

Modeling Human Environmental Interaction: Local Instabilities and Structural Persistence

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Introduction

Modeling Population Dynamics and Environmental Impact

It is virtually a truism to state that the population size trajectory of a human group is a critical aspect of understanding group/environmental interactions, especially with regard to the long term impact a group may have on its environment and the consequences this impact has, in return, for the group. The population size trajectory relates to demographic processes that derive from mortality, fertility and migration rates measured over the population viewed as occupying some geographical region. It will be assumed here that the resources being obtained from the environment are organic and so subject to their own population dynamics. From the viewpoint of a utilized (organic) resource, utilization of the resource can be thought of as contributing to the mortality rate of the organism, thereby making the overall system a system of coupled subsystems.

The population size at time t , $p(t)$, the population growth rate, $r(t) = dp/dt$, and the population growth acceleration, $a(t) = dp^2/dt^2$, form the basis for modeling the time trajectory of the population size

of the group. The impact of a population on its environment is measured in different ways by these three aspects of the population size time trajectory via the consumption rate per person per unit of time, c , of resources obtained from the environment.

For a given consumption rate, c , the total demand, D , per unit of time for environmental resources is related to $p(t)$ via $D = cp(t)$ and stipulates the productivity level, D , the environment must be able to provide per unit of time on a sustained basis if there is no change in the value of c and the population size is unchanging.

For a constant value of c the growth in demand is given via $dD/dt = cdp/dt$ and this equation permits equating growth in demand with growth in population. This leads to the common focus by demographers on the current population growth rate when considering future impacts of a population on its environment and whether or not future demands can be met indefinitely, taking into account the environmental productivity. The value of c , though, is not constant and has been growing, especially in developing and developed nations. If we allow for the consumption rate, c , to be time dependent the growth rate, dp/dt , translates into the growth rate in demand via $dD/dt = dc/dt p + c dp/dt$. In general, then, growth in demand is related both to the current population size and to population growth, hence stabilization of growth in demand requires either stabilization of both the population size and the consumption rate per person per unit of time, or a decreasing consumption rate that compensates for a growing population size.

The third measure, acceleration of the population size, has been less widely used and can be thought of as measuring the "shock" that acceleration in the population size has on the environment through comparing the magnitude of the population size acceleration with an equivalent measure made on the environment, namely acceleration in environmental productivity. (The term "shock" is used since the acceleration in the population size may lead to an acceleration in the demand, D , that cannot be matched even by attempts to increase the productivity of the environment, hence leads to overexploitation of the

environment. "Productivity of the environment" is a summation over the population dynamics of each species in the environment and includes attempts -- if any -- by the group in question to increase environmental productivity, such as the use of cultivated crops and farming.) The "shock" can be measured in terms of environmental productivity per unit area; that is, in terms of productivity over some region, $A(t)$, where the environmental area exploited by a group may be changing through time. The latter implies that we also need to consider the population density, $\mathbf{d}(t) = p(t)/A(t)$. If we take into account population density and a variable region then we have

$$D(t) = c(t)A(t)\mathbf{d}(t) \quad (1)$$

and so

$$dD/dt = (dA/dt)c\mathbf{d} + A(dc/dt)\mathbf{d} + Ac(d\mathbf{d}/dt) \quad (2)$$

and

$$\begin{aligned} d^2D/dt^2 = & (d^2A/dt^2)c\mathbf{d} + A(d^2c/dt^2)\mathbf{d} + Ac(d^2\mathbf{d}/dt^2) + 2((dA/dt)(dc/dt)\mathbf{d} + (dA/dt)c(d\mathbf{d}/dt) + \\ & + A(dc/dt)(d\mathbf{d}/dt)). \end{aligned} \quad (3)$$

Two special case are: (1) A is constant, hence $dA/dt = 0$ and (2) \mathbf{d} is constant, hence $d\mathbf{d}/dt = 0$.

For each of these two cases dD/dt reduces to

$$dD/dt = p(dc/dt) + c(dp/dt) \quad (2')$$

and d^2D/dt^2 reduces to

$$d^2D/dt^2 = (d^2c/dt^2)p + c(d^2p/dt^2) + 2(dc/dt)(dp/dt). \quad (3')$$

The demographic consequences in terms of change in population size and overall demand for environmental resources is the same regardless of whether area is kept constant or population density is kept constant. However, the environmental consequences are not the same. The former leads to *intensification* in the use of resources in the same region and the latter leads to *expansion* in the size of the region without intensification in the utilization of resources per unit area. In the absence of unoccupied

land, expansion can only occur by displacement of neighboring groups, hence may lead to conflict and to a chain reaction of one displaced group also attempting to displace another neighboring group. The chain reaction is finite hence even if the first group is able to expand, other groups will either have to intensify or the population size of the group must reduce.

If we assume a constant consumption rate, c , acceleration in population size is proportional to dp^2/dt^2 and if the later exceeds any plausible acceleration in environmental productivity then environmental degradation must ensue. With a non-constant consumption rate, $c(t)$, and a fixed area A or a fixed density d , $d^2D/dt^2 = (d^2c/dt^2)p + 2(dc/dt)(dp/dt) + c(d^2p/dt^2)$. Even with $d^2p/dt^2 = 0 = d^2c/dt^2$ (that is, no acceleration in either the population growth rate or the consumption growth rate), there will still be a positive acceleration in demand and so a increasing rate of change in demand so long as both the population growth rate and the consumption growth rate are positive. Focusing on change in $c(t)$ or $p(t)$ alone ignores the interaction effect between the two growth rates and thereby unrealistically minimizes the "shock" effect of population growth and consumption growth on exploited environmental resources.

Simplification of actual population trajectories via the common demographic practice of aggregation and averaging assumes d^2p/dt^2 is zero, hence minimizes the short-term effects a growing population may actually have on its environment via acceleration in population growth. The simplification may not be unreasonable when the time period over which $d^2p/dt^2 > 0$ is of short duration and the current demand is much smaller then the environmental productivity. But this ignores the process(es) by which the acceleration in growth rate changes value. Modeling of the time dependent acceleration in population size permits deriving population dynamics of a group as the time dependent growth rate may be obtained by integrating the acceleration function and the time dependent population size by integrating the time dependent growth rate. Hence if we have a satisfactory model of acceleration (or of the time dependent growth rate) we can derive a model of the population trajectory through time. But modeling the acceleration function or the growth rate function is not easily accommodated by

classical mathematical models, except in relatively simple cases, such as the models used for density dependent population growth.

Need for Non-Classical Mathematical Modeling

Classical mathematical models assume an unchanging structural form (such as the logistic model for density dependent growth) in which the relationships among variables are fixed and parameters that appear in the structural form of the model are constant. Even with a fixed structure and constant parameters the behavior of the system may be complex as indicated by "chaotic" systems where the complexity of the trajectories of the system arises from non-linearities in the structural representation of the system. Consequences that arise from change in parameter values, especially the possibility of discontinuities in what otherwise is a continuous trajectory followed by the equilibrium value(s) of a system under parameter change, have been considered under the rubric of catastrophe theory. The two concepts begin to merge when one tracks the change in the behavior of a non-linear system as parameter values are changed; e.g., a non-chaotic system may have a threshold value where it switches from simple trajectories to chaotic trajectories.

Though both chaotic systems and catastrophe theory have provided metaphoric models for representing some of the complexity of human systems (e.g., papers in Renfrew 19xx), neither the stronger assumption of fixed structure and constant parameters which is part of a non-linear "chaotic system" nor the weaker assumption of fixed structure and changing parameter values incorporated in catastrophe theory escapes the "summed over" or "averaging" assumptions that underlie application of system models to human systems. Also ignored, and perhaps even more critical, is the fact that human systems have agents who, to one degree or another, can monitor (deliberately or otherwise) the current state of the system and modify their behavior in accordance with the information they have received about the current state of the system and affect the future behavior of the system. Yet another difficulty arises

from the fact that averaging procedures make the assumption that all units of the same kind respond in the same manner and that all these units have complete and equal access to relevant aspects of the current state of the system, both local and global. In contrast, human agents have differential access to local and global information, may have incomplete and variable information about the state of the system, and can vary in their ability to monitor, or willingness to respond to monitored information, about the current state of the system. The acceleration function, $a(t)$, (or the growth function, $r(t)$) is ultimately driven by decision making at the agent level based upon an agent's current position in the system, degree of access to information, amount of information available, and the way all of this affects whatever action is taken by the agent that may affect mortality, fertility and/or migration rates.

The complexity of the modeling problem posed by the human system being driven by individual decision making dependent upon the situation of individuals in the overall system suggests two strategies: (1) modeling of the structural consequences of interacting agents via methods such as multi-agent simulation as multi-agent simulation allows for information upon which an agent acts to be determined by the pattern of interaction and (2) modeling of the way in which agents acquire information and transmit information from one agent to another. These are interrelated strategies as the structural consequences of agent interaction affects both access to information and transmission of information from one agent to another. Similarly, models of information acquisition and information transmission affects information transmission through agent interaction. Though the strategies are interrelated, those who have focused on agent interaction through multi-agent simulation have tended to make simplifying assumptions about information acquisition and transmission of information from one agent to another, and those who have focused on the latter have tended to be less concerned about the consequences of the structure that arises through agent interaction.

The Cultural Dimension

Yet another dimension that is crucial to human systems is the cultural dimension viewed as an ideational domain that affects the meaning assigned (or not assigned) to external phenomena and events, imposes a conceptual structure over external phenomena and events, and provides continuity in the way external phenomena and events are conceptualized and acted upon that transcends the idiosyncrasies of individual agents. Even more, I argue, the cultural domain constructs a "universe" within which agents operate and so is a frame of reference for evaluation of the nature of agent decisions; e.g., agent decision making is rational or not in with respect to the cultural context in which the agent is acting and not by reference to a universal criterion of rationality.

The relationship of the cultural dimension to external phenomena and events has (at least) two modeling problems. First, the modeling of what we refer to as culture, or more specifically, cultural constructs. Second, modeling of the instantiation of cultural constructs. The former refers to modeling of the way in which concepts, ideas, categories and the like are linked and structured at an ideational/abstract level and the latter to the way in which abstract structures and abstract concepts are mapped onto empirical phenomena and events, thereby providing a framework for assigning meaning to those phenomena and events that is not individual specific but is common to those individuals with a shared "enculturation." The former has resilience and greater resistance to change by virtue of the logic underlying the way in which concepts, ideas, categories and the like are linked and structured. The later is less constrained as multiple instantiations may be consistent with, or made to conform to, the logic of the construct being instantiated. Hence instantiations are more open to negotiation and reinterpretation and can more easily be "molded" to match the idiosyncratic interests of individuals or groups of individuals than can the cultural constructs that are being instantiated. It is easier, for example, to introduce idiosyncratic uses of kin terms that may suit individual purposes than to introduce new kin

terms that are not consistent with the structural logic of an existing kinship terminology.

Decision Making and Information Transmittal

In this paper I will consider two aspects of this larger research framework. The first relates to the cultural context of decision making and how this interfaces with the material consequences that arise when decisions are converted into action. The goal here is to bridge the dichotomy seen between models of human behavior viewed in terms of material consequences and models of human behavior viewed as arising through the identities that actors take on. The bridge I construct is based on assuming that decision making is based on the cultural meaning assigned to phenomena and events in the context of information the individual receives about the state of the environment in which one acts. I will use as an example the multi-agent simulation I constructed of birth spacing by *!Kung san* women in which it is assumed that women make "selfish" decisions but with "selfish" having a cultural aspect; that is, it is assumed women make decisions about birth spacing only by reference to the well-being of herself and her family, but what constitutes "well-being" is culturally constructed. I then trace how this same model will lead to different patterns of human-environment utilization in the context of neighboring, hence potentially competing, groups. No single pattern dominates as the pattern of interaction between groups and between a group and the environment is not determined simply by external, material conditions or by universal assumptions of decision making such as rational choice as measured against an objective reality, but also depends upon the social organization of a group and the latter reflects an internal, conceptual structure that provides the basis for the form of the social organization. One configuration of particular interest that the model suggests is the combination of instability from the viewpoint of a local group (that is, high risk of the local group going extinct) but global stability overall in the sense that the configuration of local groups going extinct and replaced by new, local groups is a kind of equilibrium.

The second aspect relates to models for the transmission of information from one individual to

another. In this part of the paper I review models that have been proposed in analogy with, derivative from, or modification of the process of biological transmission of information in the form of DNA. Three different ways in which the transmission has been modeled are considered. One derives from concepts associated with sociobiology and focuses on a genetic basis for the "behavioral phenotype", a second is sometimes referred to as dual inheritance and considers the "behavioral phenotype" to consist of both a genetic component and a component derived from direct transmission of traits from one phenotype to another, and the third utilizes the idea of memes to construct a system of "cultural selection" analogous to the system of natural selection. All of these models are found to be insufficient as none of them addresses in a satisfactory manner the way in which cultural constructs can be structured systems that constitute a conceptual whole by virtue of an internal logic that gives the structure its particular form. The latter also identifies a significant difference between "cultural knowledge" and "material knowledge"; i.e. a significant difference between the kind of information ("cultural knowledge") that is invoked when one accounts for a behavior as arising out of an identity that one may take on, versus the information that is invoked ("material knowledge") when accounting for a behavior as the outcome of the evaluation of the consequences of alternative courses of action. Unlike "material knowledge", which may be modeled as "chunks" of information that are more-or-less independent and so missing "chunks" cannot be recovered when one has incomplete information, the logic underlying the structure of "cultural knowledge" makes possible recovery of missing parts of the structure when one has incomplete information. For example, even with incomplete transmittal of a kinship terminology, the missing parts of the terminology may be recoverable from the underlying logic of the terminology. This suggests that "cultural knowledge" is more resilient and less prone to drift effects than is the case for "material knowledge" when information is transmitted from one person to another, or when only partial information is transmitted.

Implications of the cultural context of decision-making and the form and transmission of "cultural knowledge" for human/environment interactions will be discussed.

Decision Model for Birth Spacing

For a population in a given region, demographic processes are driven by fertility, mortality and migration rates. Migration rates are local phenomena and over a large enough area will average out to zero. Mortality rates may be affected by human decision making such as raiding or warfare, but largely reflect biological and health processes over which humans have had little control until recent times. Fertility rates are, then, the primary rate that is subject to decision making by individuals and groups and one that has a substantial behavioral component in all societies. When control is made for age of marriage, direct fertility reduction (post-partum sexual taboos, infanticide, induced abortion, use of contraceptive devices, etc.) and indirect reduction of fertility through prolonged lactation, a fertility rate of about 15 births/woman/completed reproductive period is obtained regardless of whether the society is western-industrialized, third world or a so-called natural fertility population. No extant population has a fertility rate matching this rate.¹ Thus women in all populations undertake behaviors that reduce the biologically possible fertility rate. Hence the matter of concern from a modeling viewpoint is variation in the degree to which behavioral practices affect the background fertility rate, both between populations and among women in a single population.

Standard models of population dynamics, such as density dependent population growth, make three unrealistic assumptions with regard to human societies. The first is the assumption that individual variation can be ignored and replaced with a single fertility rate obtained by summing over, and averaging over all females. The second is the assumption that all females respond in synchrony and in precisely the same manner to factors leading to a change in the average fertility rate. The third assumption is that population size is bounded by carrying capacity, defined as the maximal, sustainable population size

¹ Natural fertility populations are defined as those populations in which women do not make decisions to limit the total number of offspring (author 19xx:xx). The definition of a natural fertility population includes populations in which women space births but do not have a specific number of offspring as a target.

given the resource base and the means of resource procurement. The last assumption does not allow for the possibility that decision making by women with regard to behaviors that affect her fertility may have the consequences of driving the population size to a stable equilibrium value below the carrying capacity of the region. It is this possibility that we will now consider.

Decision making by women with regard to a next pregnancy is both culturally mediated by the framework within which women make decisions and through interaction of women, hence by ways that information is accessed and distributed among women. We will focus here on the former as the latter relates to the specifics of decision making within the cultural framework that defines for individual women the publicly accepted behaviors regarding pregnancy and decisions affecting fertility.

The model to be summarized here is a decision model (Read 19xx) implemented as a multi-agent simulation model (Read 1998) based on ethnographic observations made about child-bearing and female parenting by a hunting and gathering group, the !Kung san of the Kalahari Desert in southern Africa. The goal of the modeling exercise was to determine the consequences for the population as a whole of decision of "selfish" decision making by women made within the context of her family and without concern for group level consequences such as the population size that ensues from purely family-oriented decision making. Two unexpected results ensued. First, selfish decision making could have as an emergent property stabilization of the population size of the group as a whole and second, the stabilized population size was likely to increasingly fall below the carrying capacity limitation when comparing hunting and gathering groups in high resource density environments with in comparison with groups in lower resource density environments. The pattern of increasing deviation from carrying capacity would, necessarily, reverse in the model when considering hunting and gathering groups in very low resource density environments since the population size must converge to the carrying capacity as the resource density goes to zero.

The model is based on two ethnographic observations derived from comments elicited by Lorna

Marshall from !Kung san women (Marshall 19xx):

Observation 1: !Kung San women have a desire for as many children as possible

and

Observation 2: !Kung San women are concerned for, and make decisions to promote, the well-being of their family,

where family well-being includes, but is not limited to, ability of a woman to adequately nurse a newborn and to carry infants with her when foraging for resources. Decision making is based on three components of a woman's energy/time allocation to activities on a day-to-day basis: (1) total energy/time, T_f , spent on activities related to procuring and processing food resources obtained through foraging, (2) total energy/time T_p , spent on parenting activities (one of the major components of T_p is the cost of carrying nursing infants) and (3) other activities, T_o . The first is linked to the current population size as the !Kung san are foraging against a fixed resource base and the second relates to the structure of her family (number of children and age of children). The third includes activities whose time/energy costs are largely independent of either population size or family structure. The decision model assumes that as long as her total time/energy allocation $aT_f + bT_p + cT_o < T_{max}$, where a , b and c are weights that equilibrate time allocations among foraging, parenting and other activities according to her relative value for these activities, then in accordance with Observation 1 she will not decide to delay a possible pregnancy, but when T_{max} is exceeded she will delay the next pregnancy in accordance with Observation 2.

The decision rule leads to a stabilized population size where the time dependent pattern for the stabilized population size (e.g., periodic or stochastically constant) depends on the relative magnitude of the parameters a and b . For values of a large relative to b , the equilibrium population will exhibit periodicity (see Figure 2, Read 1998) due to time lags between birth and adulthood, whereas for values of

b large relative to a , the equilibrium population will be constant except for stochastic variation (see Figure 3, Read 1998). In the latter case the equilibrium population size will vary with the magnitude of the parameter b ; that is, with the relative weight that is placed on the value of time spent on parenting activities.

The equilibrium population size, K^* , will also vary in a non-trivial way with the carrying capacity, K . As resource density goes from higher to lower values the magnitude of $K - K^*$ should

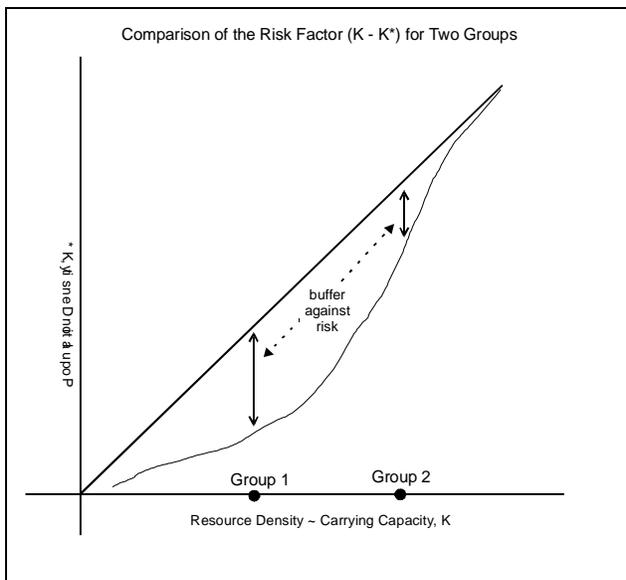


Figure 1

initially increase since foraging time costs increase more rapidly than resource density decrease. As resource density continues to decrease the magnitude of $K - K^*$ will begin to increase as the values of both K and K^* converge to 0 as the resource density converges to 0, hence $K - K^*$ converges to 0 as the resource density converges to 0. The expected relationship between K and K^* is shown in Figure 1. The pattern is matched by data on Australian hunting and gathering groups (see Figure 2).

The pattern for the values of $K - K^*$ implies that hunting and gathering groups in a relatively low resource density region will each have a stabilized population size, hence competition between groups

over resources should be minimized in comparison to hunting and gathering groups in relatively high resource density region. The latter, even if population sizes are stabilized, will be more prone to intergroup competition over resources as stochastic fluctuations in resources may lead to some groups

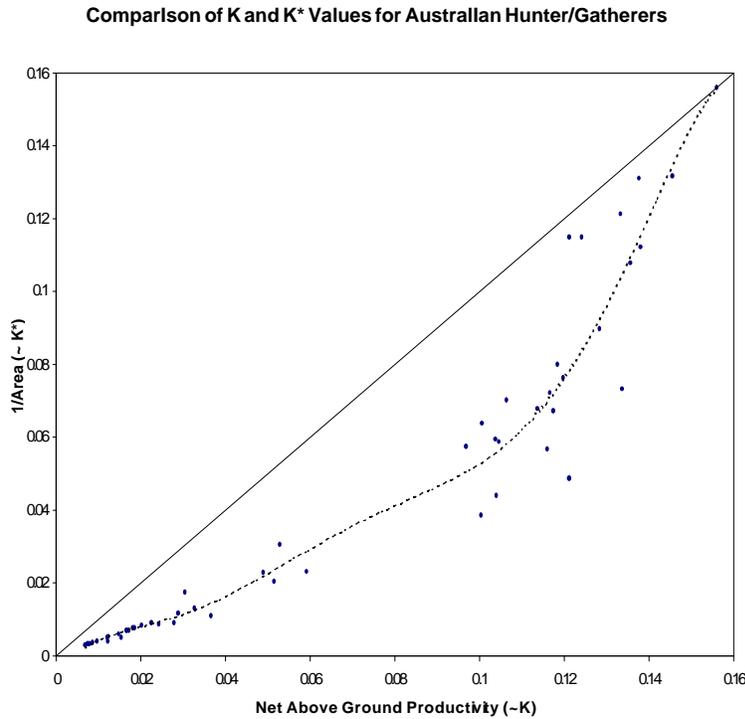


Figure 1

with an insufficient resource base for the population size of the group. Consequently the gradient in the values of $K - K^*$ as the resource density increases should also be a gradient with respect to likelihood of intergroup competition over resources. Next we consider the effect of competition between groups on the demographic patterns of the groups.

Competition Model

We will model competition between groups using the Lotka model of competition but without the assumption that the equilibrium population size of a group is the carrying capacity, K , of the group. Instead, as discussed above, we allow the equilibrium population size to be a value, K^* , where $K^* \neq K$. Competition between two groups is modeled via the following pair of differential equations:

$$dP_1/dt = P_1(a_1 - b_{11}P_1 - b_{12}P_2) \quad (1)$$

$$dP_2/dt = P_2(a_2 - b_{21}P_1 - b_{22}P_2), \quad (2)$$

where $P_i(t)$ is the population size of population P_i at time t , a_i is the intrinsic growth rate for population P_i , and b_{ij} measures the inhibitory effect of population P_j on the growth rate of population P_i , $1 \leq i, j \leq 2$.

For the case of hunting and gathering societies we may view competition between two groups as reflected by the overlap in their respective catchment areas. Further, we will initially assume that the two populations have similar parameters so that $b_{11} = b_{22}$, $b_{12} = b_{21}$ and $a_1 = a_2$. Assuming a uniform distribution of resources over space the magnitude of $b_{12} = b_{21}$ is measured by the degree of overlap of their respective catchment areas (see Figure 3).² Whereas in the full competition model four outcomes

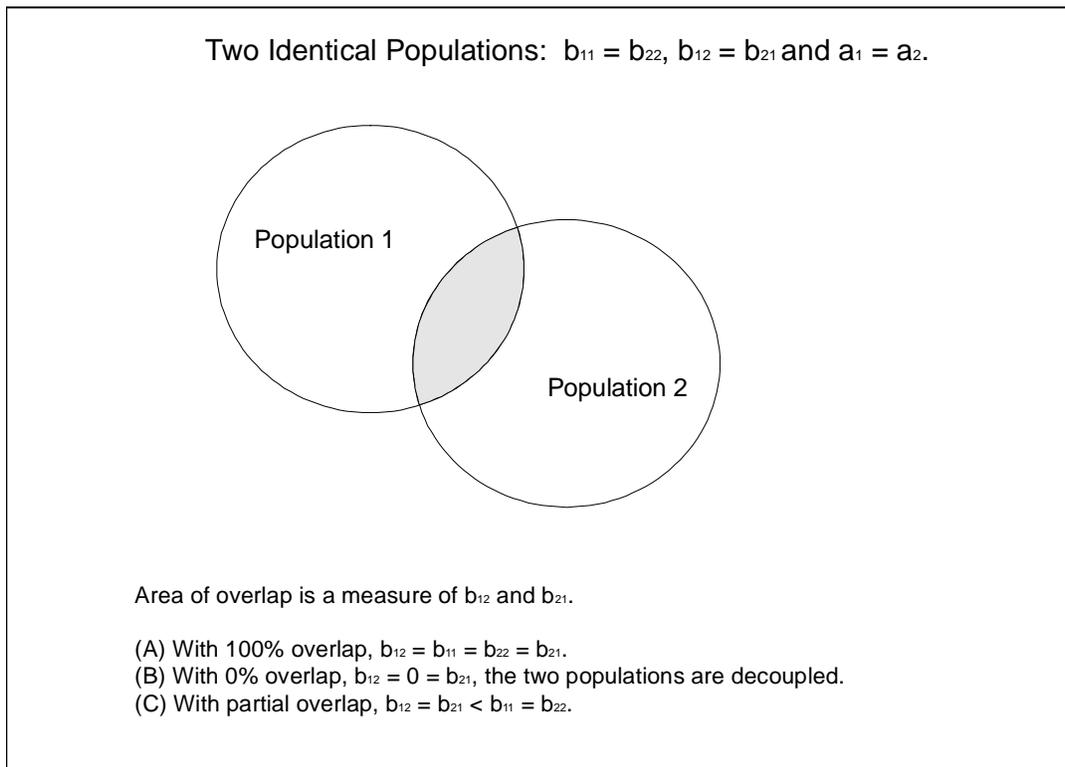


Figure 3

are possible: (1) stable equilibrium, (2) unstable equilibrium, (3) population 1 wins out and (4) population 2 wins out (Pielou 1976; see also Read n.d.), competition between hunting and gathering societies characterized by overlap of catchment areas has a single outcome, namely stable equilibrium (see Figure 4). Although this appears to contradict the widely accepted concept of competitive exclusion, competitive

² Non-uniform distribution of resources does not introduce any qualitative differences as the non-uniform distribution just requires weighting of the overlap by the resource density in the area of overlap in comparison with

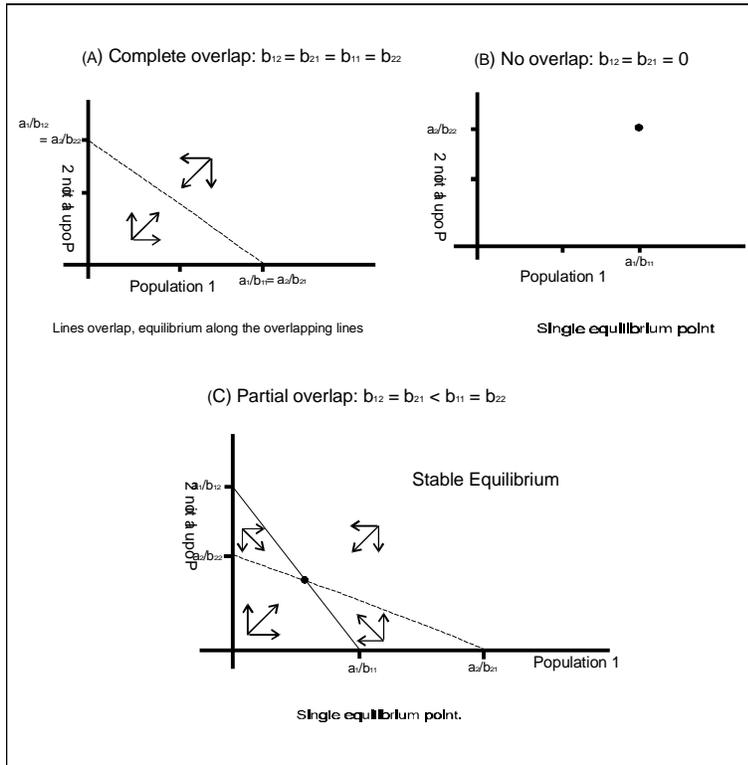


Figure 4

exclusion as a description of observed patterns of competition allows for an additional factor not included in the competition model given by Equations (1) and (2). The competition model assumes parameters are constant, whereas in actuality parameters may change in value. The configuration of complete overlap of catchment areas is stable (see Figure 5A) only so long as neither group changes the value of any of the parameters b_{ij} . If one group should, say, decrease the effect of the other group on itself (as might occur through becoming more territorial) the configuration would change to one that favored the former group and it would now win out in competition with the other group (see Figure 5B), assuming the second group made no change in its parameter values. Only if every change in parameter value by one group were matched by an equal change in parameter value by the other group would the stable configuration be time

the overall density of resources for the overlap region to be a measure of the parameters $b_{12} = b_{21}$.

persistent. The latter is unlikely and so the expected outcome of the competition model, allowing for change in parameter values, is consistent with the observation of competitive exclusion. A response by the second group might be to shift its catchment area away from group 1, thereby shifting the configuration towards the pattern illustrated in Figure 4C.

Shifting from the pattern shown in Figure 4C to one in which the first group wins out (see Figure 5B) would now require a larger change in parameter values by the first group than was the case when there was complete overlap in catchment regions. Whereas a shift from stable equilibrium for complete overlap of catchment regions to one in which one group wins out only requires a small shift in a parameter value, as the degree of overlap decreases an increasingly large change in parameter value is needed to shift from a stable equilibrium to a configuration in which one group wins out in competition. Hence as the degree of overlap decreases the configuration converges on a stable configuration. In extreme cases a stable equilibrium will occur only when the two groups become decoupled, as shown in Figure 4B.

If we couple this result with the results obtained in the previous section regarding decisions about birth spacing we can postulate that hunting and gathering groups would likely form a gradient going from stable to unstable as an overall configuration as resource density goes from low to high values. In an area with low density of resources each group would converge on a stable population size and a pattern of groups more-or-less isolated from one another would be a stable pattern for interaction between groups. The combination of individual groups with a stable population size and between groups in a stable pattern with respect to intergroup competition could potentially remain largely unchanged over long periods of time, hence accounting for very low average growth rates over large regions and long time scales.

In comparison, groups in areas with relatively high density of resources would be individually be more prone to competition induced by temporary shortage of resources due to stochastic fluctuations and the fact of more groups in closer proximity (due to the higher resource density) would increase the

likelihood of intergroup competition. Consequently conditions for aggressive encounters between groups would be much more likely. Whether such encounters would serve as an impetus larger scale social organization would likely depend on the spatial scale for, and temporal variability in, resource abundance.

Spatial Scale and Temporal Variability

According to Liebig's Law of the Minimum, populations are limited in size by the minimum time-dependent density of accessible, critical resources during the life spans of individuals. When the spatial scale of resource variation on a smaller scale than the time-dependent spatial scale of catchment regions, a single group will have a resource base that, through time, includes subareas simultaneously having both a minimum quantity of resources and subareas with larger than the minimum density, hence have a total resource based that is the average of the subregions making up the catchment region for the group. If, however, the spatial scale of time-dependent resource variation is on the same scale as, or a larger spatial scale, then that of the catchment region, the minimum density of accessible, critical resources will occur throughout the group's catchment region. An example of the former are the !Kung as time-dependent spatial variation in resource density was alleviated through movement of individuals from one locale to another according to differences in resource density due to variations in amounts of rainfall. The Netsilik Eskimo are an example of the later as they were dependent on caribou migration in the fall for survival and when the caribou did not migrate as expected starvation was likely (Balikci 19xx) as there were no other resources available in their catchment region.

We now explore the implications of time-dependent, spatial variation in resource density for competition between groups as discussed in the previous section. Call a region with time-dependent spatial variation in resource density on a scale smaller than the spatial scale of a catchment region a small-scale region and one with variation in resource density on a scale comparable to, or larger than, a catchment region a large-scale region. The former will support a population density in proportion to the

average time-dependent resource density and the latter according to the minimum time-dependent resource density. We consider the competition implications of a group, G_1 , with a catchment area overlapping with the catchment area of a group, G_3 , with which it is currently in stable equilibrium (see Figure 5A) coalescing with another group, G_2 .

In a small-scale region, since each group already has a resource base that averages over the time-dependent variation in resource density, the combined catchment areas of the two coalesced groups, G_1 and G_2 , will still have approximately the same averaged resource base after coalescence as it did before coalescence. Consequently while the total population size of the coalesced groups has increased beyond the original population sizes of G_1 and G_2 considered separately, the population density has not. Thus, as discussed in the first section above, population size has increased by expansion of the catchment region

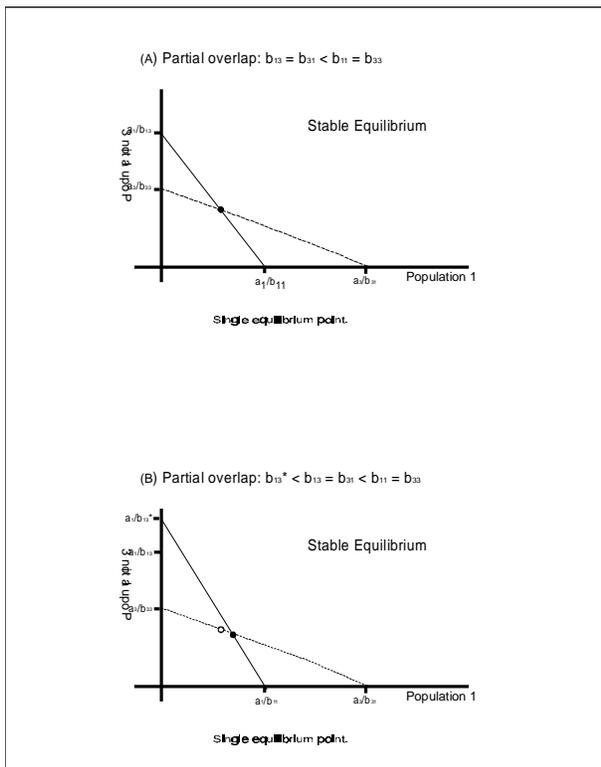


Figure 5

and not by increase in population density.

The effect of the coalescence is to decrease the magnitude of the parameter b_{13} (the inhibiting effect of G_3 on G_1) to a new value $b_{13}^* < b_{13}$ since the catchment area of G_1 has increased through coalescence with G_2 and so the overlap with the catchment area of G_3 is a smaller proportion of the catchment area of G_1 after its coalescence with G_2 . Groups G_1 and G_3 are still in equilibrium and the equilibrium value has shifted slightly in favor of G_1 (see Figure 5B).

While the competitive relationship between groups G_1 and G_3 has been little affected by the coalescence of groups G_1 and G_2 , the new configuration is not stable from the perspective of group fissioning. Lack of increase in population density implies that subgroups are not dependent upon the larger population and the expanded, total catchment region for access to sufficient food resources. Subgroups are in approximately the same relationship to resources (in terms of population density in comparison to resource density) as was true before the expansion of the catchment region. Since the population density has not changed, fissioning of the total population into subpopulations is feasible from the perspective of each fissioned subpopulation having access to approximately the same resource base after fissioning (if that should occur) as before fissioning. Since the organizational requirements of maintaining a larger population in an expanded catchment region have a cost associated with them that must be borne by subpopulations making up the total population, subpopulations such as G_1 and G_2 may find fissioning an attractive option to the cost of maintaining the larger, coalesced population $G_1 + G_2$.

In contrast, in a large-scale region the expansion of the catchment region to a size matching the spatial size scale of resources redefines the region as a small-scale region. Population density over the expanded catchment region can increase since resource density will now be the average resource density over the expanded catchment region. Under this scenario the parameter b_{11} (where $1/b_{11}$ is proportional to the equilibrium population) will decrease to a new value, $b_{11}^* < b_{11}$. The parameter b_{13} will change to a new value, b_{13}^* , as discussed in the previous scenario. If the magnitude in the change of the parameter b_{11}

is sufficient, the relationship between G_1 and G_3 will shift to one in which G_1 wins out in competition with G_3 (see Figure 6B). Consequently coalescence between G_1 and G_2 will also lead to the combined group replacing another smaller group, G_3 . It should be noted that the last result depends upon

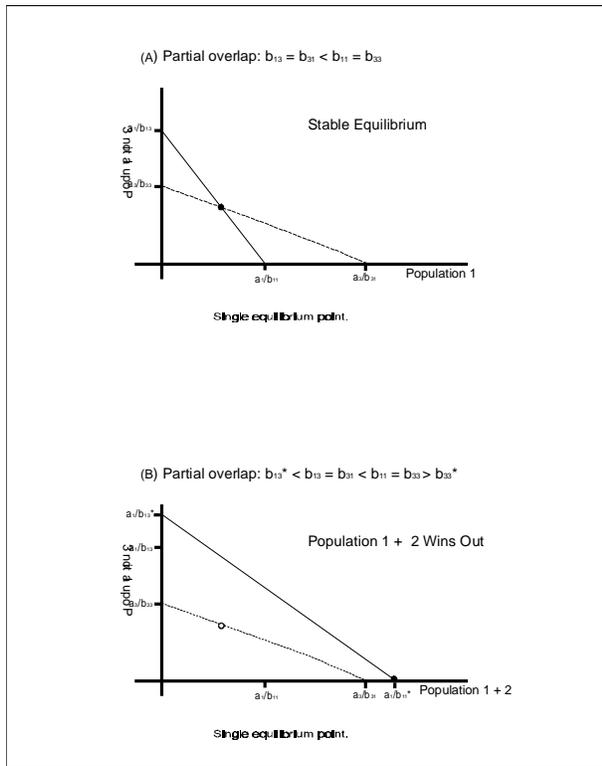


Figure 6

the magnitude of the change in the parameter b_{11} . If $b_{11}^* > b_{31}$ and G_3 and G_1 have the same intrinsic growth rates (i.e., $a_1 = a_3$) then groups G_1 and G_3 will still be in equilibrium, but with an increased population for G_1 and a decreased population for G_3 . Thus b_{31} is a threshold value that demarcates a qualitative shift in the configuration from a stable equilibrium to one population winning out against the other. This result implies that population densities should increase in a step-like manner as we go from one level of organization (e.g., the original configuration with three separate groups G_1 , G_2 and G_3 each about the same size) to a new level of organization (e.g., the coalesced groups G_1 and G_2) where the new level of organization will win out in competition with a group at the previous level of organization. This

implication is consistent with order of magnitude shifts in population size associated with changes in level of organization.

Unlike the previous scenario, subpopulations cannot maintain themselves at their new population density in isolation from the population as a whole. Fissioning now has a major cost in the form of insufficient resources for the subpopulation that splits off. Hence the cost of maintaining a larger scale social organization is counterbalanced by the cost of fissioning in the form of insufficient resources for the subpopulation that splits off.

Conclusion

If we combine these scenarios with previous results about the gradient in the likelihood of a long-term stable equilibrium for a population determined by resource density, we can identify three major configurations.

- (1) Low density resources -- populations in stable equilibrium, little intergroup competition. The configuration may be stable over long periods of time.
- (2) High density resources, small-scale region -- populations likely to exceed carrying capacity due to stochastic effects and/or parenting costs insufficient to stabilize the population, high likelihood of intergroup competition over resources. Individual groups that experience population growth either alone or in alliance with other groups likely to engage in aggressive takeover of smaller groups. Expanded group will fission due to population growth of the group as a whole is due to expansion of the catchment region and not through increase in population density. Expect a cycle of groups expanding, aggressively taking over catchment areas of smaller groups, and then fissioning. The system is unstable from the viewpoint of a single group, but the cyclical pattern is stable.
- (3) High density resources, large-scale region -- populations likely to exceed carrying capacity due to stochastic effects and/or parenting costs insufficient to stabilize the population, high likelihood of

intergroup competition over resources. Individual groups that experience population growth either alone or in alliance with other groups likely to engage in aggressive takeover of smaller groups. Population density will increase, hence fissioning is unlikely. New organizational features are expected to develop as a means to integrate the group with its increased catchment area and increased population density (e.g., a shift from simple hunter/gatherers to complex hunter/gathers, or a shift from complex hunter/gatherers to chieftains). Organizational shift to redistribution of either individuals or resources over the expanded area for local subpopulations to have access to the average resource density over the expanded region. The new configuration of a group with a larger population density will lead to further expansion against groups with lower population density. If the new configuration, with the expanded catchment region, now restructures resources so that the resources form a small-scale region in comparison to the new, expanded catchment region, the scenario will become similar to scenario (2) (e.g., the pattern of chiefly recycling (Flannery 19xx) would be a possible outcome). However, if the region is still a large-scale region in comparison to the new, expanded catchment region, scenario (3) can repeat (e.g., regions in which a succession of organizational changes have taken place going from simple hunter/gathers to states and/or empires).

Scenario (1) implies that little or not intensification of resources will occur through time, hence the long-term impact on the environment is minimal. Scenario (2) is based on catchment area expansion without increase in population density, but may be triggered by populations reaching or exceeding carrying capacity. Consequently some intensification in the use of resources would be expected. Scenario (3) is based on increase in population density, hence entails intensification in the usage of resources.

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