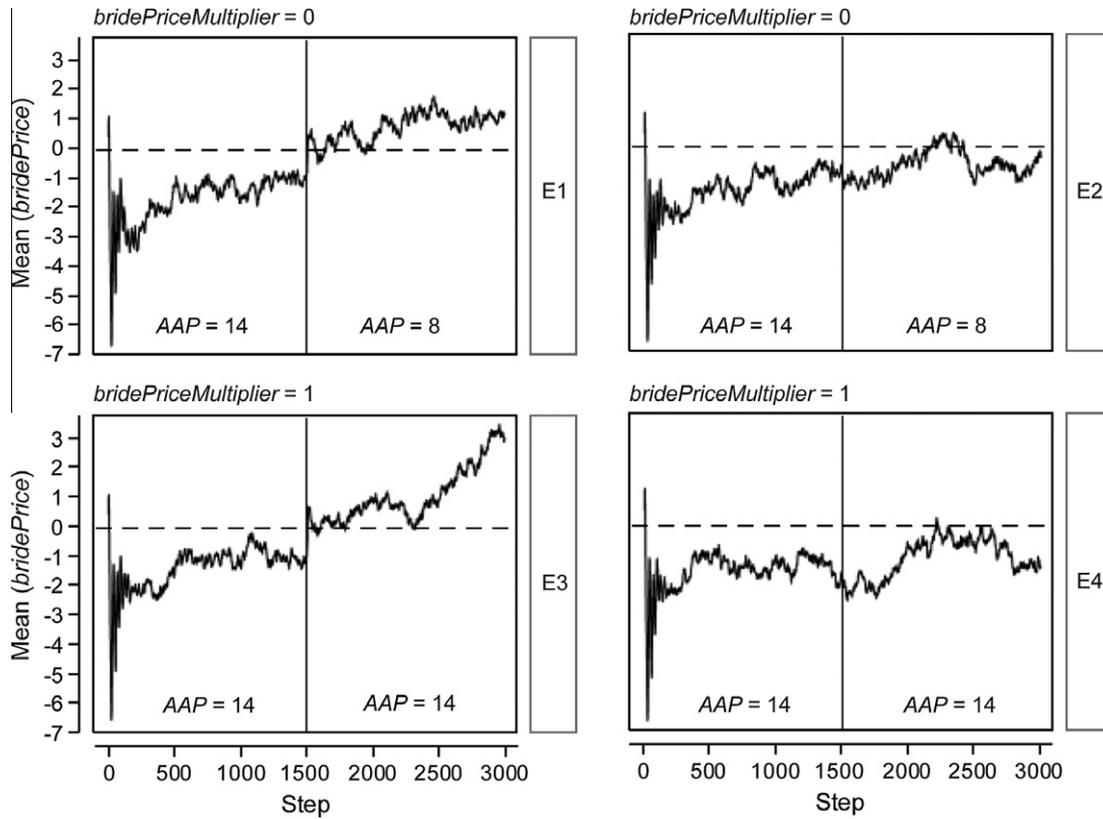
Variable	Experiment A1		Experiment A2	
	T1 (AAP = 14)	T2 (AAP = 8)	T1 (AAP = 14)	T2 (AAP = 14)
Mean family size	3.56	3.92	3.56	3.56
Maximum family size	14.20	18.36	14.11	14.21
Mean infant mortality (percent)	15.37	17.76	15.22	15.41
Mean fertility	3.73	6.28	3.70	3.75
Mean male age at marriage	22.01	17.87	22.10	21.00
Mean female age at marriage	21.85	17.53	22.01	21.81
Mean percentage polygynous marriage	3.75	5.41	3.64	3.74
Mean intensity of polygyny	2.07	2.47	2.05	2.07



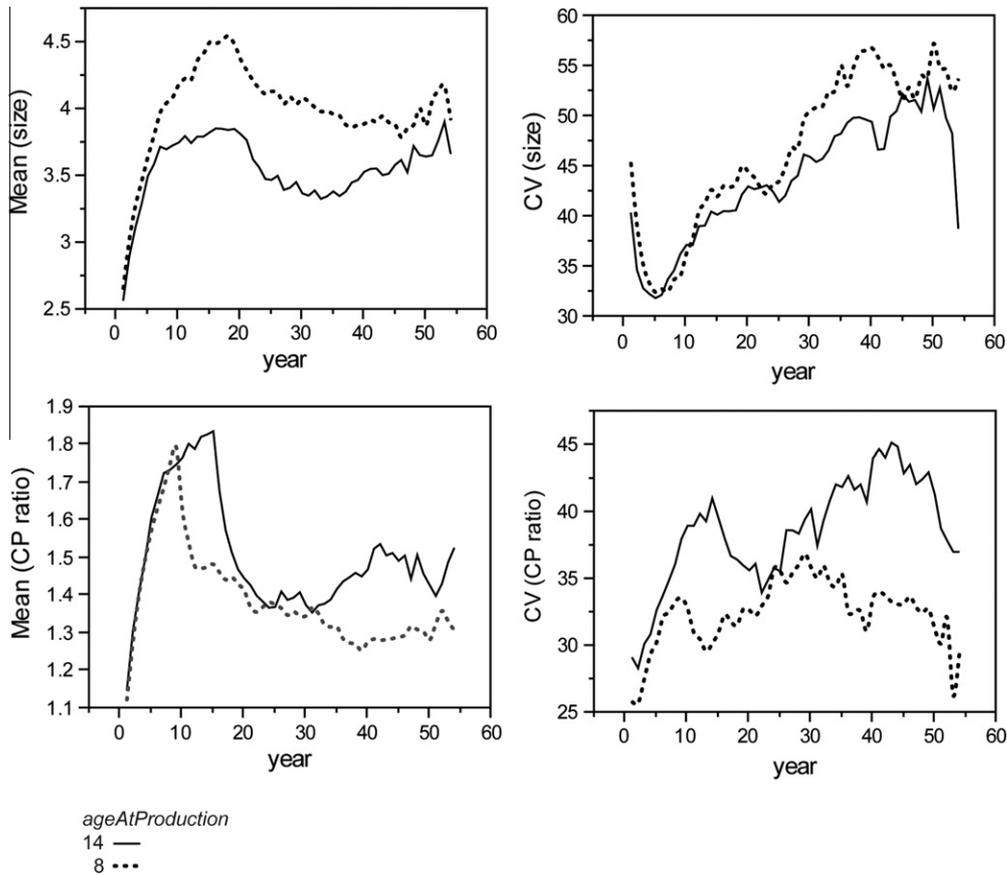
**Fig. A1.** Sample age structure diagrams produced by model runs (Experiment D).



**Fig. A2.** Examples of population sizes maintained through mortality rate adjustments based on current population size (Experiments E1 and E2). Diagrams to left show mean population levels (100 runs); diagrams to right are examples of population fluctuations during individual runs.



**Fig. A3.** Examples of mean *bridePrice* in groups of 100 runs (Experiments E1, E2, E3, and E4). When *bridePriceMultiplier* = 0 (top), the current bride price does not affect the economic calculations that males and females undertake when deciding whether or not to marry. When *bridePriceMultiplier* > 0 (bottom), males and females adjust their economic calculations based on the relative scarcity of brides.



**Fig. A4.** Yearly change in means of family size (top left), the coefficient of variation of family size (top right), dependency ratio (bottom left), and the coefficient of variation of dependency ratio (bottom right) from families during 100 steps, setting *ageAtProduction* to 14 (solid line) and 8 (dashed line) (Experiment F).

up with a lot during the on-and-off crafting of this paper, and I owe them for their support and patience. I appreciate the thoughtful comments of two anonymous reviewers that helped shape the final version of this paper. Finally, as is customary to say and is certainly true here, all faults in logic and interpretation in this paper are the responsibility of the author.

**Appendix A. Additional details of the design and validation of the FamilyNet2 model**

The purpose of this appendix is to: (1) provide additional detail to the description of the FamilyNet2 model offered in the text; and (2) describe experimental results that suggest the model is a valid representation of the dynamics of hunter-gatherer productive/reproductive systems.

The raw Java code for the model is provided online in a supplementary file. In this appendix and in the code, the term “household” is synonymous with the term “family” as used in the textual description of the model. The term “household” is sometimes used here because it was used to name classes and variables in the actual model code.

*A.1. Variables associated with persons and families*

Persons are the fundamental, indivisible units in the model. Persons are associated with the variables listed in Table A1.

Families/households are co-residential groupings of persons that were formed around a reproductively-viable conjugal core.

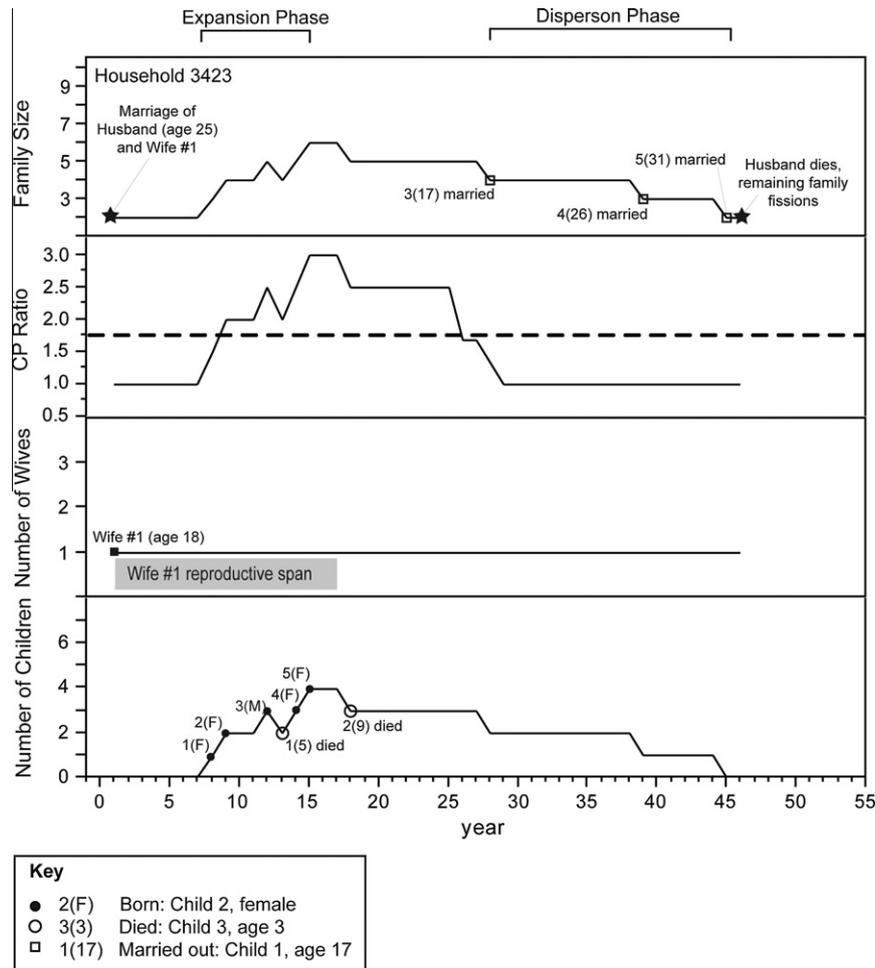
Families/households are associated with the variables listed in Table A2.

*A.2. Validation of model behavior*

A series of experiments was performed to assess the degree to which the behaviors of the systems in the model match those of the hunter-gatherer systems it is intended to represent. These experiments focused on aspects of the model system that (1) are the result of the dynamics within the model and (2) we can compare to ethnographic data. The settings used for the experiments discussed here can be found in Table 7.

Summary data from Experiments A1 and A2 (Table A3) demonstrate that the model produces values for mean family size, infant mortality, fertility, mean male and female age at marriage, and the degree and intensity of polygyny that fall within ethnographic ranges (compare the values in Table A3 with those in Table 1).

Data about individual families and persons at the beginning of both T1 and T2 can be used to characterize the age structure of the population and monitor changes in individual families through time, allowing a comparison between these aspects of the model system and those of real human systems. Fig. A1 shows example age structure diagrams (i.e., population pyramids) produced from data collected during two discrete steps at the beginning of T1 and T2 in Experiment D (100 runs). The shapes of these diagrams are generally similar to “expansive” population pyramids characteristic of populations with high rates of both fertility and mortality, consistent with what one would expect in pre-industrial



**Fig. A5.** Year by year changes in size, dependency ratio, and composition of a single monogamous family from a model run (*ageAtProduction* = 14).

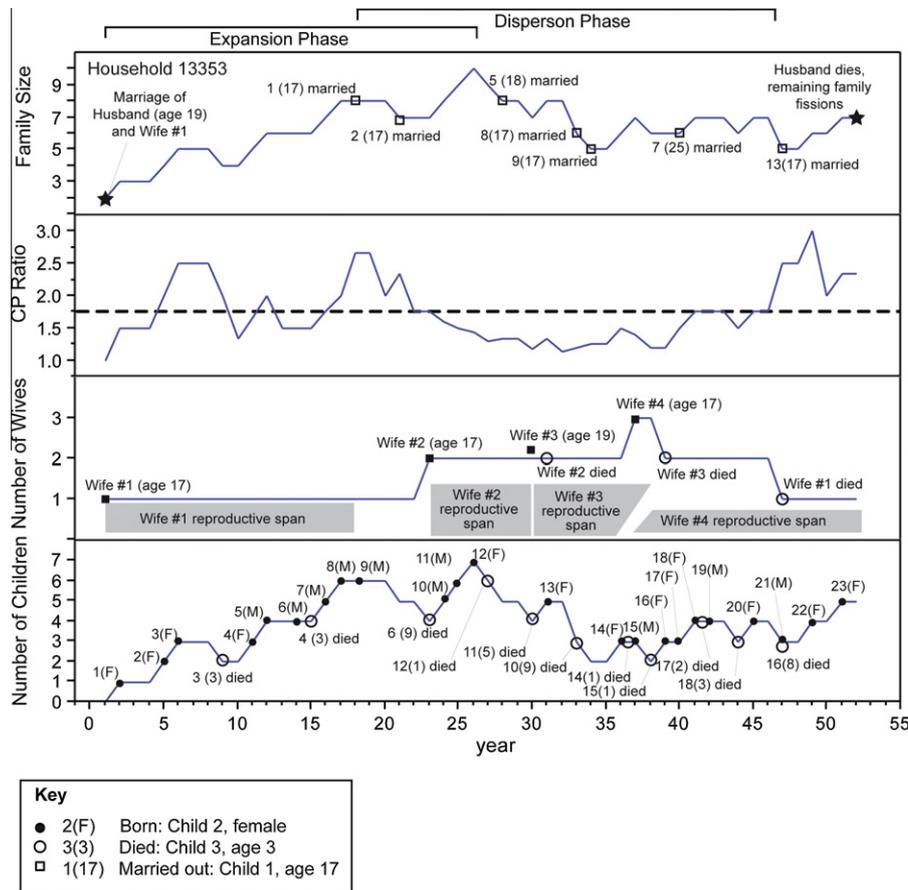


Fig. A6. Year by year changes in size, dependency ratio, and composition of a single polygynous family from a model run ( $ageAtProduction = 8$ ).

hunter-gatherer populations. Differences in shape between the two diagrams are consistent with the higher fertility rates associated with a lower age at production in T2.

Fig. A2 shows mean population changes over time from groups of 100 runs and examples from single runs (Experiments E1 and E2, initial population = 500, carrying capacity = 500). Note that a “carrying capacity” of 500 results in populations that can fluctuate between about 200 and 600 when the value of  $ageAtProduction$  (AAP) is set at 14. A spike in population is produced during the early steps of a run as many families are established and begin reproducing simultaneously. Higher mean population levels are produced when the value of AAP is set at 8. The base mortality rates set in the model remain the same, but the reproductive calculations made within families change along with AAP.

The value of  $bridePrice$ , adjusted each step based on an increase or decrease in the ratio of eligible males to available females, was constrained to between +10 and -10 for the runs discussed in this paper. Fig. A3 shows mean changes in  $bridePrice$  through time from groups of 100 runs. The graphs on the left plot mean bride price when the age at production is lowered to 8 during T2, while the data shown in the graphs on the right were produced while AAP was held constant at 14. Lowering AAP tends to raise the value of  $bridePrice$ .

Fig. A4 shows mean yearly changes in family size and dependency ratio compiled from family data collected over 100 steps at the beginning of T1 (AAP = 14) and T2 (AAP = 8) in a model run (Experiment F). These illustrate the expected increase in family size during the expansion phase accompanied by a peak in the dependency ratio, followed by a decline in family size and dependency ratio through the dispersion phase. Yearly changes in the mean coefficient of variation of family size indicate that families vary most in size between years 30 and 50.

Figs. A5 and A6 illustrate two examples of changes in size and composition from individual families produced during model runs. The monogamous family in Fig. A5 was produced under conditions where the age at production was 14. A total of five children were born, 2 of which died before reaching before marrying and leaving the family. The expansion and dispersion phases of this family are discrete. The dependency ratio was over 1.75 during about 17 years of this family’s 45 year lifespan. The history of the polygynous family in Fig. A6 is more complicated. This family produced over 20 children (over half of which died before marrying) by four different wives over the course of 52 years. There is significant overlap in the expansion and dispersion phases. These two figures are intended to illustrate that the rules of the model produce families that, when examined individually in detail, are verifiably like those produced by actual hunter-gatherer systems.

## Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.jaa.2012.12.003>.

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