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Peopling of the Arctic: A Computer Simulation

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ABSTRACT. The research described in this paper involved the development of a computer program designed to simulate population growth and migration patterns among hunter-gatherers, especially with respect to the Arctic. The program, which handles up to 200 discreet geographical locations, each with its own particular demographic and environmental characteristics, begins with an initial population and its vital statistics and simulates the events that occur through time. The fertility and mortality rates used in the simulations were those of modern and former Eskimo populations and other anthropological populations. The program was run under five different conditions. Condition 1 included high mortality and fertility rates and no female infanticide and resulted in extinction with little population dispersion. Condition 2, a situation of low mortality and high fertility with no infanticide, resulted in the occupation of nearly the entire Arctic in 1300 years. Condition 3 included the same mortality and fertility rates as condition 2, with the incorporation of a 30% rate of female infanticide. Under this condition, the population declined very slowly, while migration proceeded to some extent. Condition 4 represented a situation of very high fertility and mortality with 30% female infanticide and resulted in relatively rapid growth and migration rates. Condition 5, which incorporated the same high fertility and infanticide rates as condition 4 and lower mortality rates, produced very rapid population growth and migration.

Key words: computer simulation, demography, Eskimos, female infanticide, fertility, paleodemography

RÉSUMÉ. Les recherches décritent dans ce journal concernent le développement d'un programme de computateur avec le dessein de simuler des modelès de croissance de la population et d'émigration parmi les chasseurs, surtout en ce qui concerne l'Arctic. Le programme qui comprend au moins 200 local géographique discrètement choisi, chacun avec sa démographie particulière at son environ charactéristique, commence avec une population initiale et ses statistiques vitales et simule les évènements qui arrivent avec le temps. Le niveau de fertilité et mortalité utilise dans cette simulation sont celles de la population Eskimo antérieur et moderne et autres populations anthropologique. Le programme fut entrepris avec cinq conditions différentes. Condition no. 1 inclue un haut niveau de mortalité et fertilité et aucun infanticide feminin et eut comme résultat l'extinction avec peu de dispersion de population. Condition no. 2, une situation peu éleveé de mortalité et haute fertilité sans infanticide, et le resultat fut l'occupation de toute l'Arctic durant 1300 ans. Condition no. 3 inclus le même niveau de mortalité et fertilité que la condition no. 2, avec l'incorporation d'un niveau de 30% infanticide feminin. Sous cette condition la population decline très lentement pendant que l'émigration procède jusqu'a un certain point. Condition no. 4 represente une situation de très haute fertilité et mortalité avec 30% infanticide feminin et eu comme résultat un niveau de haute croissance et d'émigration. Condition no. 5 incorpore le même niveau de haute fertilité et d'infanticide que la condition no. 4 et un bas niveau de mortalité, ce qui a produit une croissance rapide de population et d'émigration.

Mots clés: simulation de computateur, demographie, Eskimos, infanticide feminin, fertilité, paleodemographie

COMPUTER SIMULATION IN PALEODEMOGRAPHY

Anthropologists have long been concerned with the history of population movements and the relationships between population and environment. Methods developed to describe present-day human populations have been found useful in the description and analysis of prehistoric populations and communities of anthropological interest living in various parts of the world today (Weiss, 1973, 1975; Zubrow, 1975; Storey, 1984). These methods provide quantitative descriptions of populations and of the processes that affect their size and composition. Acsadi and Nemeskeri (1970), Moore *et al.* (1975) and Hassan (1981) provide an extensive discussion of the history of paleodemographic research and analyses of the relationship between anthropology and demography. In order to study the various effects of disease, accidents, social mortality (infanticide, invalicide, etc.) and the other agents of natural selection in general, it is necessary to describe populations in terms of their rates of fertility, mortality and migration. These rates may be considered as discreet events that occur during the life cycle of individuals, as well as processes that apply to entire populations (Schrire and Steiger, 1974; Chapman, 1980).

The development of modern high-speed computers has allowed for the incorporation of descriptive and analytic demographic methods into computer programs designed to simulate events that occur over time in actual populations (Arriaga *et al.*, 1976). These computer programs are important because they can be of value in evaluating theories of human biological and cultural development and theories that concern the relationship between ecology and behavior in human societies. In addition, they are useful in situations in which experimental manipulation is either not possible or not feasible and where actual demographic histories are unavailable. In these situations, the models can be designed to predict the changes in relevant variables under different conditions, as well as to provide retrospective simulations (Mosimann and Martin, 1975).

In general, population simulation programs and models are designed to start with an initial population and its characteristics, to simulate the relevant events that occur in the population over time and, finally, to predict the nature of the population at some future date. The two major approaches to accomplishing this end are termed "micro" and "macro" models. In micro models, each individual is identified separately and uniquely and described by all of his relevant characteristics, such as age, sex, marital status, genealogical relationships, etc. As the program runs, the characteristics of each individual are changed in accordance with events that occur. This type of program can produce an account of all individuals and their characteristics at any time and is useful in situations in which knowledge of particular individuals or of the relations between them is important. In macro models, individuals are not identified separately, but are considered as part of a group possessing a particular set of characteristics. These characteristics include age, sex, marital status and other factors of interest, any change in which is called a change of state for an individual. The program will simulate how many persons will enter other states according to

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the events that occur. Thus, at any time, the macro program will describe the population in terms of the number of individuals in each possible state. Frejka (1973), for example, used a macro simulation program to produce a number of projections of future world population and to make predictions of possible future sizes and growth rates of the world's population based upon differing levels of fertility. Macro models are useful in situations in which it is not necessary to record or report the fate of each individual in the population.

Demographic simulation programs also differ in the way they treat events. The programs may be deterministic or stochastic. Deterministic programs simulate vital rates by multiplying the number of individuals by the probability of occurrence for each event during each period of elapsed time. This type of procedure will predict the number of persons in various subgroups at any time. Stochastic programs, which use a Monte-Carlo method to subject each individual in turn to the probability of each event during each time period, assume that events occur randomly to individuals. This procedure will predict the frequency distribution of subgroup sizes at any time. The stochastic procedure requires several simulation runs for each condition in order to establish expected values of the various attributes of the population. They have the benefit, however, of producing a more realistic view of the true variation in population changes (Shah, 1974; Howell and Lehotay, 1978).

ARCTIC PALEODEMOGRAPHY AND PREHISTORY

Although researchers disagree regarding the precise location and date at which the earliest ancestors of today's Eskimos and Aleuts arrived in North America, they do agree that the numbers of these early immigrants must have been very small, perhaps several hundred or even fewer. These people, who were already equipped to survive as hunters in a harsh northern climate, eventually increased in numbers and occupied a vast area extending some 7000 km from Alaska to the shores of Greenland. Stewart (1960:264) described the peopling of America as "the filling of a humanly uninhabited and generally attractive cul-de-sac through a relatively inaccessible northern entrance."

Valuable accounts of arctic prehistory and population dynamics are contained in the works of Damas (1972), Dumond (1977) and Maxwell (1985). These reports, as well as earlier works such as those of Weyer (1932), Krzywicki (1934) and Kroeber (1939), were used in the present study to develop the criteria of population movements, group dynamics, population density and maximum and minimum group size that were used in the computer simulations. For example, the maximum percentage of a population that can emigrate during a program cycle (ten years) was set to 10% for all locations, since this value results in approximately the same level of intermigration among "nations" as reported in Damas's (1969a, 1969b, 1972) discussion of band structure among the Eskimos. Further, the figures used in the present study for carrying capacity were derived from Krzywicki (1934) and Kroeber (1939). These data were used to set the carrying capacity by location and region and resulted in a grand total of 37 716 people for the carrying capacity of the entire region under study. The maximum population allowed at each habitable location shown in Figure 1 is limited to the population totals estimated by these authors for the corresponding geographical areas. Therefore, the carrying capacity of the habitable locations varies from a low of around

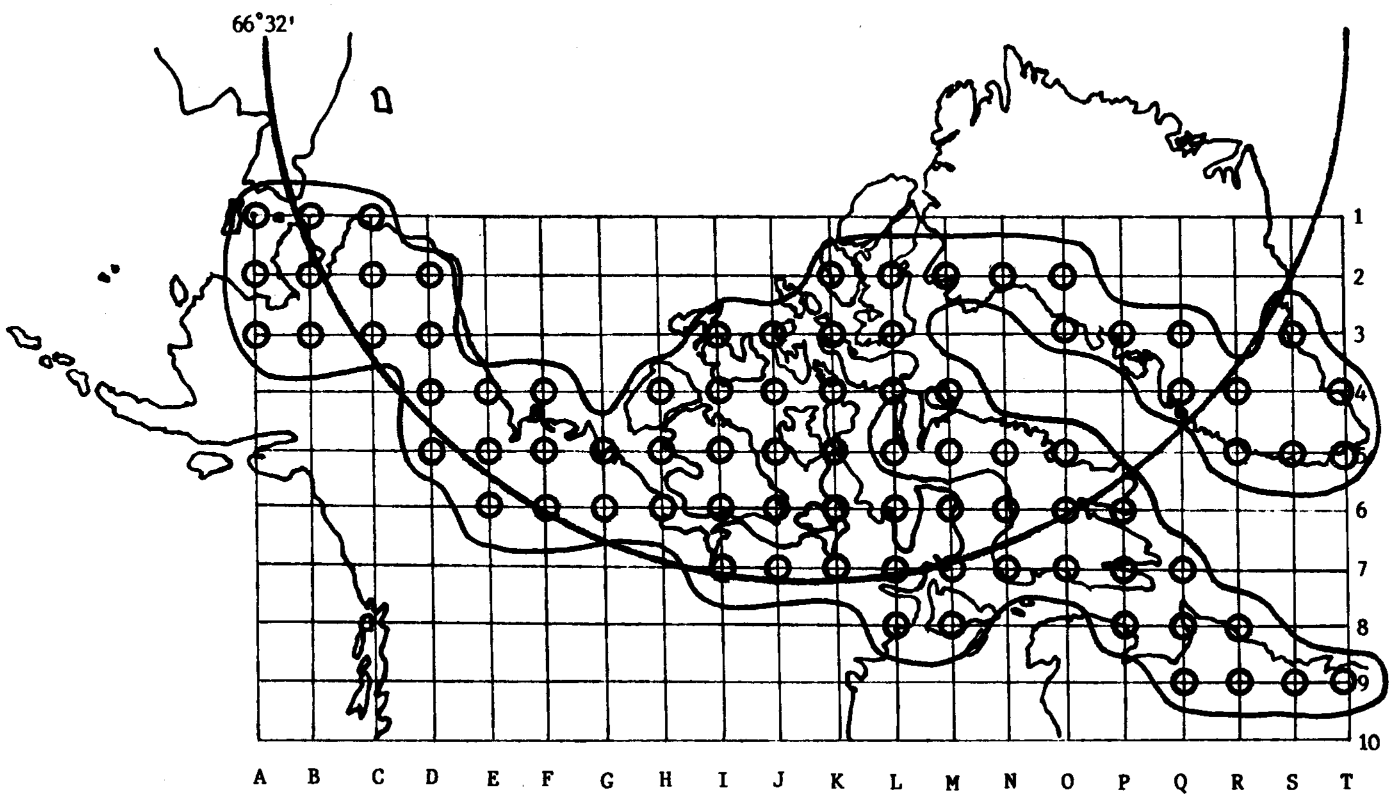

FIG. 1. This map indicates the habitable locations used in the arctic population simulations. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

110 for several locations in central Canada to a high value of over 1000 for several locations in Alaska and southern Greenland. If the carrying capacity is exceeded during a simulation run and it is not possible for anyone to emigrate to another location, the population level remains constant until, at some subsequent time, it becomes possible for some portion of the population to emigrate.

Factors related to the rigors of the arctic climate and to the technology and economy of primitive societies were also incorporated into DEMO6, the computer program used in the current study (see Appendix). For example, Speiss (1979) described several cases in which resource failure and starvation reduced Eskimo tribes to remnant populations. This type of failure could be caused by a particularly severe winter or a thinning of game resources in a particular region. These remnant populations would often join more fortunate tribes in neighboring regions, leaving their original territory temporarily unoccupied. This type of process is simulated in DEMO6 in that when a local population drops below a certain critical number the inhabitants must either move into a neighboring area or become extinct.

Hanlon (1972:235) stated that the Eskimos, Aleuts and arctic Indians developed "a most remarkable ability to survive in what is unquestionably one of the most difficult and hostile natural environments on the planet." However, the general pattern of adaptations in the region, as represented by physical artifacts, remained remarkably stable over long periods of time. Laughlin (1963:4), in discussing several sites in the Aleutians, stated that "there is no single change in kind or category of artifact over 5000 years that appears to have made a detectable change in the system of adaptation or way of life." Regarding the natives of St. Lawrence Island, Giddings (1960:129) stated that "no basic change appears abruptly in the pattern of subsistence." Thus, the unpredictable nature of the Arctic regarding climate and distribution of food resources was adequately met by the stable technological and economic adaptations of the aboriginal populations. This is reflected in the DEMO6 simulation program, which assumes that these adaptations and behaviors remain constant during each simulation run. Similarly, the factors of climate and latitude that affect maximum group size and population density are also assumed to be constant over time.

The purpose of the computer programs presented in this paper is to simulate, based upon differing demographic preconditions, how a migration such as the one described above by Stewart would take place and how much time would be required. The programs could be used to simulate any of the particular waves of migration, with the proper sets of preconditions and demographic parameters. The situation chosen for simulation, however, is the one in which the entire region is initially unoccupied except for a small founder population that enters south of Norton Sound, near the mouth of the Yukon River (Fig. 1). The small circles in Figure 1 indicate the locations designated as habitable in the simulations performed for this study. The population inhabiting a particular location is not necessarily restricted to the region within the circle; rather, each location is considered to be contiguous with adjacent locations. A location, therefore, that appears on the map to include only water, actually includes adjacent land areas as well.

The programs also simulate the effect of systematic female infanticide on population growth and migration. The rate of infanticide is one of the stochastic variables that must be set prior to each simulation run. This is the probability for female infants at birth of becoming a victim of infanticide.

SOURCES

In paleoanthropology, the population sample is often based on information derived from a skeletal population. A number of problems are associated with the use of skeletal samples. Among these are infant underenumeration, sampling error, small population size and assumptions concerning population growth rate (Weiss, 1973, 1975; Moore *et al.*, 1975). In spite of these difficulties, vital rates derived from this type of data can be useful in the generation of hypotheses, and life tables generated from these rates can be incorporated into models of ecological and cultural processes (Ubelaker, 1974, 1978; Harper, 1979).

Estimated ages at death compiled from the skeletal remains of the Sadlermiut Eskimos, who became extinct in the early years of this century, are used in this study as an example of an Eskimo group characterized by high mortality rates and low life expectancy (Harper, 1975). Their age-specific mortality rates are reproduced as part of Table 1 and were used in the computer simulation runs in which a high-mortality scenario was required.

Another source of paleodemographic information is available in first contact records made by missionaries and explorers (Boas, 1901; Jenness, 1922; Rasmussen, 1931). This type of data has been widely used in making inferences concerning the pre-contact nature of the populations under study. Harper (1975) employed missionary data recorded at the Moravian Mission of Hebron during the decade of the 1840s to develop a life table for Labrador Eskimos (Table 1). The mortality rates from this population were used in the computer simulations to represent an Eskimo group characterized by a comparatively low mortality rate.

The most important works that represent the size of the aboriginal population of North America also relied to a great extent upon early census data. Krzywicki's (1934) and Kroeber's (1939) works on native population distribution and density form the basis of the pre-contact Eskimo population estimates used in this study. The grand total and the regional totals correspond to Kroeber's estimates for the corresponding regions.

Modern anthropological populations constitute another source of data used in paleodemography. In this case, the assumption is made that the characteristics of the present-day anthropological populations constitute a good approximation of the relevant characteristics of the prehistoric populations being studied, as in Binford's (1978) work among the Nunamiut Eskimos.

TABLE 1. Age-specific survival and fertility rates

	Survival rates							
Age:	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70+
Sadlermiut (F) (Harper, 1975)	.524	.872	.756	.482	.108	.000	—	—
Labrador (F) (Harper, 1975)	.736	.840	.948	.745	.756	.548	.294	.000

	Fertility rates[1]				
Age	0-9	10-19	20-29	30-39	40-49
Savoonga (Ellanna, 1983)	0	.017	.121	.086	.016
Average of 13 anthropological populations (Weiss, 1973)	0	.052	.273	.187	.029

[1]These are expected annual number of female births per woman.

The fertility rates used in the computer simulations performed in this study were compiled from contemporary populations. The age-specific fertility rates for Savoonga were reported by Ellanna (1983) and are shown in Table 1. Ellanna's field data were gathered over the course of a decade (1970-80) during a total residence of five years in the study region. Her research methodologies included participant observation, informal interviews, formal interviews documenting family histories and resource use data, household censuses and resource harvest and use surveys. In 1975, household data were systematically gathered on the entire populations of the five Bering Strait area communities included in her study. Although the village of Savoonga cannot be said to closely resemble an ancient semi-nomadic hunter-gatherer band, these fertility data are as good as any available and can be considered to represent a typical pattern of fertility for Eskimo groups. The introduction of birth control techniques in recent years, however, has considerably reduced Eskimo birth rates in comparison to previous decades. Analyses of the effect of modern birth control methods on the fertility rates of Eskimos have been reviewed by Alpern (1971), Bloom (1972) and Masnick (1976). Although the introduction of modern birth control methods is known to have produced a considerable decline in birth rate among modern Eskimos, it is known that aboriginal populations including Eskimos employed several methods of reducing fertility. It is also probable that the effects of poor nourishment during lean times and other factors of the harsh arctic climate combined to lower the fertility rates among prehistoric Eskimo tribes.

The other table of fertility rates used in the computer simulations was based upon the average age-specific fertility rates of 13 contemporary anthropological populations compiled by Weiss. Weiss (1973:32) considers it to be "a fertility schedule of wide applicability and sufficient reliability for models to be constructed from it." Weiss's fertility rates are considerably higher than those reported by Ellanna. Both the Savoonga fertility rates and Weiss's composite fertility rates were used in the computer simulation runs performed in this study.

THE PROGRAMS

DEMO6 is the demographic simulation program developed for the current study. It is a stochastic program that uses the "macro" method of modeling groups of individuals. Further, it is a one-sex based program with discreet-time simulation of events pertaining to individuals and groups. The program begins with an initial population of individuals and its vital statistics and simulates the demographic events that occur through time. Numerous simulation programs have been developed and used in recent years to help answer various questions in paleodemography (Dyke and MacCluer, 1973; Schrire and Steiger, 1974; Weiss, 1975; Howell and Lehotay, 1978; Chapman, 1980). The present program, however, differs in certain important aspects from all of the others. These differences include the particular nature of the questions addressed and the special geographic, cultural and ecological factors that pertain to the populations under study. One major difference is that the present program is designed to simulate the origin and development of a large number of discreet populations through time. Another distinction between DEMO6 and most other simulation programs results from the fact that it is designed to study the fate of a small initial population in a vast unoccupied territory. These considerations determined the manner in which the DEMO6 program was developed and also determined the values to which the various initial parameters were set. A detailed description of the structure of the programs and how they function is contained in the Appendix.

All the necessary demographic rates and statistics must be set prior to each simulation run. The initial census and location or locations must also be set. The only variables that must be updated for each run of DEMO6 are those whose values are to be altered; all the others will maintain their previous values. This may be accomplished rather easily by using the MAINT program, which was designed to facilitate the maintenance of information in the DEMO6 data file. This program is self-documentary, through prompts and messages to the operator regarding functions to be performed.

RESULTS

Twenty-five computer simulation runs were made using five different combinations of fertility, mortality and infanticide rates (Table 2). Since DEMO6 is a stochastic program, it is necessary to run the program several times under each condition to generate a frequency distribution of possible outcomes. In the following discussion and tables, the means and standard deviations reported refer to the calculated values of these statistics within the simulation runs for the particular condition being discussed. The r values reported are the exponential growth rates or the average growth rate of the entire population under each condition and are calculated as follows: $r = \{\log(FP/IP)\} / \{(Y)(\log(e))\}$, where FP is the final population count, IP is the initial population count, Y is the elapsed time in years and e is the constant 2.71828 . . . (Wilson and Bossert, 1971). The initial population size, age distribution and location were the same for each run. It has been shown (Weiss, 1973; Coale, 1974; Cowgill, 1975; Frejka, 1973) that minor variations in the absolute numbers of the founding population have virtually no effect on the ultimate population level after hundreds or thousands of years have elapsed. The operation of the various demographic forces over time usually produces similar results whether the initial population was 500, 700, etc. The initial population was divided into age categories according to the approximate stable population distribution expected, by the method discussed by Wilson and Bossert (1971:124-126). In the discussion that follows, the term EOJ (End of Job) refers to the statistics obtained at the conclusion of a computer run.

TABLE 2. Summary of conditions for simulation runs

Condition	# of runs	Fertility	Mortality	Infanticide	# of years
1	5	High (Ellanna, 1983)	High (Harper, 1975)	None	500
2a	6	High (Ellanna, 1983)	Low (Harper, 1975)	None	990
2b	3	High (Ellanna, 1983)	Low (Harper, 1975)	None	EOJ when pop. exceeds 30 000
3	3	High (Ellanna, 1983)	Low (Harper, 1975)	30%	3000
4	4	Very high (Weiss, 1973)	High (Harper, 1975)	30%	1000
5	4	Very high (Weiss, 1973)	Low (Harper, 1975)	30%	EOJ when pop. exceeds 30 000

The maximum distance any group of emigrants can travel in any ten-year interval must be set before DEMO6 is run. In all of the executions of DEMO6 for this study, the maximum distance was set to two units. Since each unit is equal to 298.9 km, this is equal to a maximum possible migration distance of 597.8 km in ten years, or 59.8 km per year. This figure is very conservative and well within actual figures cited in the literature — see, for example, Rasmussen, 1927, and Petersen, 1962.

Condition 1

The condition of high fertility and high mortality with no infanticide shows a steady and consistent population decline in each of the five simulation runs (Table 3). The r values for these runs, which average −.001287, were lower than the r values for any of the other conditions simulated. According to the fertility rates used, those of Savoonga Eskimos from Ellanna (1983), each woman who survives to the age of 30 would be expected to produce on average 2.78 children, while each woman who survives to age 50 would produce an average of 4.78 children. This fertility rate is not sufficient, however, to overcome the high rate of mortality to which this hypothetical population was subject. The mortality rates used, those of Sadlermiut Eskimos reported by Harper (1975), result in the expected death of approximately 65% of a birth cohort by the age of 30 and in the expected death of nearly 98% of the cohort by the age of 50.

The dispersion of the population under these conditions, as shown in Figure 2, was also less than the dispersion under any of the other conditions. The populations managed to disperse to some extent, achieving a maximum of eight occupied locations and a distance of 1232.4 km from the point of origin. In spite of a decline of nearly one-half during the 500 years simulated, the migrants managed to occupy most of northern Alaska and extend their range to the region north of the Bering Strait and nearly 900 km to the east toward the Canadian border region. This result serves to illustrate the concept that "population pressure" is certainly not the only factor involved in the occupation of new territory. Under these demographic conditions, however, the populations are doomed to eventual extinction.

Condition 2

Condition 2 represents a situation of high fertility and low mortality with no infanticide. The fertility rates used are the same as those used in condition 1. The mortality rates, however, were those of Labrador Eskimos from Harper (1975). These rates, which are considerably lower than the mortality rates for Sadlermiut Eskimos, would result in the death of approximately 40% of a birth cohort by the age of 30 and in the death of 67% of the cohort by the age of 50. This means that one-third of the women in this population would survive through the end of their reproductive period, as compared to only 2% among the Sadlermiut. The effect of this difference can be seen in the population increases and in the extent of migration observed under condition 2.

In the first six runs (Table 3, condition 2a) the number of years per run was limited to 1000. During this time, the total population increased from 1000 to an average population slightly in excess of 22 000. The corresponding r values averaged .003123. An r value of .003 would result in a population doubling every 231.0 years. Therefore the final population totals under condition 2a represent a little over four population doublings. This serves to emphasize the fact that exceedingly

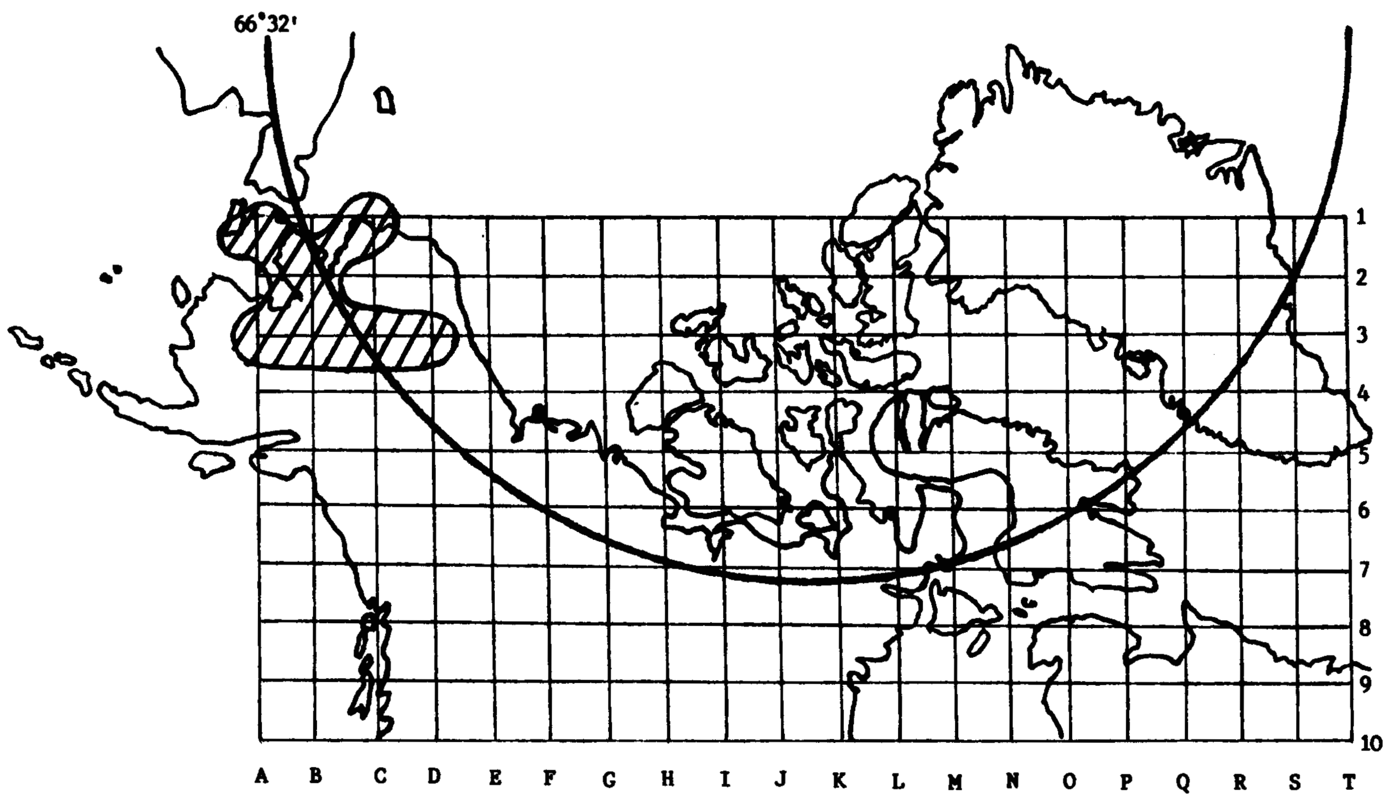

FIG. 2. This map indicates the area occupied under condition 1. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

TABLE 3. Results of computer runs by condition

		Condition 1 5 runs	Condition 2a 6 runs	Condition 2b 3 runs
# of years	$\overline{X}$:	500	990	1330.0
	S.D.:	NA	NA	57.2
r	$\overline{X}$:	−.001287	.003123	.002566
	S.D.:	.0006	.00008	.00011
Initial N (male & female)	$\overline{X}$:	1000	1000	1000
	S.D.:	NA	NA	NA
Final N	$\overline{X}$:	550	22075.7	30154
	S.D.:	156.8	1743.6	62.0
Total births	$\overline{X}$:	14330.8	65128.7	92076.7
	S.D.:	2003.4	5180.0	3557.4
Total deaths	$\overline{X}$:	14780.8	44055.0	62916.7
	S.D.:	1874.9	3550.3	3518.9
Ratio B/D	$\overline{X}$:	.968	1.48	1.46
	S.D.:	.015	.019	.025
# locations occupied at EOJ	$\overline{X}$:	6.8	49.7	66.3
	S.D.:	.748	5.82	.471
Avg. pop./location at EOJ	$\overline{X}$:	81.3	446.8	454.7
	S.D.:	25.6	24.5	2.65
Maximum distance in km from origin	$\overline{X}$:	1032.9	3920.1	4929.6
	S.D.:	148.6	433.2	0.0
Count of infanticide	$\overline{X}$:	NA	NA	NA
	S.D.:	NA	NA	NA

NA — Not applicable.

small r values are required to populate exceedingly large regions very rapidly. The average number of locations occupied was 49.7, with a maximum of 59, while the overall population per location for these runs was 446.8. The maximum migration distance was 4640.2 km. This amounts to a rate of migration equal to 4.69 $km \cdot yr^{-1}$, a distance that would pose no problem at all to any band of Eskimo hunters.

In the next three simulations (condition 2b) the same demographic rates were used, but the number of years per run was not limited to 1000. Rather, the runs were terminated only when the total population exceeded 30 000 (Table 3).

The figures that indicate migration and population distribution differ dramatically from those under condition 1. The average number of locations occupied at EOJ in condition 2b was 66.3, but only 6.8 in condition 1. The maximum distance from origin of 4929.6 km was obtained in all three runs. The increase in area occupied is not in direct proportion, however, to the greater population numbers, since the population density is also greater. Correspondingly, the average population per location under condition 2b is 454.7, but only 81.3 under condition 1. Thus, the average final population under condition 2b was 60 times greater than the corresponding numbers under condition 1, while the number of locations occupied was only 10 times greater. Figure 3 shows the region that would be occupied in a typical simulation run under condition 2b. We find the complete colonization of northern Alaska and the Canadian Arctic including Baffin Island and the High Arctic islands. Greenland has also been occupied to two-thirds of the distance down the western coast. The only region not reached at all is the coast of Labrador. Further simulation runs of longer duration would serve to establish the times required to reach the farthest points and to fill the entire region to its carrying capacity.

Condition 3

Condition 3, which included a 30% rate of female infanticide, is the first condition in which infanticide is included; otherwise, the demographic parameters are identical to those used in condition 2. The results of the simulation runs (Table 4) are quite different from the results obtained under condition 2. Rather than showing a rapid increase, the populations under condition 3 show a very slow decline. The r value for this condition, which averaged only −.000294, was sufficient to reduce the population from 1000 to 433 after 3000 years, the lowest final population figures as well as the lowest population densities for any of the simulation conditions. The average number of locations occupied at EOJ was 7.0, with a population of 60.7 per location. The maximum distance from origin averaged 1426.9 km, while the greatest distance achieved was 1524.1 km. Eventual extinction is indicated under these conditions; but the r value is so close to zero that a small but favorable change in any one of the demographic parameters could tip the balance in the other direction. In other words, this population is poised on the border between extinction and survival. Further runs of DEMO6 could be made to establish the maximum rate of infanticide that could be tolerated while still allowing the population to increase over time. These runs, nevertheless, serve to demonstrate that 30% female infanticide is sufficient to ensure the eventual demise of populations with the vital rates used here.

It can be seen in Figure 4 that the total population displays a remarkably slow but steady decline. The simulations for condition 3 were allowed to run for 3000 years, longer than any of the other conditions, because the population change over time was so gradual that long runs were required to establish a trend. The area occupied is very small compared to the area occupied under condition 2 and is also broken up into non-contiguous regions (Fig. 5.) Not only were the populations growing smaller, but they were also becoming isolated from each other under condition 3. It is interesting to note also that the location from which the entire population originated (location 3,A) has become abandoned.

Condition 4

Condition 4 represents a situation of very high fertility and high mortality with 30% female infanticide (Table 4). Under these conditions, the population size grows relatively rapidly, with an r value of .003305. The average number of locations occupied at EOJ was 58.0, with a population of 472.2 per location. The mortality rates used here are the same high rates that resulted in population extinction in condition 1. In addition, the simulation runs of condition 4 also included a 30% rate of female infanticide. The fertility rates used here are considerably higher than the Savoonga Eskimo fertility rates used in all of the previous simulations. These rates are computed from the average birth rates of 13 anthropological populations from around the world (Weiss, 1973). According to these rates, each woman who survives to the age of 50 would be expected to produce 10.8 children during her lifetime. These high fertility rates more than compensated for the other disadvantages, and the simulated

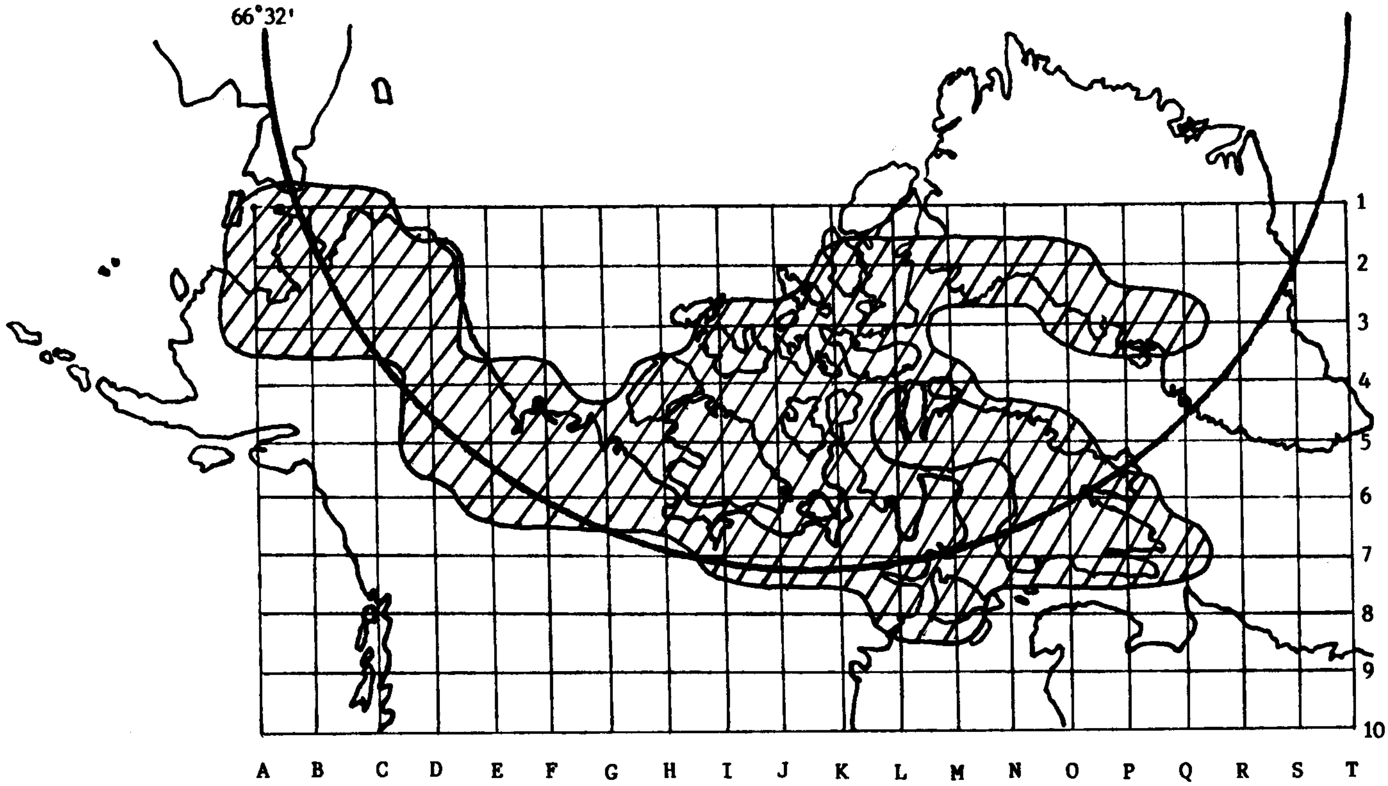

FIG. 3. This map indicates the area occupied under condition 2b. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

populations occupied a major portion of the Arctic. As shown in Figure 6, the area occupied includes all of northern Alaska as well as nearly all of arctic Canada, including the High Arctic islands. The migrants have also gained a foothold in northwestern Greenland; but the southern portion of Baffin Island and the Ungava and Labrador coasts remain unoccupied.

Condition 5

Condition 5 employs the same very high fertility rates and 30% infanticide rate as were used in condition 4. The mortality rates used, however, were the relatively low mortality rates of Labrador Eskimos (Harper, 1975). As expected, the population size increased quite rapidly under these conditions, faster than it did under any of the other conditions (Table 4). The average r value for the four simulation runs of condition 5 was .006828. An average of only 505 years was required for the total population to increase from 1000 to over 30 000. The number of locations occupied at EOJ was 37.3, with an overall average of 823.5 people per location. The maximum distance from origin averaged 3241.0 km, with the greatest distance of 3948.5 km. The number of locations occupied, however, was considerably lower than the number seen under other conditions with comparable population figures. This, of course, means that the population density was higher under condition 5, a fact reflected also in the high average population per location of 823.5. The reason for this situation is that the population under these conditions is increasing faster than the rates of migration and dispersal. Many of the locations rapidly reached their carrying capacity, the limit in size beyond which the location is not allowed to increase. If future runs were made under condition 5, with no limit on the number of years or on population size, the final results would show more similar population sizes and distribution, since most locations would be populated to their respective maximum carrying capacities. Figure 7 illustrates the extent of migration expected under the restrictions of condition 5. All of northern Alaska is occupied, as well as the eastern Canadian arctic region and most of the High Arctic islands of Canada. Baffin Island, Southampton Island, Ungava and Labrador have not been reached, however, nor has Greenland. The relationship between population growth and density can be seen by comparing Figures 4 and 8, which show the total number of locations occupied versus the number of years simulated. In the fastest

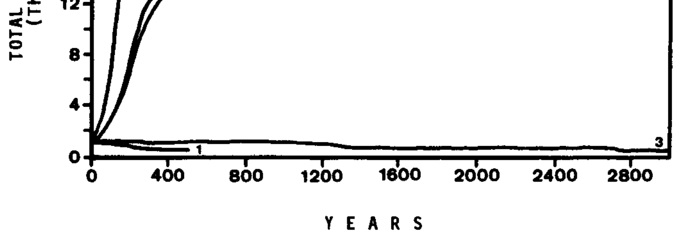

FIG. 4. The relationship between total population vs. the number of years simulated is shown in this graph. Line 1 = condition 1; line 2 = condition 2; line 3 = condition 3; line 4 = condition 4; line 5 = condition 5.

TABLE 4. Results of computer runs by condition

		Condition 3 3 runs	Condition 4 4 runs	Condition 5 4 runs
# of years	$\overline{X}$:	3000	1000	505.0
	S.D.:	NA	NA	51.2
r	$\overline{X}$:	−.000294	.003305	.006828
	S.D.:	.00010	.00006	.0007
Initial N (male & female)	$\overline{X}$:	1000	1000	1000
	S.D.:	NA	NA	NA
Final N	$\overline{X}$:	433.3	27288.5	30318.0
	S.D.:	136.0	1633.3	141.6
Total births Including i-cide	$\overline{X}$:	71947.3	120391.3	64043.5
	S.D.:	4160.6	7193.3	573.1
Without i-cide	$\overline{X}$:	58906.7	98609.0	52436.0
	S.D.:	3387.1	6017.1	396.4
Total deaths Including i-cide	$\overline{X}$:	85554.0	115885.0	46333.0
	S.D.:	5067.8	6759.7	711.4
Without i-cide	$\overline{X}$:	72513.7	94100.5	34725.5
	S.D.:	4292.9	5578.9	533.4
Ratio B/D	$\overline{X}$:	.841	1.039	1.382
	S.D.:	.0014	.0033	.0097
# locations occupied at EOJ	$\overline{X}$:	7.0	58.0	37.3
	S.D.:	1.4	2.5	3.9
Avg. pop./location at EOJ	$\overline{X}$:	60.7	472.2	823.5
	S.D.:	6.8	17.7	92.0
Maximum distance in km from origin	$\overline{X}$:	1426.9	4270.6	3241.0
	S.D.:	137.5	234.7	246.5
Count of infanticide	$\overline{X}$:	13040.3	21782.3	11607.5
	S.D.:	776.0	1190.8	182.5

NA — Not applicable.

growing simulation, the population rises to 30 000 in only 440 years (r = .0077) but occupies only 35 locations. Under conditions of slower growth, however, the results are different. In conditions 2 and 4, the population growth and dispersion proceed at more nearly the same pace. In conditions 1 and 3, which represent conditions of population decline, a comparison of the two figures shows that migration and dispersion can proceed to some degree even while population size remains steady or decreases.

CONCLUSION

In observing and comparing the results obtained under the various population simulations, the usefulness of computer simulations in paleodemography becomes apparent. Some combinations of vital rates and parameters show results that are highly interesting and plausible when compared to archeological and ecological interpretations of prehistoric events, while others produce results at odds with these interpretations of prehistory. This kind of analysis also clarifies the situations in which more elaborate and extensive computer simulations of greater resolution or duration would be desirable and interesting. It further suggests the idea that some conditions of simulation, while unlikely to represent conditions that prevailed for extended durations of time, might nevertheless represent transient circumstances. This, of course, suggests future modifications to the programs to include changes in demographic parameters or changes in conditions such as climate, resource availability and technology over time.

The colonization of the arctic regions by people of the Arctic Small Tool tradition appears to be modeled most closely by the simulations performed under condition 2b. The current evidence indicates that this early migration of people to the east began near the Bering Strait before 4000 B.P. and resulted, within a few centuries, in the occupation of the entire Canadian Arctic, including Baffin Island and the Labrador coast, as well as the northeastern coast of Greenland (Maxwell, 1985). This simulation used the fertility rates of Savoonga Eskimos and the mortality rates of Labrador Eskimos. According to these demographic conditions, in combination with the migration scenario employed by the DEMO6 program, nearly the entire arctic region was colonized in a period of approximately 1300 years, beginning with an initial population of 1000 persons in the area of Norton Sound and ending with over 30 000 people at distances up to 5000 km from the point of origin (see Fig. 3). This represents a population growth rate of approximately .0026, small in comparison to modern-day population growth rates, but among relatively small populations of primitive hunters this is just the kind of growth rate involved in the kind of migration and territorial expansion indicated in archeological reconstructions of the peopling of the Arctic.

Regarding the effects of infanticide, we have noted that the simulations that most closely parallel the actual colonization of the Arctic (condition 2b) incorporated a zero rate of infanticide. This result is not adequate in itself to allow one to state categorically that infanticide could not have occurred to a significant degree among the people who initially colonized the Arctic, but it does suggest that it would be interesting to study further the question of whether female infanticide was less important in early arctic prehistory than it became later. It is also interesting to note the inclusion of a 30% rate of infanticide to the above conditions produced the results seen in condition 3. The populations under condition 3, rather than growing and occupying vast regions, remained virtually stationary in numbers and location during a period of 3000 years. This differs from the results described by Chapman in a study in which he simulated the rate of survival of Eskimo populations engaged in the practice of infanticide. He states "that Eskimo populations could indeed survive rates of female infanticide as high as 30% to one-third" (Chapman, 1980:325). Chapman's method of estimating female fertility, which is an indirect one based on lifetime fertility data from a number of cultures, gives a lifetime fertility considerably higher than that obtained from Ellanna's (1983) data. According to Chapman's estimate, a woman who survived her entire reproductive period would be expected to produce 7.66 children, rather than the 4.78 children she would produce according to Ellanna's data. This produces results more comparable to the results obtained in conditions 4 and 5 of this study. Since infanticide and fertility rates are not necessarily independent, it would be of value in future simulation runs to investigate the relationship between them and the effect of this relationship on population growth and migration patterns. This subject was not investigated in the present study due to limitations on available computer resources. Since Chapman's program did not consider immigration and emigration, further

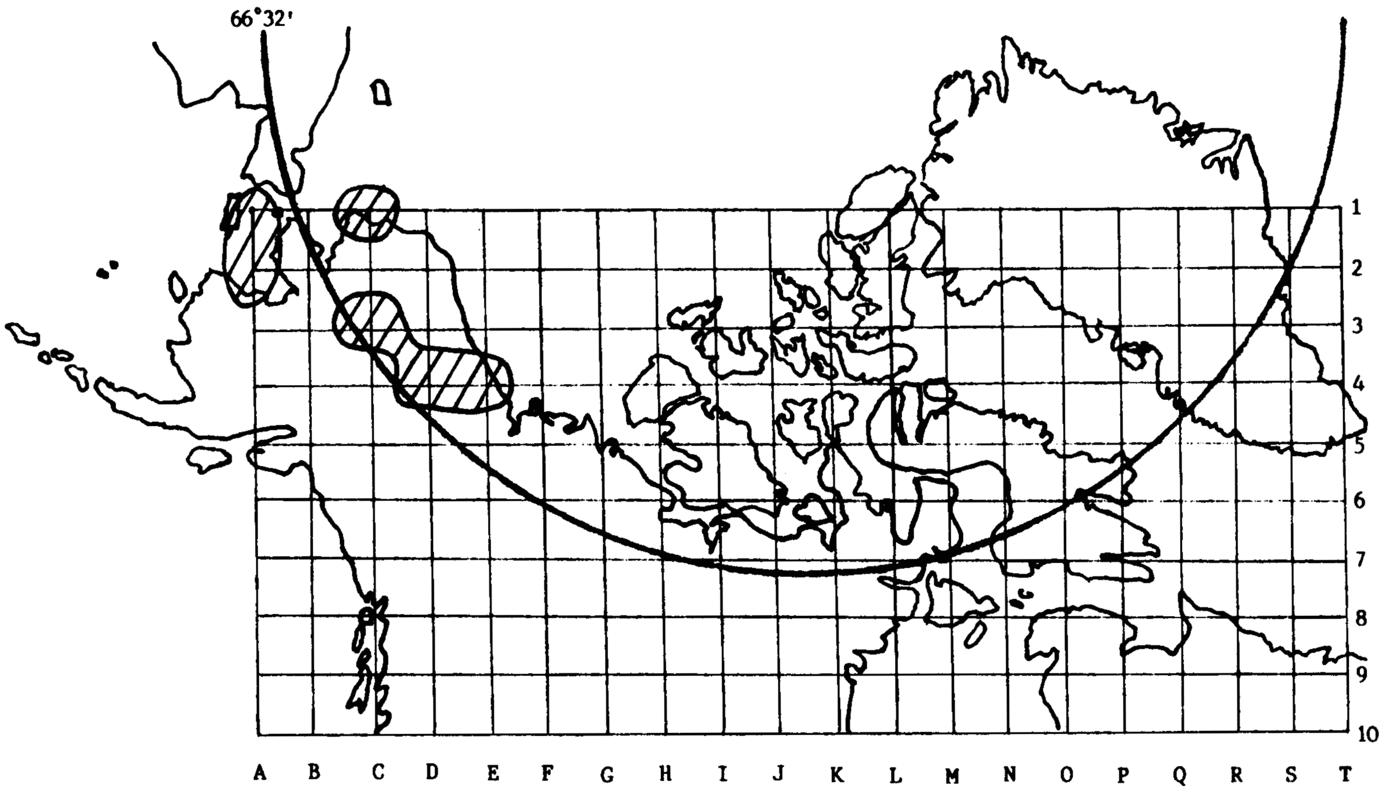

FIG. 5. This map indicates the area occupied under condition 3. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

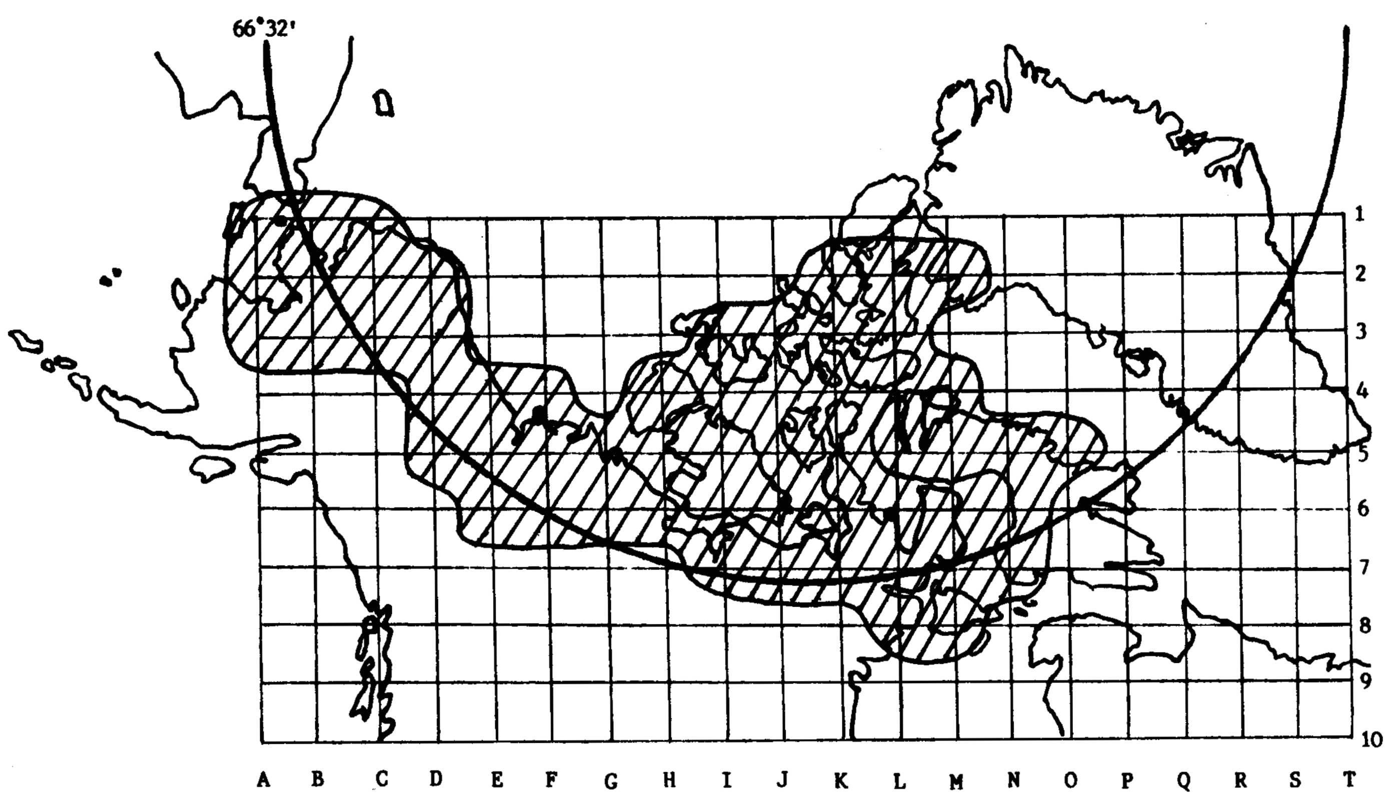

FIG. 6. This map indicates the area occupied under condition 4. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

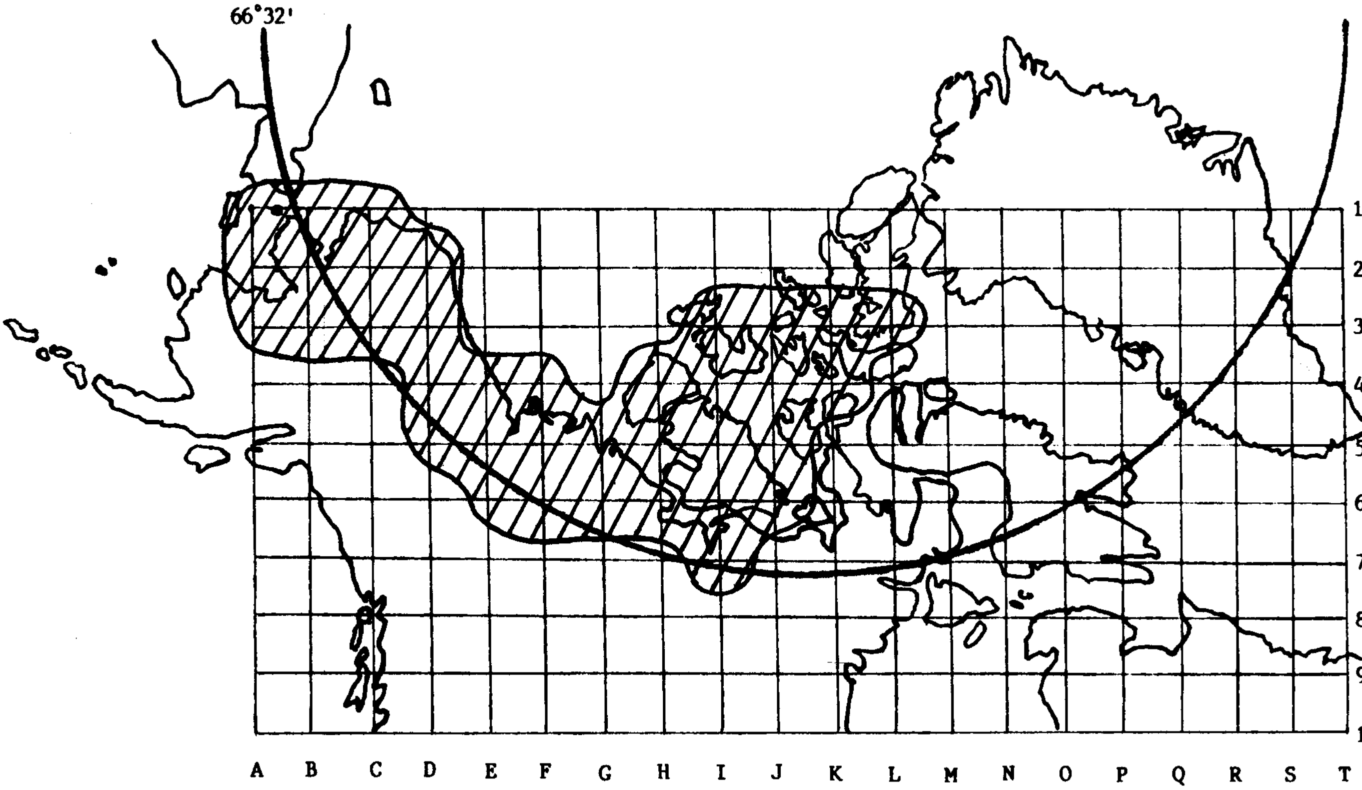

FIG. 7. This map indicates the area occupied under condition 5. The total distance across the map equals 5679 km, while each unit represents 298.9 km.

comparisons between the present study and Chapman's work would not be relevant. Under conditions 4 and 5, which also included a 30% rate of infanticide, the populations grew and migrated at a rapid rate. In comparison to other conditions that included the same mortality rates, it is obvious that the very high fertility rates used in conditions 4 and 5 were responsible for the rapid increases seen in spite of such a high infanticide rate. Prehistoric Eskimo populations could only have maintained such high fertility rates under very favorable environmental circumstances.

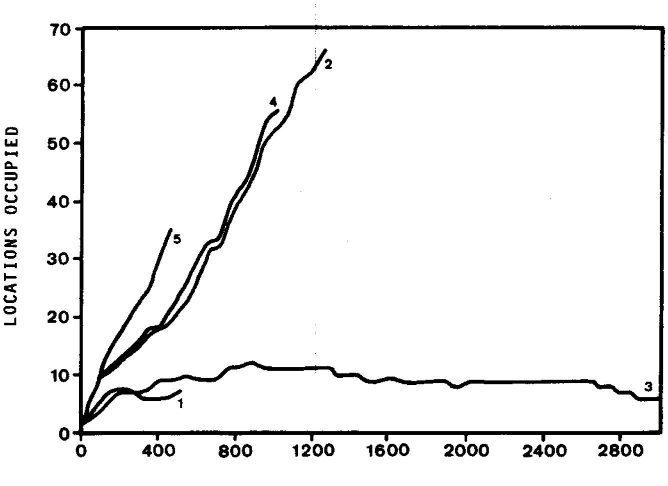

FIG. 8. The relationship between the number of locations occupied vs. the number of years simulated is shown in this graph. Line 1 = condition 1; line 2 = condition 2; line 3 = condition 3; line 4 = condition 4; line 5 = condition 5.

Future runs of DEMO6 would be of interest in the further investigation of a number of topics, including variations in the rate of migration and in the rate of population growth as a function of time. Another subject of interest is the degree of infanticide that can be tolerated by different populations under varying demographic and environmental conditions. The number of locations and the geographical area under consideration could also be varied to focus attention on particular regions and events. This last modification would be very useful in simulations that incorporate the effects of variations in such factors as climate, disease, accidents and famine. The DEMO6 program could also be modified to incorporate changes in level of technology and cultural innovation that would alter the capacity of various groups to sustain themselves.

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APPENDIX: THEORY OF DEMO6

The primary program in the system is DEMO6, which actually performs the paleodemographic simulation. The other programs in the system are used for various maintenance or "housekeeping" functions, such as setting up the initial parameters before each run and printing reports of the data on file.

Since DEMO6 is a discreet-time program, population changes are applied only in discreet pre-set time periods in which the interval of time used is ten years. The notation used in the following discussion is adopted and slightly modified from that used in Rees and Wilson (1977). All of the events that have occurred during each ten-year interval are applied to the file at the end of the interval. These events are births and deaths, which are intra-locational events, and migrations, which are inter-locational events. The simplest function describing the changes that occur at each location is as follows:

new population = f(old population, births, deaths, migrations)

or more specifically:

new population = old population + births – deaths + immigrants – emigrants

If w(t) is used to designate the population size at time t, and w(t+T) is used to designate the population size after the elapse of the increment of time T, then the model can be expressed as:

$$w(t+T) = w(t) + B(t,t+T) - D(t,t+T) + M^{IN}(t,t+T) - M^{OUT}(t,t+T)$$

where w(t) = population size at time t; w(t+T) = population size at time t+T; B(t,t+T) = births between time t and t+T; D(t,t+T) = deaths between time t and t+T; $M^{IN}(t,t+T)$ = number of immigrants between time t and t+T; $M^{OUT}(t,t+T)$ = number of emigrants between time t and t+T.

This logic is applied by DEMO6 to each location during each interval of time (T). The program is currently configured for 200 locations, any number of which may be active, inactive or isolates at the end of each interval of time. The program first determines all births and deaths for each location, then determines all migration between locations for each interval. Since these events occur on an age specific basis, the formula for births in each location is:

$$B(t,t+T) = \sum_{\alpha}^{\beta} b_r w_r(t)$$

where B(t,t+T) = births between time t and t+T (as above); α = lowest childbearing age group; β = highest childbearing age group; b_r = birth rate for females in age group r; $w_r(t)$ = number of females in age group r at time t.

The lowest childbearing age group used in DEMO6 is 10-19 years, and the highest used is 40-49 years.

The formula for the calculation of deaths for each location is:

$$D(t,t+T) = \sum_{1}^{R} d_r w_r(t)$$

where D(t,t+T) = deaths between time t and t+T (as above); R = the highest age group attainable (no one survives it, R = 8 in DEMO6); d_r = death rate for females in age group r; $w_r(t)$ = number of females in age group r at time t.

The formula for the calculation of out-migration (M^{OUT}) for each location is:

$$M^{OUT}(t,t+T) = \sum_{1}^{R} m_r w_r(t+T)$$

where $M^{OUT}(t,t+T)$ = number of emigrants between t and t+T (as above); R = the highest age group capable of producing migrants (R = 6 in DEMO6 which represents 50-59); M_r = the migration rate in age group r; $w_r(t,t+T)$ = the number of females in age group r at time t+T.

In addition to the logic described above, several parameters that control migration patterns and group size must be set before the simulation runs are performed. These variables help to control the occurrence of events, such as whether a particular location will be abandoned or whether an unoccupied location will receive emigrants, and in general provide limits to population movements. For example, the particular location to which a group of emigrants settles is determined randomly within the constraints of the parameters set prior to the simulation run. The most important of these are:

MAXD — the maximum migration distance per ten-year interval
MAXG — carrying capacity (maximum group size for a location)
MIGN — minimum population size that must be attained by a group before it is able to produce any emigrants
MIGPCT — the percent of the population that will migrate, provided other factors determine that emigration will occur
MINN — the minimum population required to establish a new settlement
MINS — the minimum size of a viable population group
PR1 — the probability that migrants will travel a particular distance during a program cycle
S1 — the relative suitability factor (0 through 1.00) for each habitable location
R — random number seed to initiate generation of the probability distribution of random events

Program listings of the DEMO6 and MAINT programs as well as a logic flowchart and data-file layout for DEMO6 are available from the author.