Modeling dispersal in the prehistoric West Indies

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Introduction

Between 2500 and 3000 years ago, Arawakan-speaking peoples of northeastern Venezuela and the Guiana coasts began to colonize the islands of the West Indies (Fig. 1). By the time Europeans arrived in 1492, almost every island was colonized. Archaeological investigations in the region have emphasized a culture-historical paradigm in which similarities in pottery modes (or other artifacts) are grouped into classes called series. Radiometric dates are then obtained for these series, and the distributions of prehistoric peoples and cultures are charted in time and space (Rouse 1986, 1992). The use of this ceramic taxonomy, in which cultures are defined according to general *similarities*, has led to a focus on frontiers, with a corresponding assumption that areas behind the frontiers were culturally homogeneous (Rouse 1986).

Efforts to interpret the distributions of cultural materials have demonstrated that settlement patterns were influenced by the physical, biogeographical and social environments in which population movements took place (Davis 1988; Haviser 1993; Keegan 1992; Keegan and Diamond 1987; Keegan and Maclachlan 1989; Roe 1989; Rouse 1986; Siegel 1991; Watters and Rouse 1989). However, these studies have largely ignored the cultural and biological processes that produced the observed patterns of expansion. The present study seeks to resolve this deficiency by focusing on the relationship between population growth and resource procurement.

In the first part of this paper the two models that will be used to describe population growth and dispersal are discussed. The first is the Verhulst-Pearl logistic model, which is used to describe the general relationship between population growth and population density (Pianka 1974; Vandermeer 1981). Because population growth is a function of birth and death rates in the logistic model, a second model is needed to describe the behavioral processes of population dispersal, expansion or migration. The model of population dispersal used in this study is deduced directly from the logistic one.

The second part of the paper uses the logistic and dispersal models to examine two episodes of population expansion in the prehistoric West Indies. Population expansion during the early ceramic age produced patterns which match those expected from unconstrained A-type dispersal, in which maximization of the population growth rate and resource capture were favored. Following a hiatus of nearly 1,000 years, the second wave
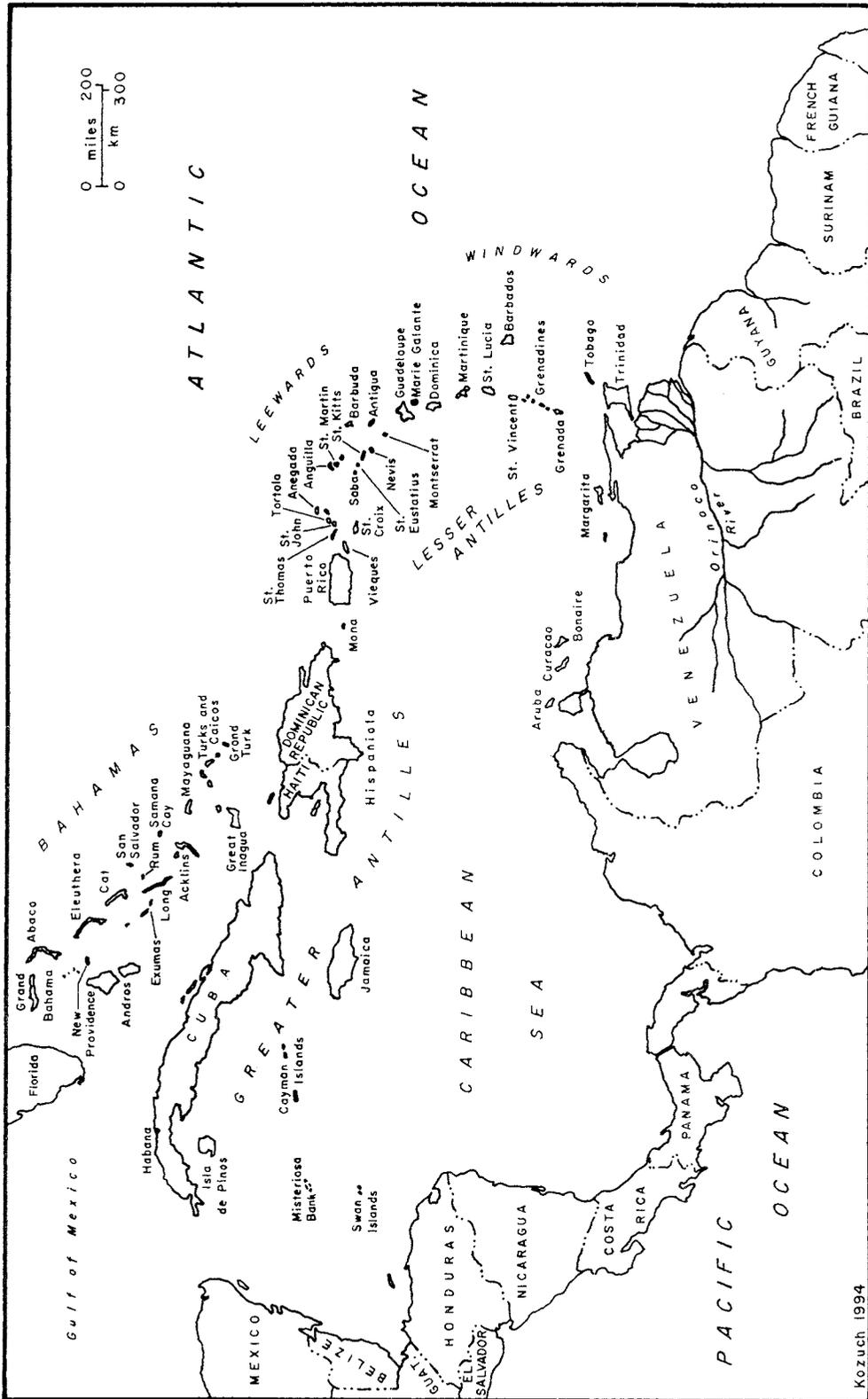
Figure 1 Map of the West Indies.

also moved at a rapid rate; this, in contrast, appears to have been constrained by social factors. Significant insights into episodes of expansion and stasis are gained by using the logistic and dispersal models.

Models of population growth

Population movements in the prehistoric West Indies are here viewed as reflecting the relationship between population growth and the availability of resources. Beginning from the reasonable premises that the colonizing populations were growing and that there was an absolute limit to the number of people who could inhabit an island (i.e. a carrying capacity), it is possible to specify the model parameters.

Populations change size in only four ways: through births and deaths and through immigration and emigration. The first set is an intrinsic characteristic of all populations, while the second is a behavioral response involving movement into or away from an area. Although our primary interest is in population movements, the basis for such movements is found in the relationship between births, deaths and resources. If we accept that carrying capacities exist, the logistic model of population growth provides a first approximation of demographic patterns.

The Verhulst-Pearl logistic equation

Although the process of density-dependent population growth could be described by an infinite number of equations, the Verhulst-Pearl logistic equation has survived as a central concept in population biology (Pianka 1974; Vandermeer 1981: 8). As Hutchinson (1978: 23) expressed it, 'We choose the logistic to study because it is realistic in that it makes simpleminded biological sense. It is an excellent base from which to set out on further, more elaborate theoretical and, we hope, more accurate investigations.'

The logistic equation has been known since the work of the Belgian mathematician P. F. Verhulst in the middle of the last century, although Verhulst's contributions went largely unnoticed until their rediscovery by R. Pearl in the 1920s. In the interim, the equation appeared in a number of forms, and had become widely known as an equation expressing autocatalysis (Hutchinson 1978: 21). Given Diamond and Keegan's use of autocatalysis to describe the colonization of islands by humans (Keegan and Diamond 1987: 67; also see Irwin 1992: 62–3), the equation would seem to have special relevance to island colonization.

The logistic equation is a mechanical rate equation that describes the consumption of an unspecified fixed input. It is worth remembering that the logistic equation is not inherently demographic; it also describes the rate at which a catalyst is consumed in a chemical reaction, the economic concept of diminishing returns (Hirshleifer 1980; Schultz 1981), and it recently has been used to describe the rate at which innovations are adopted (Braun 1987; Rindos 1984). The model describes a situation in which growth is linearly dependent on the relative population density (Hutchinson 1978).

The equation generates an S-shaped curve that describes population growth as beginning slowly as opportunities for growth become available, as gathering momentum as
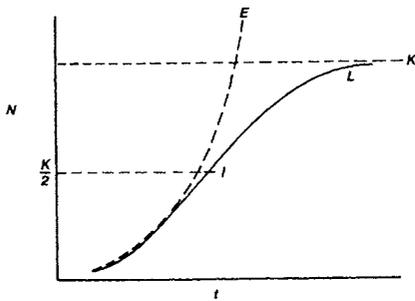
Figure 2 Logistic (L) and exponential (E) growth curves. N is population size, K is carrying capacity, t is time and I is the inflection point of the curve (where $d/dN \times dN/dt = 0$).

the power of population to grow exponentially when unimpeded is expressed, and as slowing down as the limits in resource availability are approached (Fig. 2). This scenario recognizes that, as population size increases, more of the finite resource base is allocated among existing members and fewer new members can be sustained throughout their lives. The result is a decline in the growth rate by the linear factor $1/K$ for every additional individual. The population continues to grow until the growth rate equals zero ($r = 0$), at which point population size (N) equals carrying capacity (K).

In applying this model, social scientists have tended to follow Thomas Malthus (1798) in assuming that food supply is the factor on which the density relationship is based (e.g. Cohen 1977; Hassan 1981: 144; Malthus 1959). The relationship is usually expressed in terms of 'carrying capacity' or 'population pressure', in which a finite food supply is assumed to have set a limit to the number of people who can live in an environment. The biological models make no such assumption, and experiments have demonstrated that space, disease and even the accumulation of excrement can affect population growth rates under laboratory conditions (Hutchinson 1978).

Moreover, the anthropological assumptions can be compared with perspectives on the same question as developed in ecology and economics. In ecology, carrying capacity is a constant which sets the theoretical maximum number of a species that can be supported in a habitat throughout their lives (Pianka 1974). In economic terms, the logistic equation addresses the pattern of population growth in a habitat of constant economic potential. Under these microeconomic conditions of inelastic supply and inelastic demand, neither supply (resource capture) nor demand (population numbers) can change (Schultz 1981). In sum, the logistic model works only when carrying capacity sets an absolute limit to population size: 'when the possible value of K is continuously increasing, Verhulst's equation loses its value' (Hutchinson 1978: 21).

In addition, most anthropologists use an ecologically obsolete definition of carrying capacity (Belovsky 1988). In Dewar's (1984: 606–8) critique of the anthropological use of the concept he identified three underlying assumptions: 1) 'The equilibrial level of a population is determined by the productive capacity of the environment [$K = f(Cc)$]'; 2) 'achieved population levels are equilibrial [$N = K$]'; and 3) 'there is a direct relationship between a particular population's size and the productive capacity of its range [$N_i = Cc_i$]' (where K is carrying capacity and Cc is the productive capacity of the environment). A more accurate view is that there is continuous feedback between 'the consumer populations and their food [or other resource] populations' (Belovsky 1988: 330; Winterhalder et al. 1988). Thus, when resource supply is susceptible to cultural manipulation, continuous models of

resource capture which specify the economic and demographic relations of the particular case must be developed (Dewar 1984; Keegan et al. 1985; Orians 1980; Schultz 1981).

Optimal foraging theory provides one approach to developing such models (Belovsky 1988; Winterhalder et al. 1988; Keegan 1992; Rogers 1992). In fact, 'the original rationale in animal ecology for using these models was to gain insights into how animals perceive potential food resources, so that a food-based definition of carrying capacity could be constructed' (Belovsky 1988: 330). Using a linear-programming optimal-foraging model, Belovsky (1988: 346) has demonstrated that 'hunter-gatherer densities are related to food availability'.

Population growth and dispersal

Having described the limiting case, attention is now directed to cases in which the density relationship is modified through migration. Migration can operate in two ways, through immigration, in which new arrivals increase the local population density, or through emigration, in which the departure of people decreases the local density. Immigration and emigration are actually twin processes, because one cannot occur without the other.

Insights into the processes and timing of emigration are gained by dissecting the Verhulst-Pearl logistic equation (Fig. 3). In the logistic equation there are two equilibrium points, which occur where the population density function, $F(N(t))$, crosses the 45° line at K and A (Vandermeer 1981: 50–2). The first is an asymptotically stable equilibrium point which occurs when population density is equal to carrying capacity. The second equilibrium point, A, corresponds to the inflection point of the continuous logistic curve where the growth rate, r, changes from monotonically increasing to monotonically decreasing (where the second derivative equals zero: $d/dN \times dN/dt = 0$).

The equilibrium point at A is asymptotically unstable. Unless the population can maintain the equilibrium number exactly, the population will diverge from this point (Sibley 1983; Vandermeer 1981). One trajectory reflects the critical density of an Allee effect. An Allee effect occurs when a population must maintain some critical density in order to remain viable. Should the population's size fall below the critical density, the population will be unable to grow and will eventually become extinct. This effect merits further investigation with regard to local extinctions on, or the abandonment of, islands in Oceania and in the circum-Caribbean during prehistory (Keegan and Diamond 1987; Irwin 1992), and following the arrival of Europeans (Crosby 1986; Keegan 1992). A second possible outcome occurs when population size exceeds A. Under this condition, the population continues to grow until it stabilizes at K. This second trajectory was discussed above as the outcome of logistic growth.

Between these extremes there are a variety of possible behavioral responses. In the logistic equation, the unstable equilibrium at A occurs at one-half the carrying capacity, which approximates the point at which density-dependent constraints initiate a divergence of the exponential and logistic curves (Fig. 2). In other words, up to this point, population fluctuations are largely the outcome of density-independent factors. Yet, as Kirch (1984) has noted, the logistic equation assumes that density-dependent constraints are in effect even during this initial sequence of growth. These constraints, summed as the linear factor $1/K$, have a negligible effect on the growth rate when carrying capacity (K) is large relative
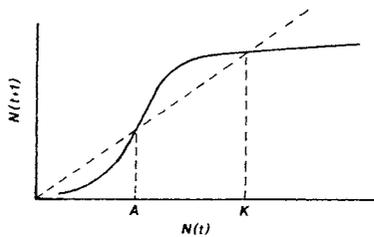
Figure 3   Discrete graph of the logistic equation. N is population size and t is time. Equilibrium points A and K exist where the dashed 45° line crosses the curve (after Vandermeer 1981: 51).

to population size. The difference between true exponential growth and density-independent logistic growth is minimal.

Finally, when the population is able to regulate its density through dispersal, the equilibrium point may reflect a target population density. If reproductive success is a measure of cultural success, then this point reflects a target density because it defines the point of maximum potential increase in population numbers with respect to time (max dN/dt occurs when $d/dN \times dN/dt = 0$). However, because it occurs at the point of maximum potential increase, the population will grow beyond the equilibrium point with every subsequent unit of time unless there is some mechanism for removing the excess population (Sibley 1983). Such is the dilemma of wildlife biologists who define this point as the maximum sustainable yield and then must determine what percentage of a population should be culled to maintain this equilibrium value (Pianka 1974).

Thus, when opportunities for dispersal are available, we would expect groups to have population sizes that oscillate around the equilibrium value at one-half of carrying capacity. A number of anthropologists have noted that actual population sizes are often 40–60 per cent of the average short-term estimate of carrying capacity (Birdsell 1957; Hassan 1981: 166–7; Lee and De Vore 1968; Johnson and Earle [1987: 28], citing the same sources, give population size as 20–30 per cent of average carrying capacity). These values have been interpreted as reflecting a population's conservatism with respect to long-term fluctuations in the resource base (Hayden 1975), but an alternative explanation is that these values represent oscillations around the point of maximum population increase.

An increase in population numbers is promoted by the population-maximizing characteristics in effect prior to this point (i.e. density independence), while intra-group competition for resources (density dependence) would promote fissioning, dispersal and the reduction of local group size to the equilibrium value after the point is passed. Furthermore, the shift from an unstable equilibrium to a stable equilibrium would be promoted by inter-group competition for resources within a region because such competition tends to favor larger size groups while the shared use of resources depresses the average return rates in an area.

A-type and K-type dispersal patterns

Population dispersal on islands has in the past been discussed in terms of *r*-selected and *K*-selected life history strategies (see MacArthur and Wilson 1967; Horn 1978). 'The distinction between *r*-selection and *K*-selection . . . is fundamental to much of contemporary evolutionary ecology' (Hutchinson 1978: 27), and has obvious attractions for students

of plant, animal and human distributions. For instance, Diamond (1977a, 1977b; Keegan and Diamond 1987) has commented on the striking similarities in the distribution of *r*-selected 'Supertramp' birds and human cultures in Oceania, and Kirch (1980) once recognized the *r*-selected characteristics of Polynesian colonists. Kirch (1984: 86) has since concluded that 'the *r/K* selection model is itself too simplistic to explain Polynesian adaptation to the reproductive challenge of colonization'. I certainly agree that the *r*- and *K*- selection model does not explain human reproductive behavior. However, the *r/K* dichotomy can serve as a useful analog, a general model of reproductive strategies that requires complementary models to specify the relationship between production and procreation. The *A*-type and *K*-type dispersal model avoids the *r/K* trap of focusing exclusively on patterns of procreation, and instead emphasizes the more easily measured density relation.

The equilibrium points of the Verhulst-Pearl logistic equation can be used to define two distinct patterns of population dispersal. The first, *A*-type dispersal, approximates the population-maximizing equilibrium point. Population grows at a rapid rate and the population is dispersed at low and equal densities. Dispersal is directed toward maximizing access to critical resources. Resource use emphasizes the highest ranked resources in the optimal set. The ultimate product is a steady-state distribution of population at equal densities throughout a region.

The second, *K*-type dispersal, occurs at a slower rate due to the reduced rate of population increase. Access to resources reflects 'satisficing' behavior such that the next suitable, but not necessarily maximizing, habitat is occupied. 'In a satisficing model, search terminates when the best offer exceeds an aspiration level that itself adjusts gradually to the value of the offers received so far' (Simon 1978: 10). The ultimate product of *K*-type dispersal is a weighted distribution in which the core area has higher densities than the expanding periphery.

The *K*-type pattern of expansion would look like a 'wave of advance' (Ammerman and Cavalli-Sforza 1973), and also conforms to patterns of predatory expansion (Bettinger and Baumhoff 1982; Sahlins 1961). *K*-type expansion is most likely to occur when one culture encroaches upon the territory or home range of another. Under this condition, inter-group competition favors larger groups that are able to outcompete the population that occupies the territory into which the colonists are expanding.

Summary

The preceding models were developed to examine two dimensions of human behavior under conditions of population growth. The first concerned the growth of a population in relation to resource distributions, while the second focused on mobility in relation to the same resources. Two possible outcomes, which define the limits of a continuum, were deduced from the Verhulst-Pearl logistic equation. These outcomes were labelled *A*-type and *K*-type dispersal.

An ideal case can be outlined as follows. A population living on an island enjoys some potential for long-term population growth. This potential is defined by the carrying capacity of the effective environment. As the population grows and increasing amounts of the limited resource base are allocated to living members, it becomes increasingly difficult

to make a living. In terms of the logistic model, the rate of population growth begins its monotonic decline.

Previously, most anthropologists have assumed that migration or culture change did not occur until the carrying capacity was reached (e.g. Curet 1992). Yet the logistic equation indicates that, when a population reaches one-half of the carrying capacity (K), it begins to reflect the constraints of density-dependent growth through a reduction in the growth rate. It is here proposed that people recognize this decline in subsistence efficiency and act to alleviate these 'population pressures' before the population size approaches the carrying capacity.

Faced with diminishing marginal returns to production, the members of the population have a variety of options. For example, they might limit further demand for resources by eating less; they might add new foods or new technologies to their subsistence pursuits, such that the carrying capacity is raised, but at the cost of higher labor inputs; or they might limit procreation to achieve an equilibrial population size. In simple terms, they lower the floor, raise the ceiling or maintain the status quo. In some cases there is a fourth option: some or all of the group may migrate to a new area.

A formal model of when to migrate can be constructed from time and resource allocation models as developed in microeconomics and optimal foraging theory (Belovsky 1988; Winterhalder et al. 1988; Hames 1992; Keegan 1992). For the present, I have chosen to emphasize a more general model which characterizes migration as conforming to population-growth-maximizing (A-type) or to competitive-ability-maximizing (K-type) patterns.

Island Arawak dispersal in the prehistoric West Indies

The first wave

The West Indies were first settled by at least two migrations of preceramic colonists (for overviews of the preceramic see Veloz Maggiolo 1991; Rouse 1992; Keegan 1994). The first migrants crossed the Yucatan Passage into Cuba around 5000 BC and spread eastward into Hispaniola. The second apparently moved through the Lesser Antilles and into the Greater Antilles about 2500 BC, and spread westward across Puerto Rico into Hispaniola. There appears to be some mixing of these populations in Hispaniola, but their material cultures remain distinctive. When the early ceramic age peoples[1] entered the Antilles about 500 BC, there were aceramic foragers living on Cuba (Guarch Delmonte 1992), Hispaniola (Veloz Maggiolo 1991), Puerto Rico (Rouse and Alegría 1990) and perhaps some of the Lesser Antilles (one Archaic site on Antigua has a radiocarbon date of AD 70 ± 50, UM-4001; Nodine 1990).

The early ceramic age dispersal into the West Indies apparently involved a direct jump from Venezuela/Trinidad to the Leeward Islands,[2] US Virgin Islands (St Thomas, St Croix and St John) and eastern Puerto Rico (Fig. 1). Further progress to the west was apparently constrained by the presence of Archaic foragers. This constraint may have involved direct conflict or 'diffuse competition' in which a reliance on similar terrestrial foods lowered the marginal and average return rates from foraging in previously exploited habitats. It has

Table 1 Early Ceramic Age sites in the Lesser Antilles (compiled by Jay Haviser, AAINA, Curaçao, Netherlands Antilles, used with permission).

Association by:	Radiometric dates	Artifact comparison
Early period (c. 500–1 BC)	Cedros, Trinidad	Pearls, Grenada
	Palo Seco, Trinidad	Black Point, Grenada
	Fond Brulé, Martinique	Morel, Guadeloupe
	Trants, Montserrat	Vielle Case, Dominica
	Radio Antilles, Montserrat	Indian Creek, Antigua
	Hope Estate, St Martin	Cayon, St Kitts
	Sorcé, Vieques	Sugar Factory, St Kitts
	Teela, Puerto Rico	Prosperity, St Croix
	Maisabel, Puerto Rico	St Georges, St Croix
	Punta Candelero, Puerto Rico	
Late period (c. AD 1–500)	Atagual, Trinidad	Vielle Case, Dominica
	Pearls, Grenada	Sugar Factory, St Kitts
	Chatham Bay, Union Is.	Hichmans, Nevis
	Kingston PO, St Vincent	Godet, St Eustatius
	Buccament W, St Vincent	Sufferers, Barbuda
	Arnos Vale, St Vincent	Rondevous, Anguilla
	Chancery Lane, Barbados	Coral Bay, St John
	Grand Anse, St Lucia	Prosperity, St Croix
	La Salle, Martinique	Longford, St Croix
	Vivé, Martinique	Salt River, St Croix
	Diamant, Martinique	Richmond, St Croix
	Morel, Guadeloupe	Monserrat, Puerto Rico
	Taliseronde, Marie Galante	
	Mill Reef, Antigua	
	Indian Creek, Antigua	
	Golden Rock, St Eustatius	
	Spring, Bay, Saba	
	Hope Estate, St Martin	
	Friars Baym, St Martin	
	Main Street, St Thomas	
	Tutu, St Thomas	
	Lower Camp, Culebra Island	
	Hacienda Grande, Puerto Rico	

been suggested, for example, that Archaic foragers were responsible for the local extinctions of sloths and manatees (Veloz Maggiolo and Ortega 1976: 160–2), animals with very high return rates and rankings.

In his compilation of settlement data and radiocarbon dates, Haviser (1993) noted that the earliest sites (500 BC to AD 1) are located on Puerto Rico, US Virgin Islands and the Leeward Islands (Table 1). The only exceptions are the radiocarbon-dated site of Fond Brulé, Martinique (2480 ± 140 bp; 2215 ± 115 bp; 2100 ± 210 bp, LY-2197; and

2010 ± 300 bp, BDX-156), and sites on Grenada and Dominica which are attributed to this period by artifact comparisons (see Haviser 1993). Moroever, with the exception of Puerto Rico, 54 per cent (n = 8) of the sites are located on the northern half of the islands, which suggests a northward-looking focus.

The second phase in the colonization of the Antilles dates from AD 1 to 500, and ends with at least one site on every major island (Haviser 1993). The Leeward Islands and US Virgin Islands, perhaps by virtue of their earlier colonization, have an inordinate number of sites relative to their size (Table 1). In addition, sites established during this phase show a marked shift to the southern half of the islands (80 per cent, n = 24). This shift occurs even when a site is the only one on the island, so it is not simply a response to the preceding phase during which north-coast locations were preferred.

The present evidence indicates that the early ceramic age dispersal into the West Indies occurred at an extremely rapid pace – so rapid, in fact, that arrival in eastern Puerto Rico is almost simultaneous with departure from South America. It could be argued that these patterns are an artifact of the available data, and that future research will show that each island was colonized in turn as the colonists made their way northward from the mainland. However, this alternative model can be rejected by calculating the reproductive potential of the human colonists. It is clear from these calculations that the colonists could not have reproduced fast enough to settle the islands in sequence (Keegan 1985: 58).

The rapid pace of this migration has been interpreted as an effort to maintain an adaptive strategy that was developed in the South American lowlands (Keegan 1985; Roe 1989). Roe (1989) cites the survival of pottery *topias* (pot rests), along with continuity in pottery decoration and 'culinary remains', as evidence for a mainland orientation. Roe's conclusions have been challenged by Siegel (1991), who correctly noted that the mainland *orientation* apparent in pottery and other artifacts does not denote a mainland *adaptation*. In addition, Siegel noted that some of the earliest sites were located on some of the smallest islands and he interpreted the high incidence of marine fishes and mollusks in the faunal remains at the Maisabel site Puerto Rico (110 BC to AD 430), as reflecting a maritime orientation (see deFrance 1988, 1989).

With regard to settlement patterns, island size is irrelevant. What is important is whether higher economic returns are available from the land or the sea. In other words, it is possible to maintain a terrestrial adaptation while living on a very small island. With regard to diet, the stable-isotope analysis of skeletal remains contradicts Siegel's conclusions. Although marine species are undeniably present in the archaeological deposits, the bone-collagen carbon-isotope signatures of humans from Maisabel and other early sites reflects a nearly complete reliance on terrestrial sources of protein (Klinken 1991; Stokes 1993). In fact, one individual from the Hacienda Grande site (110 BC to AD 370; Rouse and Alegría 1990), Puerto Rico, exhibited a 93 ± 7 per cent reliance on terrestrial sources of protein (Keegan and DeNiro 1988).

The early ceramic age reliance on terrestrial foods was not simply an exercise in maintaining a mainland adaptation. A terrestrial-based diet made good economic sense. The microeconomic calculation of return rates and resource rankings indicates that terrestrial protein sources were, for the most part, ranked higher than marine protein sources (Keegan 1989). Thus, according to the specifications of this formal economic approach, the initial reliance on terrestrial foods is to be expected.

Through time the use of marine foods increased, with the most obvious shift occurring under density-dependent conditions. West Indian archaeologists have long recognized that an abundance of land crab remains in early sites is replaced by an abundance of mollusk shells toward the termination of the early period (circa AD 500), although the timing of the shift is slightly different on every island (see, for example, Carbone 1980; Goodwin 1980; Rainey 1940). Roosevelt has shown that the ancestors of the early ceramic age colonists, while living on the Orinoco River in Venezuela, exhibited a major shift in protein source when the population doubled from about 1.5 to 3.0 persons per sq km (Roosevelt 1980). On St Kitts, the only island for which comparable demographic data are available, the shift from land crabs to marine mollusks also occurred when the population doubled from 1.5 to 3.0 persons per sq km (Goodwin 1979; Keegan 1989).

Spatial, temporal, economic and demographic data all indicate that the initial Island Arawak dispersal into the West Indies conformed to unconstrained A-type dispersal. The earliest settlers jumped directly from South America to Puerto Rico, the US Virgin Islands and the Leeward Islands, whence further progress to the west was apparently constrained by the presence of Archaic foragers. From eastern Puerto Rico population growth fueled slow expansion to the west and more rapid dispersal south into the Virgin and Leeward Islands, which may account for the north-coast emphasis in settlement locations.[3] During this phase the diet was based on terrestrial food sources with a very limited use of marine foods.

It is likely that the conditions which stimulated the initial migration into the Antilles continued to fuel dispersal from South America. Given the large areas over which general pottery series were shared (see Rouse 1992: 53), different ethnic groups probably entered the Antilles at this time. Unfortunately, cultural differences have been disguised by a taxonomy that focuses on similarities and continuities. Chanlatte Baik (Chanlatte Baik and Narganes Storde 1990) and Haviser (1993) may be correct in identifying separate geographical origins for the cultures represented at certain early ceramic age sites (e.g., la Hueca, Vieques and Hope Estate, St Martin).

Dispersal during this phase continued to conform to an A-type pattern, such that only one or two settlements were established on each island. Dispersal during this phase was also constrained by previously established settlements. Because colonies had already been established in the Virgin and Leeward Islands, settlement focused on the un(der)-populated Windwards. Moreover, most initial-phase sites are in north-coast locations which may be responsible for the south-coast emphasis of later sites. Alternatively, the south-coast locale may reflect closer ties with the South American mainland.

After all of the major islands were colonized, further opportunities for dispersal were limited by the presence of similar peoples on neighboring islands. As opportunities for dispersal to unoccupied islands disappeared, further population growth had to be accommodated on the island. As the population density on each island reached a critical value, diet breadth was expanded to include larger quantities of marine foods. Throughout the culture historical sequence, the contribution of marine foods increased from virtually zero to perhaps as much as 30 per cent of diet (Keegan and DeNiro 1988; Klinken 1991; Stokes 1993).

The long pause

Recent radiocarbon dates indicate that eastern Puerto Rico may have been settled as early as 430 ± 80 BC (uncalibrated radiocarbon date from the Tecla sita, I-1385b), and was certainly settled by 150 BC (Haviser 1993). Yet population expansion out of Puerto Rico into the rest of the Greater Antilles and the Bahamas did not commence until around AD 600. The reasons for this nearly 1000-year 'long pause' have never been adequately addressed.

Two things are clear. First, there was a well-established Archaic population in Hispaniola and Cuba, if not in Jamaica and the Bahamas, which could have constrained expansion into these islands by early ceramic age peoples (Veloz Maggiolo 1991; Rouse 1992; Keegan 1994). Second, there was sufficient interaction across the border between early ceramic age and Archaic peoples to allow the diffusion of pottery-making and other cultural elements. This combination of pottery, with decorations lifted from Archaic stone-work, and an Archaic lithic technology is a widespread phenomenon in Hispaniola and Cuba, where it is classified as belonging to a proto-agricultural period (500 BC and AD 500) (Veloz Maggiolo 1991; Veloz Maggiolo et al. 1991; Dacal Moure and Rivero de la Calle 1984; Guarch Delmonte 1990; Keegan 1994).

Although migration to the west ceased, the population on Puerto Rico continued to grow at a rapid rate and the entire island was settled. Recently, Curet (1992) used a 'carrying capacity' model to examine population growth and culture change in the Maunabo valley in southeastern Puerto Rico. He demonstrated that the population exhibited continuous growth until the period just before the arrival of the Spanish, at which time the population declined in numbers. These changes in demography took place even though the total population of the Maunabo valley never achieved even the minimal carrying capacity as estimated from manioc cultivation. Unfortunately, the study suffers from application of an outmoded concept of carrying capacity (i.e. he assumed that the population would grow to carrying capacity before changes were instituted), and from the use of calories (manioc) as the currency from which carrying capacity was estimated (see Keegan 1986).

The second wave

When the second wave of population expansion began about AD 600, dispersal occurred at a rapid pace, with sites appearing simultaneously across Hispaniola and into Cuba, Jamaica and probably the Bahamas (Berman and Gnivecki 1991; Keegan 1992). It is possible that the larger islands were transformed by the diffusion of materials rather than the movement of peoples. Chanlatte Baik and Narganes Storde (1990) have suggested that a hybridization of the indigenous preceramic peoples and the in-migrating ceramic age peoples occurred in the early centuries AD. Beyond that suggestion, dispersal across the larger islands has not been addressed.

In contrast, population expansion into the Bahama archipelago has been the subject of intense scrutiny (Berman and Gnivecki 1991; Granberry 1993; Keegan 1985, 1992; Winter et al. 1985). Over the past decade, most of the islands in the Bahama archipelago have been intensively surveyed (see Craton and Saunders 1992: 11; Keegan 1992: 70–1), and
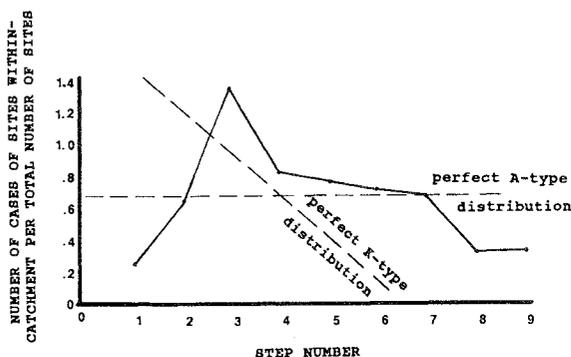
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Figure 4 A plot of the ratio of the number of sites separated by less than 1.5 km (the radius of site catchments; see Sullivan 1981; Wing and Scudder 1983) divided by the total number of sites. Step numbers are: 1 Great Inagua; 2 Mayaguana; 3 Acklins Island; 4 Crooked Island; 5 Long Island; 6 Great and Little Exuma Islands; 7 Cat Island; 8 Rum Cay; and 9 Eleuthera (Keegan 1985: 237).

settlement distributions on the eight main islands in the archipelago have been identified during archaeological surveys that sought 100 per cent coverage of their coastlines (Keegan 1985: 198–212).

In order to derive the mode and tempo of colonization from settlement patterns, it was assumed that the archaeologically observed patterns were the product of two parts: (i) the colonization of the island, and (ii) continued population growth at a constant rate. It follows from these assumptions that the observed density is a reflection of colonization processes. For example, if a steady-state distribution obtains, then colonization must have conformed to an *A*-type mode; and if the population distribution was weighted, then *K*-type dispersal was at play.

To measure density distributions on different islands, settlements were compared with respect to a settlement-packing index and to the ratio of site length to coastline length. These measures were used to reduce the impact of unsurveyed areas, and because linear nearest-neighbor analysis provided unusable results due to the pairing of settlements (Keegan 1985: 229–33; see Pinder and Witherick 1975: 17).

Plots of these data provide evidence for both steady-state and weighted distributions (Figs 4 and 5). There is a general trend of decreasing settlement packing along with a decrease in the site length per coastline length ratios from south to north. This northward trending decrease is significant because it corresponds to the expected direction of expansion (i.e. from Hispaniola toward Grand Bahama). The indices also identify a steady-state distribution of population in the central zone where island sizes vary in a manner that facilitated dispersal at equal densities and that prevented the time lags generating the overall weighted distribution of population from south to north.

A time-series model was then used to explore the manner in which the expansion of population at equal densities might generate a *K*-type distribution. The sequence of expansion was examined under the assumptions that population growth occurs at a constant rate and that expansion events occur when the population has doubled in size. The doubling-time equation from population biology model was used to operationalize the model ($D_t = 0.6931/r$).

There are two possible outcomes with each doubling of population: either a new settlement is established on the same island, or the next island in the sequence is colonized. It is assumed that the option selected was determined by the density relationship between adjacent islands. New settlements would continue to be established on the same island
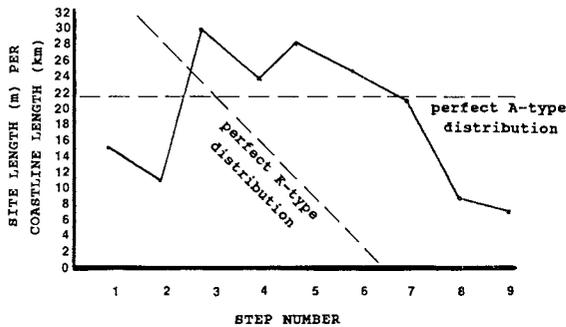
Figure 5 Plot of site length (m) per coastline length (km) ratios. Step numbers are: 1 Great Inagua; 2 Mayaguana; 3 Acklins Island; 4 Crooked Island; 5 Long Island; 6 Great and Little Exuma Islands; 7 Cat Island; 8 Rum Cay; and 9 Eleuthera (Keegan 1985: 237).

until a lower density could be achieved on the next island in the chain. It should be noted that the population of every settlement is assumed to double at each doubling time, which produces a geometric growth in the population density.

This model generated predictions that accurately characterize the observed settlement distributions on all of the islands from Acklins north. For example, Rum Cay, for which the most complete survey data are available, was predicted to have six to twelve terminal period settlements of equal size, which would have supported a total population of 300–600. A total of eleven sites (of unequal size) were found during surveys, and the population was estimated from site-size measurements to have been 356 persons (Keegan 1985).

The model also provided an explanation for the weighted (i.e. *K*-type) distribution. In this linear-branching archipelago, the number of unoccupied islands to which colonists could be supplied varies. Acklins Island would provide colonists only to Crooked Island, while Long Island would provide colonists to Rum Cay, Great Exuma and Cat Island. The repeated loss of population through emigration would have kept the aggregate population on Long Island significantly below that on Acklins Island, even if both were initially settled at approximately equal densities.

It should, however, be noted that, if population expansion conformed to a true maximization of access to resources, then the largest islands in the archipelago would have been colonized first. This is not the pattern of expansion that is observed. Instead, social relations have been shown to constrain the distances between parent and offspring community such that the next island in the sequence was the next to receive colonists (Keegan and Maclachlan 1989). Given this constraint, the pattern of expansion does conform to an *A*-type pattern.

Finally, *K*-type dispersal is also apparent in the southern Bahama archipelago. The analysis of pottery decorations long ago suggested that there were two waves of stylistic influence and one or more associated migrations into the Bahamas from Hispaniola and/or Cuba (Granberry 1956: 131–2; 1993; Sears and Sullivan 1978). Recent investigations in the Turks and Caicos Islands and on Great Inagua Island have revealed that Tainos from Hispaniola and/or Cuba began to establish sites on these islands after AD 1000 and continued to do so up to European contact (Keegan 1991, 1993). The sites are considered to be Taino colonies because they contain exclusively Taino pottery whose temper inclusions indicate that the pots were imported from the Greater Antilles. Some of the sites show evidence for permanent settlement while others were clearly established for the

extraction and export of locally abundant resources. The arrival of the Spanish appears to have truncated the Taino incursion into the Bahamas, as it did in central Cuba.

Lastly, maximization of access to resources also conformed to that expected for A-type dispersal. The optimization of currency capture[4] was examined by ranking the Lucayan Taino resource set with respect to calorie and protein returns per unit handling time, and then identifying changes in resource use by conducting a stable-isotope analysis of the consumption practices as measured in the bone collagen of seventeen Lucayan skeletons. The stable-isotope analysis documented dietary differences that are correlated with changes in settlement patterns and conform to the predicted path of diet-breadth expansion (Keegan and DeNiro 1988). These conclusions must, however, remain tentative until radiocarbon dates can be obtained for the skeletons themselves.

The long-term population growth rate for the archipelago, the packing and densities of settlements on different islands, the pattern of expansion and evidence for their subsistence practices all support the conclusion that population expansion into the Bahamas occurred at a rapid rate that conformed to the A-type dispersal mode. A later expansion, beginning around AD 1000, progressed at a slower rate through the underpopulated southern Bahamas and was terminated by the arrival of the Spanish.

Conclusions

This paper has outlined two models for the purpose of improving our understanding of the processes of human dispersal. It began with the global Verhulst-Pearl logistic equation and identified two population equilibrium points. These equilibria were then used to operationalize the concepts r-selection and K-selection with regard to episodes of human dispersal. By specifying the parameters of the general models of population change, a middle-level predictive model was deduced. The two types of dispersal, A-type and K-type, corresponding to the equilibrium points in the logistic equation, provide a framework for organizing otherwise disparate sources of data for the logical evaluation of colonization processes.

The model was developed to examine population expansion in the prehistoric West Indies. Models of this type are necessary because present archaeological techniques and preservational biases preclude direct answers to most distributional questions. It will always be necessary to build a case of strong inference from a variety of seemingly unrelated sources. By organizing such circumstantial evidence in logical frameworks that can be subjected to further testing and refinement, more accurate constructions of past human behavior can be produced.

The early ceramic age expansion (500 BC to AD 500) very clearly conformed to the unconstrained A-type model. The earliest migration moved directly from the South American mainland to the US Virgin Islands, Leeward Islands and eastern Puerto Rico, and only later colonized the intervening islands of the Lesser Antilles. Moreover, although colonists used a wide variety of resources, there is evidence that their subsistence practices emphasized the highest ranked resources in the optimal set.

The analysis of prehistoric population expansion in the Bahama archipelago was also shown to conform to that expected for A-type dispersal. That conformity was demonstrated

by reference to the estimated long-term aggregate growth rate, settlement distributions and resource capture. Furthermore, evidence for changes in subsistence practices support the conclusion that the rapid dispersal of population occurred to maximize access to the highest ranked resources, within limits imposed by the kinship system. Kinship is important as the basis for economic organization, also known as relations of production (see Keegan and Maclachlan 1989).

A final note of more general interest concerns whether human populations are regulated by density-dependent or density-independent factors. The model presented here indicates that when a population is able to regulate its density through dispersal, density-dependent constraints may establish an upper limit to group size that is then avoided through fissioning and dispersal. These responses act to reduce the population density to a level at which density-independent factors *appear* to exert the primary regulating influences. However, under such conditions, population growth is ultimately responsive to density-dependent constraints.

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Notes

1 Peoples from this time period are commonly called 'Saladoid' after the classification scheme that is used to describe their pottery styles (Rouse 1992). However, both Haviser (1993) and Chanlatte Baik (Chanlatte Baik and Narganes Storde 1990) have suggested that non-Saladoid peoples also entered the Antilles at this time. In order to recognize the possible multi-ethnic origins of Ceramic Age West Indians, I follow Haviser (1993) in using the term 'early ceramic age' to describe this period.

2 The Lesser Antilles have been divided into Windward and Leeward groups based on British colonial administrative units. The Leewards are the islands from Guadeloupe north, while the Windwards are south of Guadeloupe. This division captures meaningful ecological and prehistoric cultural characteristics.

3 It is clear from radiocarbon dates that some of the sites in the US Virgin Islands and Leeward Island predate or are contemporaneous with those in eastern Puerto Rico.

4 Currency capture is the equivalent of 'price' in economics. It is measured by defining resources in terms of the common benefit obtained from a set of resources, e.g. calories or protein, with regard to a common unit invested in obtaining the currency, e.g. time or

energy. In other words, West Indian foragers do not pursue iguanas, hutias and fishes; they pursue different packages of calories which are obtained for different investments of time and/or energy.

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Abstract

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Modeling dispersal in the prehistoric West Indies

In an effort to study population movements in the prehistoric West Indies, a model that describes dispersal under two specific sets of conditions was deduced from the Verhulst-Pearl logistic equation of density-dependent population growth – the same equation that previously gave us the carrying-capacity concept and r- and K-selection model. Population expansion in the prehistoric West Indies is shown to have occurred at a rapid pace during which only the most highly ranked resources were pursued. These conclusions contradict the conventional wisdom and provide insights into the economic, social and political foundations of Taino culture.