Population and Warfare:

A Test of the Turchin Model in Puebloan Societies

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Abstract. Ecologist Peter Turchin and anthropologist Andrey Korotayev (2006) propose that pre-state societies exhibit a deterministic relationship between population size and incidence of internal warfare or sociopolitical instability. We examine their model with data from Southwest Colorado between A.D. 600 and 1300 and find that it fits well during those periods when this area is a more or less closed system. It fits poorly during the time from about A.D. 1000-1200 when this area is heavily influenced first by the spread of the Chacoan system, and then, by its collapse and the local political reorganization that follows. The model is helpful in isolating periods in which the relationship between violence and population size is not as expected. The mechanisms by which it achieves its success need to be elaborated, a task we begin here.

Ecologist Peter Turchin and anthropologist Andrey Korotayev (2006) propose that pre-state societies exhibit a deterministic relationship between population size and incidence of internal warfare or sociopolitical instability. Important to their thesis is that both population size and incidence of instability are, and must be treated as, dynamic variables: population growth eventually causes an increase in instability, with a lag, whereas increased instability, also with a lag, eventually leads to decreases in population size.

Because of these lags, they argue that a straightforward attempt to crosstabulate current incidence of warfare against current population size, as done by Keeley (1996:117-121, 202) for example, is theoretically indefensible and, practically, likely to lead to spurious results. Indeed, Keeley’s tabulation failed to confirm a positive relationship between population size and instability in a series of societies of various scale,[i] although Ember (1982) demonstrated a positive relationship between population density and likelihood of warfare for land in a sample of 26 societies, and a positive relationship between the frequency of warfare and the severity of food shortages in an almost non-overlapping sample of 15 societies.

In his 2003 book *Historical Dynamics: Why States Rise and Fall*, Turchin has developed the case for fundamentally similar but somewhat more complicated relationships between population and warfare in agrarian states (see also Turchin 2005). His thesis has not been met with unalloyed enthusiasm. Joseph Tainter's review of the book (Tainter 2004) faulted it for reviving a cyclical theory of history, for simplistic analysis, and for naïve social theory. We have seen no discussion of Turchin's model for pre-state societies, but the analysis deserves attention because of the extreme importance of the universal relationships claimed.

We have a more modest motivation here as well. One of the cases that Turchin cites as supporting his model is a sequence of tree-ring dates published by Varien (1999) from a portion of the prehispanic Mesa Verde region. In this paper we will examine the relationship suggested by Turchin and Korotayev with data from a nearby location in the same region, developed in the context of a current NSF Biocomplexity project (Kohler et al. 2006; Ortman et al. 2006; Varien et al. 2006). Because of advantages for which we cannot take most of the credit, this 700-year time series represents one of the most accurate and precise demographic datasets for any prehistoric society in the world.

The Turchin Models for Population Dynamics and Internal Warfare in Non-state Societies

Turchin proposes two related models for the interaction of the variables population density *N* and warfare intensity or frequency *W*. Both assume the same equation for N:

$$\frac{dN}{dt}=rN\left(1-\frac{N}{K}\right)-cWN \qquad (1).$$

Except for the c*WN*, this is the familiar function for the logistic growth of human population to some carrying capacity *K*. Turchin defines *W* here as the annual death rate due to warfare.[ii] The constant c refers to the rate at which the warfare leads to additional death in the population; we added this during fitting and it is not part of Turchin's published model.

The dynamics of the other state variable, warfare *W* might be understood in two slightly different ways. In the first case, Turchin assumes that *W* is directly proportional to the encounter rate among individuals of different groups (for example, in foraging parties). If two groups send out foraging parties at the same rate, then their total number is proportional to *N*, a single party will encounter parties from the other group at a rate also proportional to *N*, and the total number of encounters will thus be proportional to the product of *N* x *N* or N^2.

The second assumption of the first variant of this model is that warfare declines gradually at the exponential rate *b* in the absence of new hostilities. The prominence of revenge as a motive for warfare in non-state societies in general (e.g., Chagnon 1988), and quite possibly in the northern U.S. Southwest (Lekson 2002) suggests the utility of this term here. Since *b* and *W* are multiplied in the final term *bW* (which is the rate at which combatants are willing to give up on warfare as a strategy) high values for warfare intensity will lead to more rapid de-escalation, presumably as a result of warfare fatigue. In sum, then,

$$\frac{dW}{dt}=aN^2-bW \qquad (2).$$

An alternative form for the second equation specifies that the rate at which groups send out war parties is proportional to the product of population density and warfare intensity. This leads to a redefinition of the first term on the right-hand side of (2) as follows:

$$\frac{dW}{dt}=aWN-bW \qquad (3).$$

The two models (as specified by equations 1 and 2, and by equations 1 and 3) have similar dynamic behaviors and both achieve a single equilibrium approached in an oscillatory fashion. In Figure 1 we graph the behavior of the system described by equations 1 and 2 for some arbitrary parameter values, first through time (Figure 1a), and then in the phase plane relating population size to incidence of warfare (Figure 1b). From these we can see that (1) high levels of warfare eventually take a toll on population density, (2) decreasing population density eventually causes warfare to subside, and (3) low levels of warfare eventually result in higher rates of population growth. In the absence of changes in K (carrying capacity), the two variables eventually find a stable equilibrium after exploring the phase space in a counterclockwise spiral of decreasing amplitude. An important additional point is that if contemporaneous values of N and W are sampled from the series in Figure 1a, they will have only a very slight relationship when in fact we can see that increasing incidence of warfare has a deterministic negative impact on the *rate of change* in population growth, and population growth affects the rate of change in warfare positively (Turchin and Korotayev 2005:5).

This model, they suggest, will not apply to external warfare. Among relatively complex societies such warfare may be due to other considerations, notably territorial expansion. Presumably a related assumption is that the area examined is, or can be treated as, a closed system with no important immigration or emigration.

To examine how well this model fits the prehispanic Puebloan case in our well-studied portion of the northern U.S. Southwest, we need estimates of N (population density), W (incidence of warfare), K (carrying capacity), the coefficient of instantaneous population growth r, and the proportionality constants a, b, and c. In the following sections we develop each of these in turn.

The Village Ecodynamics Project

“Village” is an interdisciplinary project to describe and model the dynamics of settlement growth, aggregation, and abandonment in an 1800-km^2 area of Southwest Colorado (Figure 2) between A.D. 600 and 1300. It is a joint undertaking of archaeologists at Washington State University and Crow Canyon Archaeological Center, hydrologists at the Colorado School of Mines and BBL, Inc., computer scientists at Wayne State University and the University of Windsor, and several other researchers and disciplines.

Paleodemography (N)

Scott Ortman, Mark Varien, and others at Crow Canyon Archaeological Center and Washington State University reconstructed the paleodemographic trajectory for our study area based on a massive review of all existing site forms along with some new survey. Using a Bayesian framework, Ortman developed a method for combining chronological and demographic information that efficiently exploits the information available from previous excavations, ceramics on site surfaces, tree-ring dating, architectural characteristics, site locations, and various measures of site size to arrive at estimates of momentary numbers of households in known habitation sites for in each of 14 periods from A.D. 600 to 1300 in which our study area was occupied by farming populations (Ortman et al. 2006). Using three slightly different techniques, Varien et al. (2006) extrapolated from these sample numbers to estimate the total population of households in the study area. To keep the following analyses as simple as possible, as our estimate of N in the following we use the estimates for the population of contemporaneous households provided by their “Method 3,” which they also prefer. Table 1 reports these estimates by period.

Carrying Capacity (K)

Estimates of carrying capacity for human populations are notoriously difficult to make because humans are so flexible in their behavior. One well-studied class of flexibility is economic (or subsistence) intensification; in the case at hand we are particularly interested in agricultural intensification, which we define as either working longer or implementing new techniques to derive the same (or more) per capita production from domesticates under population increase or environmentally imposed restrictions on production. Similar processes are described by numerous authors, beginning in anthropology notably with Boserup (1965), but in fact finding intellectual parentage with the British political economist David Ricardo, who recognized that increasing input into production generally succeeds in increasing yield, but only at a decreasing rate. In the case analyzed by Boserup, agricultural intensification provoked by population increase involved both shortening the fallow cycle and introducing the plow; the resultant intensive agricultural system required more hours per person per week. The initial Neolithic domestication of plants and animals is frequently considered an example of subsistence intensification (e.g., Wright 1994). Intensification can involve switching to less desirable animal or plant species if more desirable and easier-to-exploit species become depleted.

Even ignoring the complexities of intensification, it is not clear how to estimate human carrying capacity for a given environment. Five main difficulties stand out. First, humans are flexible in their use of space, and unless prevented by considerations of ownership or distance tend to switch patches to maximize return to effort as returns from patches currently exploited decrease to the point where equal or better returns on effort are available elsewhere. Farmers, however, are more territorial than implied by this construction, and usually end up distributed across space according to the "ideal despotic distribution" (Sutherland 1996) in which late arrivals are forced into less-desirable patches. This is hard to deal with outside of a dynamic spatial model.

Second, humans need to meet their subsistence requirements within the context of also meeting other needs (in our model they consider water, fuels, protein from hunting, and carbohydrates from agriculture). These constraints may put some areas outside of practical limits for exploitation. Third, all the calories or protein on a landscape are not available to people, whether because of food taboos or because the cost of exploitation is greater than the return, as for low-density or hard-to-process foods. Fourth, especially in the part of the world we are discussing, inter-annual climatic variability in temperature and precipitation amounts and timing can have significant effects on production, but the magnitude of these effects is hard to estimate. Finally, beyond the consequences of territoriality discussed above, human use changes the environment in complicated ways. Some usage (for example, harvest of woods for fuel and construction and deer hunting) certainly degrades the environment for those purposes at least temporarily, but the cleared land and reduction in agricultural pests might boost production for agriculture.

The agent-based simulations we are developing in the Village project provide at least partial solutions for these problems. (Kohler et al. [2005] review in a non-technical way how agent-based modeling is assisting our interpretations of Southwestern prehistory.) It is beyond the scope of this paper to explain in detail how the model works (see Cowan et al. 2006; Johnson et al. 2005; Kohler et al. 2006). Most relevant here is that we track caloric production and consumption carefully in the model, "charging" expenses for hunting, gathering of fuel and water, agricultural fieldwork, and basic metabolism, against the production and storage achieved by each household. Production of maize is affected directly by climatic variability, as is growth of woody biomass for fuels; we model densities of the three most important prey species (cottontail, jackrabbit, and mule deer) as a function of the growth of the species they graze or browse (and this vegetation itself is also affected by climatic variability) and the level of predation. Household efforts to acquire adequate protein and calories may be assisted by processes of generalized exchange (among kin) and balanced reciprocity (among non-kin neighbors).

Base human mortality and fertility parameters are taken from Weiss' 27.5-55.0 model table (1979:156) and in the simulations used here to develop estimates of K, favorable caloric and protein balances increment natality probabilities, and decrement mortality rates, by 10 percent relative to that table. On the other hand, an unfavorable protein or caloric balance returns those rates to those in the life table. Inadequate caloric consumption that cannot be immediately offset by new production, existing storage, or exchange, causes households to try to move to better areas, but households have no way to exit the study area. When relocating, households choose from among the cells that are favorable for agriculture and are under-occupied, that cell from which it will be least calorically expensive to satisfy their water, fuel, and hunting needs. Households may perish from lack of calories if relocation or buffering techniques are unsuccessful, but in the simulations shown here, inadequate protein consumption by itself never kills a household (though it may increase the likelihood that its individual members may perish).

As a result, the populations achieved by our model households can be regarded as rough estimates of carrying capacity for populations of maize farmers/deer-rabbit-hare hunters under the parameters in each particular simulation. Our households are capable of limited intensification: they can work harder (for example, by going further to hunt or gather fuels as the need arises, or by tending more plots of maize if they have enough workers) and they can switch prey species, among the three that we model, in response to changing local availability.

One important thing that they cannot do in the current simulations, though, is to domesticate and raise turkey. Yet we know that domesticated turkey becomes an increasingly important part of the diet in some sites in the northern Southwest in the A.D. 1000s, and then continues to increase in importance through time in most areas, including our own, replacing declining artiodactyls (chiefly mule deer) (Driver 2002).

Our current simulations show that when human population numbers reach those achieved in our area in the mid-A.D. 800s they significantly deplete deer (Cowan et al. 2006). In the absence of turkey domestication, or greatly increased long-distance hunting of deer, or other accommodations, the inhabitants of this landscape may well be protein-limited at the considerably larger population sizes they achieved in the 1100s and 1200s (Table 1). Decreasing protein on the landscape (and increasing energy required to hunt for it) contribute to a general decline in agent populations in most simulations. Although agent populations could, most likely, be higher in later periods were our agents able to raise and eat turkey, it is impossible for us to estimate how much higher without completing a detailed analysis of the costs and benefits at the level of the household, and simulating the result.

For the purposes of this paper we take most estimates of *K* from agent-based simulations in which various parameter values are set to maximize the number of households on the landscape (while not exceeding what we view as plausible values for those parameters). Even so, for periods 15-18 our population estimates from the archaeological record are higher than those achieved by our agents, probably due to the intensifications that we don't model. In those cases we use the highest actual population estimate as the *K*, given abundant evidence (rehearsed in Kohler 2000) that these populations were under considerable stress at those levels. The other exception to this rule is that we assign *K* the highest simulated agent counts for the first 5 periods (periods 6-10), since the agent numbers early in the sequence are limited by the fact that we begin our simulations with 200 immigrant households in year 600.

Incidence of Internal Warfare (W)

In the absence of a written record, archaeologists infer warfare and conflict indirectly from a variety of evidence, including site location and size, frequency of defensive features such as walls, artifacts with potential aggressive or defensive function, and skeletal trauma. Here we develop only one of these lines of evidence, skeletal trauma. To make the database as large as possible, we extended the collection of these data beyond the boundaries of the study area to include the area just south of Ute Mountain, all of Mesa Verde National Park and on south to the Colorado/New Mexico border, and into southeasternmost Utah, as far south as the San Juan River. We believe that cultural processes were similar enough across this somewhat larger region that this should not distort our findings.

The kinds of trauma used to identify violence consisted of fractures (healed or not) to the ulna and/or radius, which most likely resulted from a blow to the arm raised in defense. We also considered perimortem and antemortem cranial fractures as warfare-related trauma. However, not all cranial fractures are likely to result from such circumstances. Accidental falls are the most common source of cranial trauma among children and the elderly (Hussain et al. 1994), and facial fractures to the nasal bone or occipital region are more likely to occur during spontaneous interpersonal violence (Walker 1997). Thus, such fractures were not included in this analysis. Finally, we included cultural modification and disarticulation of human remains (as might result from cannibalism) such as the Cowboy Wash and Aztec Wash sites, Mancos 5MTUMR-2346, and Castle Rock Pueblo. We did not count other types of fractures to other parts of the body (the most common being rib fractures) because we could not confidently determine that these were not accidental in origin.

Sarah Cole collected these data from the literature and not via direct examination of the materials (some of which has been reburied). The kinds of sources used largely consisted of site reports and “gray” literature. She could usually determine the age and sex from these reports; they also usually included a detailed description of any skeletal trauma and pathological conditions, and the position and location of interment. Thus, she was able to decide which kinds of trauma to attribute to violence—and her determination did not necessarily agree with that of the original author. She used Turner and Turner’s (1999) *Man Corn* as a secondary source when considering the cultural modification and disarticulation of human remains. Large-scale excavation projects such as the Dolores Archaeological Program, the Towaoc Canal (Reach III), the Ute Mountain Piedmont project, and the Sand Canyon Archaeological Project provided most of the data.

Table 2 shows the n of individuals for each period, the number of those with skeletal trauma suggestive of warfare, and the resultant estimate of W (slightly refined using Bayesian techniques as explained in notes to the table).

Turchin and Korotayev considered W to be warfare intensity or frequency, so the death rate to warfare cWN (in [1]) is assumed to be directly proportional to its intensity. In the same way, we consider our estimate of W to measure intensity of conflict, and we therefore must make the same assumption, that this intensity will be directly proportional to a death rate from warfare.

Coefficients r, a, b, *and* c

The instantaneous coefficient of population growth (Odum and Barrett 2005:239) is the growth rate achievable in the absence of limiting factors. We calculate a minimum estimate for r by assuming that the N of households in our study area by A.D. 860 (1030, Table 1) could have grown from about 304 colonizing households present by ca. A.D. 663, leading to an estimate for r of .006 (annual). In our attempts to fit Turchin’s model to our data we used values ranging from 0.007 to 0.014 for r in recognition that the maximum attainable r for human populations is higher than .006, perhaps as high as .02 (Ehrlich and Ehrlich 1970). We also add fluxes to the model at various points where we identify growth in excess of that achievable through in-place processes, or emigration (see Table 1 and Varien et al. 2006). We estimate best-fit values for the proportionality constants *a*, *b,* and *c* in the context of fitting the models, below.

Evaluating the Model

There are several ways to determine how well Turchin and Korotayev's models fit these data from Southwest Colorado. First, we can inspect the time series of *N* and *W* (Figure 3) to see if they bear any resemblance to the relationships claimed in the models (Figure 1a). These two series are graphed to a common scale in Figure 4, after smoothing using 40-year running means, following Turchin's procedure. Discounting the slightly higher-than-expected *W* in our earliest period, we see that in the first cycle of this historical sequence, *N* peaks before *W*, just as expected, and then falls in the context of high *W*, as expected, and then *W* falls too, just as *N* begins to rise again. This is all as it should be. But between about A.D. 1000 and 1200, increases in *W* lead increases in *N*, very much contrary to the model.

Another way to evaluate the models is to inspect the phase plot of *N* against *W* (once again after smoothing), keeping in mind the shape proposed by the model (Figure 1b). The plot generated from our data (Figure 4) shows the expected relationships from the 600s through the mid-900s, with mild reversals not far outside of the expected pattern through 1040. There is a strong reversal of the expected pattern for the next three data points (1080-1160) with a return to the expected pattern in the 1200s, albeit in a different region of the phase space.

A third way to evaluate the models is to realize that, if the lag suggested by the models in the effect of increasing *N* on *W* in the actual record is about 40 years in length, then we ought to be able to see a strong positive relationship between *N*, lagged 40 years, and *W*. Here, once again, we replace the observed values for *N* and *W* with 40-year running means for both, sampled at 40-year intervals. Figure 5 shows that there is indeed a positive relationship, but not a significant one, at least when all periods are included. The data points for the late 1000s and mid-1100s are particularly strong outliers. Once again, the 1200s appear to represent a consistent regime, but one that is very different from the regime in place from the 600s-900s.

Finally, and most rigorously, we can fit values of *a*, *b*, and *c* for this model, using the time series of our empirically known *N* and *W* (Table 1), and then assess the goodness-of-fit obtained using the parameters so derived. Here we consider the model proposed by equations [1 and 3] only, since initial exploration showed that we obtained better fits with this model than the one in equations [1 and 2]. We start by assuming that initially, at year A.D. 600, the population size is N_0 = 152 households, and the intensity of warfare is, as given in Table 2, W_0 = 0.0519. With this assumption and known values for *r* and *K*, we estimate the remaining parameters *a*, *b*, and *c* using the weighted least square regression. Let us define the functional

$$J(a,b,c) = \sum_{i=1}^{n} \omega_N (\log(N_i) - \log(N_{data_i}))^2 + \sum_{i=1}^{n} \omega_W (W_i - W_{data_i})^2,$$

where *n* represents the number of data points (in our case the 17 time periods) indexed by *i*, N_i and W_i are the population size and war intensity at times t_i predicted by the solution of equations [1 and 3], $Ndata_i$ and $Wdata_i$ represent the data values for the populations and for warfare at times t_i, and ω_N , ω_W , are additional weights that insure that we give equal influence to both the population N and the war intensity W observations. They are given by

$$\omega_N = \frac{1}{\sigma_N^2} = \frac{1}{\frac{\sum_{i=1}^{n}(N_{data_i} - \overline{N_{data}})^2}{n-1}},$$

and

$$\omega_W = \frac{1}{\sigma_W^2} = \frac{1}{\frac{\sum_{i=1}^{n}(W_{data_i} - \overline{W_{data}})^2}{n-1}},$$

where $\overline{N_{data}}, \overline{W_{data}}$ are the average values of the measured populations N and W. Differences in logarithms, rather than differences in numbers was used to accommodate the changes seen in population size (large population sizes from A.D. 1080-1280, versus small populations in the A.D. 640-880 period). We give equal weight to the warfare intensity data and to the population data in the minimization algorithm. The optimization analysis was performed using the Nelder-Mead nonlinear iterative routine in Matlab (fminsearch) and the resultant values for *a*, *b*, and c are shown in the captions of Figure 7.

Of interest here is that the fitted values for *W* far exceed those observed in the 1200s, and even exceed the possible values for this parameter, which are from 0 to 1. The model cannot accommodate both the very high W and moderately high N values seen in the 1000s and 1100s with the very high *N* and moderate or low *W* values experienced in the 1200s. This emphasizes both of these departures as things that need to be explained.

Discussion

We find relatively strong support for the version of the Turchin-Korotayev model represented by equations [1 and 3] during the first population cycle, when exogenous factors appear to have been weak. The rise and fall of population and frequency of warfare in this first cycle do not require any explanation beyond that provided by the model, although we must still elucidate the mechanisms underlying this relationship. The apparent failures of the model during the second population cycle may be due to the relative strength of exogenous factors in our area, discussed below.

Why are population size and warfare linked in this manner proposed by the model, and seen in our area from A.D. 600 through the 900s? Explaining why increased warfare might eventually cause decline in population is relatively easy. First of all, there are of course some direct deaths due to warfare that affect present and future population size. Second, Divale and Harris (1976) suggested that protracted warfare may lead to female infanticide, as parents attempt to raise more boys to become warriors. Such female infanticide, if present, can perhaps be identified in young adult sex ratios if we look carefully, and would, of course, depress current and future population size. Third, to the extent that warfare stimulates aggregation, and aggregation promotes disease, warfare may depress populations through a back channel. Fourth, by comparing our agent distributions from our simulations, which are efficient in their use of space, and the actual household distributions from the archaeological record, we have noted that people are very inefficiently distributed at time of maximum population and aggregation. It seems reasonable to infer that warfare, to the extent that it is linked to these conditions, causes inefficient population distributions, perhaps even to the extent of subverting energies otherwise invested in reproduction. Finally, we know from much sad contemporary experience that people will leave war-torn areas if they are able to do so. Therefore, population decline in periods of great violence may be due in part to flight from danger to safety.

The opposite of all these conditions tends to explain why populations increase in the absence of warfare.

It may be slightly more difficult to detail the mechanisms by which more people on a landscape eventually cause more warfare. Obviously, absent innovations to increase production (either technical in nature, or sociopolitical, having to do with the organization of the means of production or distribution) more people will lead to more conflicts over (fixed) resources. But more subtle mechanisms may also be at work. More people increase the relative importance of the social milieu, and warfare is a time-honored means for achieving social status and wealth, either through reputation for bravery in battle, or through land or chattel acquired in victory.

Implications for Local Culture History

This analysis suggests some novel explanations for various aspects of the prehistory of this area. For example,

- The onset of aggregation in this area in the Pueblo I period in the mid-A.D. 800s takes place in a climate of little violence, which weakens warfare as a general explanation for early aggregation in the Southwest;
- The depopulation of this area at the end of the Pueblo I period may be as closely related to a rising incidence of warfare, and inhabitants' desires to leave those conditions behind, as it was to unfavorable climatic conditions;
- The first increases in violence that are unanticipated by the model occur in the late 900s and early 1000s, well before the earliest structures in our area that look "Chacoan" (Lipe and Varien 1999:272). This anomaly pointed up by the model suggests that we need to look for external influences before they become obvious as Chacoan-style architecture. Perhaps sites like the Dobbins stockade (Kuckelman 1988), dating to the early 1000s, represent resistance—ultimately unsuccessful—to Chacoan expansion. The ca. 1080s immigration (spanning the period from 1060-1100) represents the first successful Chacoan intrusion into this area—quite possibly achieved via violence given contemporaneous values for *W*—followed by a second wave of consolidation in the early 1100s. The slight decrease in violence around 1100, if real, represents as close to a "Pax Chacoensis" as our area ever experiences.
- The collapse of the Chacoan system in the mid-1100s brought violence to unprecedented levels in our area, perhaps in the form of score settling as old (but apparently resented) power structures fell apart.
- A major surprise is the sudden re-appearance of much less violent conditions in the early 1200s, returning our area to a regime in which population and warfare were again related as proposed by the model, except that warfare was much lower than would be anticipated by the model, given its relationship to population in the first population cycle.

It has been a puzzle to explain the history of aggregation in our area. It is clearly connected with population size, but people continued to live in aggregated settings ca. A.D. 900 and in the late 1200s, even as populations were decreasing. The lagged effect of population size on prevalence of violence assumed by the model and visible in our data suggests that aggregation for protection would continue to be important after population peaks. On the other hand, initial aggregation (for example, in the late 700s and mid 800s, and perhaps again in the mid-1200s) appears to take place in an atmosphere in which warfare-related trauma was unusual. We hypothesize that initial phases of aggregation were connected with economic and political factors scaling with population size, whereas retention in aggregates at and after population peaks was due, at least in part, to considerations of safety.

Implications for Evolutionary Analysis

The Turchin model posits a close association between warfare and population size, and is thus inescapably relevant to evolutionary concerns with population size effects on cultural transmission (e.g., Henrich 2004; Shennan 2000).

More fundamentally, warfare can be an important mechanism for cultural group extinction. If the cycles identified by Turchin take place repetitively over evolutionary time scales in patchy environments among competing groups with differential group success, and if these processes are typically linked with migration to new patches by some groups as they are in the record discussed here, we have the key ingredients required to make cultural group selection a strong force in human cultural evolution. Such conditions could strongly promote the evolution of altruistic behaviors such as bravery in warfare that may be deleterious to the individual but benefit the group and contribute to its success relative to its competitors. Of course, the prosocial but individually costly behaviors, norms, and values that can become part of cultural practice via this mechanism need not be related to warfare (Boyd and Richerson 1985).

Conclusions

Like any model that works reasonably well, the Turchin model has two main strengths. First, for those regions of the problem where it fits, it tells us that no additional causal processes are needed to explain the phenomena of interest, so long as we can identify satisfactory mechanisms for the processes invoked, and can with reasonable certainty eliminate equifinality (the possibility that *other* models might explain the phenomena equally well). We also learn from those circumstances where the model fails, since those regions of the problem require additional or different causal processes.

For the cultural-historical case discussed here, the relative success of the model suggests that low incidence of warfare enhances population growth, but that high population sizes tend to entrain violence, and once violence becomes prevalent, it tends to decay slowly because of revenge effects. Warfare may be a significant factor in the cessation of local population growth in the mid-late 800s, and its prevalence may contribute to declines in population, including emigration, around 900 and in the late 1200s. Southwestern archaeologists have typically thought about warfare as a dependent variable (what causes it?), when they have thought about it at all; this analysis makes clear that it has independent effects as well.

On the other hand, we also see that these tendencies can be overridden (climate permitting) by strong sociopolitical factors that can result in population growth even amid violence, as experienced from the late 900s through the mid-1100s in the area discussed here. The fact that our model does not explain the relationship between population and warfare during this period, and that the Ember and Ember model (1992) used by Lekson (2002) to explain warfare in the Southwest fails locally for the early 1200s demonstrates that, as Keeley suggested, “no complex phenomenon [such as war] can have a single cause” (1996:17). Despite this, the Turchin model identifies a simple set of relationships that has explanatory power when the conditions required by the model are met, as we have demonstrated.

On the somewhat less positive side, we suspect that the situations where this model works well may be few and temporary; at least in the post-Neolithic world, we cannot often find places and times where exogenous factors are of little import for long periods. Specifically, as in the case reviewed here, the relationships within the model are subject to being upset, or at least complicated, by the increases in geographic scope and sociopolitical scale typical of post-Pleistocene societies when viewed over long enough periods. Perhaps the conditions required by the model would be more frequent in the pre-Neolithic world.

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Tables

Table 1. Summary data for chronology, population, and carrying capacity (*K*). Study area is colonized by farmers shortly before A.D. 600, and is completely depopulated by shortly after A.D. 1280. Periods 1-5 are reserved for non-farming groups not discussed here.

Village Modeling Period	Begin (A.D.)	End (A.D.)	Mid-point (A.D.)	Traditional Pecos Period	Total Momentary Households[a]	Flux	Carrying Capacity Estimate (*K*)
—	600			BMIII	0		—
6	600	725	663	BMIII	304		1580
7	725	800	763	PI	326		1580
8	800	840	820	PI	836	180	1580
9	840	880	860	PI	1030		1580
10	880	920	900	PII	370	-477	1580
11	920	980	950	PII	289		1515
12	980	1020	1000	PII	653	92	1345
13	1020	1060	1040	PII	671		1430
14	1060	1100	1080	PII	1385	110	1635
15	1100	1140	1120	PII	1940		3234
16	1140	1180	1160	PIII	2077		3234
17	1180	1225	1203	PIII	2326		3234
18	1225	1260	1243	PIII	3234		3234
19	1260	1280	1270	PIII	1770	-1430	1770
—		1300			0		1400

[a] Using Varien et al. (2006) Method 3.

Table 2. Instability index *W*: Raw data and calculation of index.

Period	Midpoint	x	n	x/n	a	b	μ''	Raw instability index	W (final version)
6	663	2	11	0.1818	-0.12119	-0.4058	0.1794	0.1038	0.1038
7	763	1	10	0.1000	-0.12119	-0.4058	0.0928	-0.0162	0.0000
8	820	0	6	0.0000	-0.12119	-0.4058	-0.0222	-0.3231	0.0000
9	860	3	55	0.0545	-0.12119	-0.4058	0.0529	0.0358	0.0358
10	900	6	18	0.3333	-0.12119	-0.4058	0.3365	0.3154	0.3154
11	950	0	13	0.0000	-0.12119	-0.4058	-0.0097	-0.1071	0.0000
12	1000	5	20	0.2500	-0.12119	-0.4058	0.2506	0.2220	0.2220
13	1040	17	70	0.2429	-0.12119	-0.4058	0.2430	0.2353	0.2353
14	1080	24	45	0.5333	-0.12119	-0.4058	0.5370	0.5387	0.5387
15	1120	44	108	0.4074	-0.12119	-0.4058	0.4083	0.4065	0.4065
16	1160	30	35	0.8571	-0.12119	-0.4058	0.8668	0.8894	0.8894
17	1203	4	34	0.1176	-0.12119	-0.4058	0.1159	0.0915	0.0915
18	1243	6	75	0.0800	-0.12119	-0.4058	0.0789	0.0673	0.0673
19	1270	51	121	0.4215	-0.12119	-0.4058	0.4223	0.4210	0.4210

Note: Bayes' Theorem can be used to generate an improved estimate of π from the observed sample proportion *p* (where *p* = *x/n*; *x* is the count of skeletal remains with warfare-related trauma, and *n* is the number of individuals). Measures of central tendency and dispersion can be used to generate both the prior (observed) and posterior (improved) estimates of π. The mean μ' and the variance σ'^2 of the *prior* distribution (according to the proportion for each site in the dataset rather than each period) are defined by the following formulas:

$$\mu' = \frac{a}{a+b} \qquad \sigma'^2 = \frac{\mu'(1-\mu')}{a+b+1} \qquad \text{(1a, b)}$$

Thus, the values for constants *a* and *b* can be defined and are also crucial in deriving a *posterior* distribution for π.

$$a = \mu'\left[\frac{\mu'(1-\mu')}{\sigma'^2} - 1\right] \qquad b = (1-\mu')\left[\frac{\mu'(1-\mu')}{\sigma'^2} - 1\right] \qquad \text{(2a, b)}$$

Calculating the mean μ'' and the variance σ''^2 of the *posterior* distribution for π can be derived by using the constants *a* and *b* and the *n* of individuals and those with warfare-related skeletal trauma (*x*) according to each period.

$$\mu'' = \frac{x+a}{n+a+b} \qquad \sigma''^2 = \frac{\mu''(1-\mu'')}{n+a+b+1} \qquad \text{(3a, b)}$$

The purpose of using μ'' rather than *p* is to reduce the amount of variability in small sample sizes. The peak, or the most probable value, of the *posterior* distribution (i.e., the raw instability index) is calculated using the following formula:

$$f(\pi)_{\max} = \frac{(x+a-1)\cdot(n+b+a)}{(x+a)\cdot(n+b+a-2)}\cdot\mu'' \tag{4}$$

See Robertson (1999) for a more detailed discussion of this method.

Figures

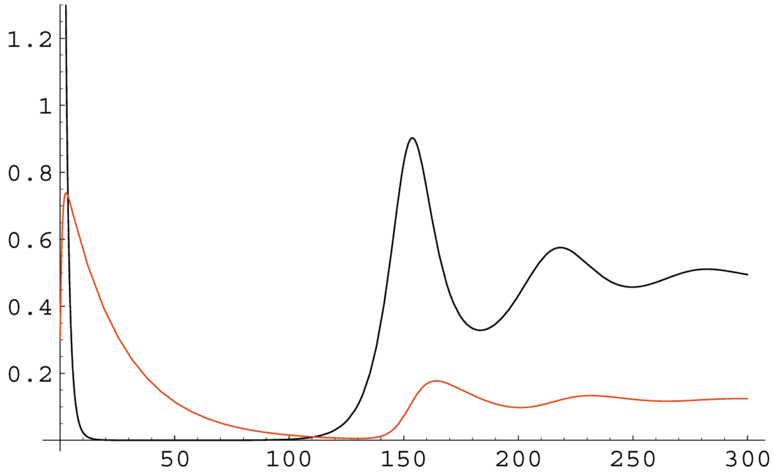

Figure 1a. The relationship of N (black line) and W (red line) through time for the system of equations (1) and (2). Parameter values: r = .13, a = .02, b = .04, K = 8; initial conditions N = 5, W = .3.

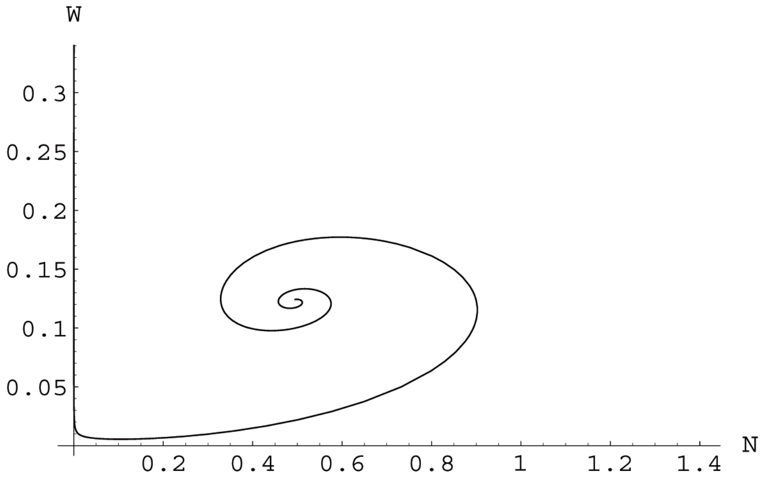

Figure 1b. Relationship of N and W; time begins at the periphery of the spiral and moves towards the equilibrium point at the center. Parameters and initial conditions as in Figure 1a.

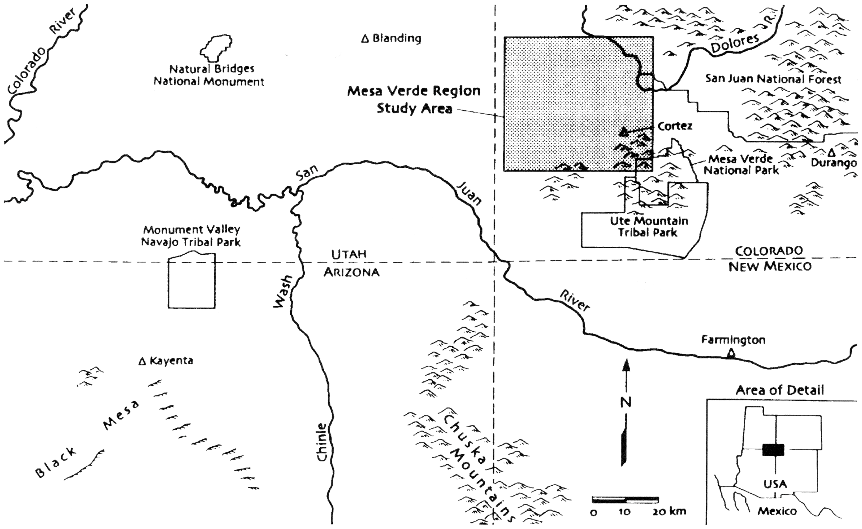

Figure 2. Location of the Village Ecodynamics project area in Southwest Colorado, USA.

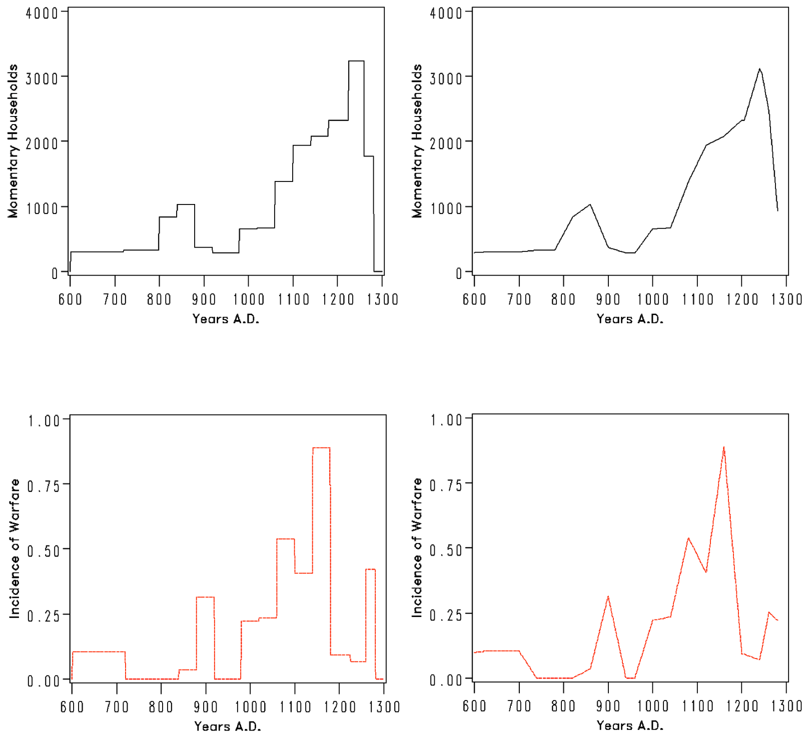

Figure 3. Unsmoothed (left column) and smoothed (right column) versions of *N* and *W*.

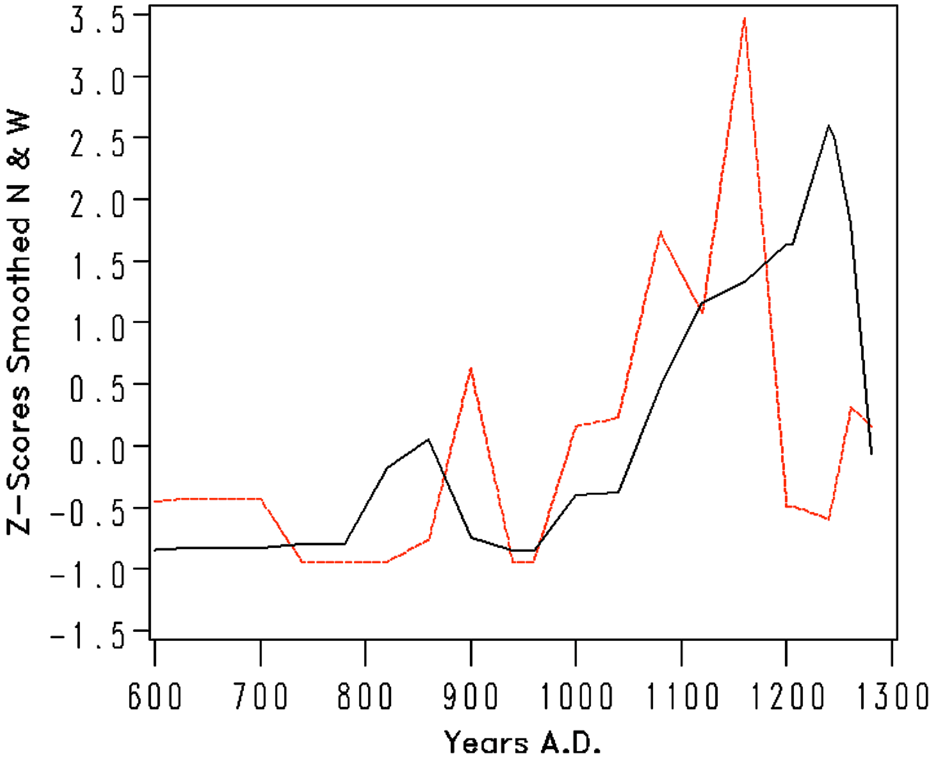

Figure 4. Graph of standardized, smoothed population (*N*, black) superimposed on smoothed warfare frequency (*W*, red).

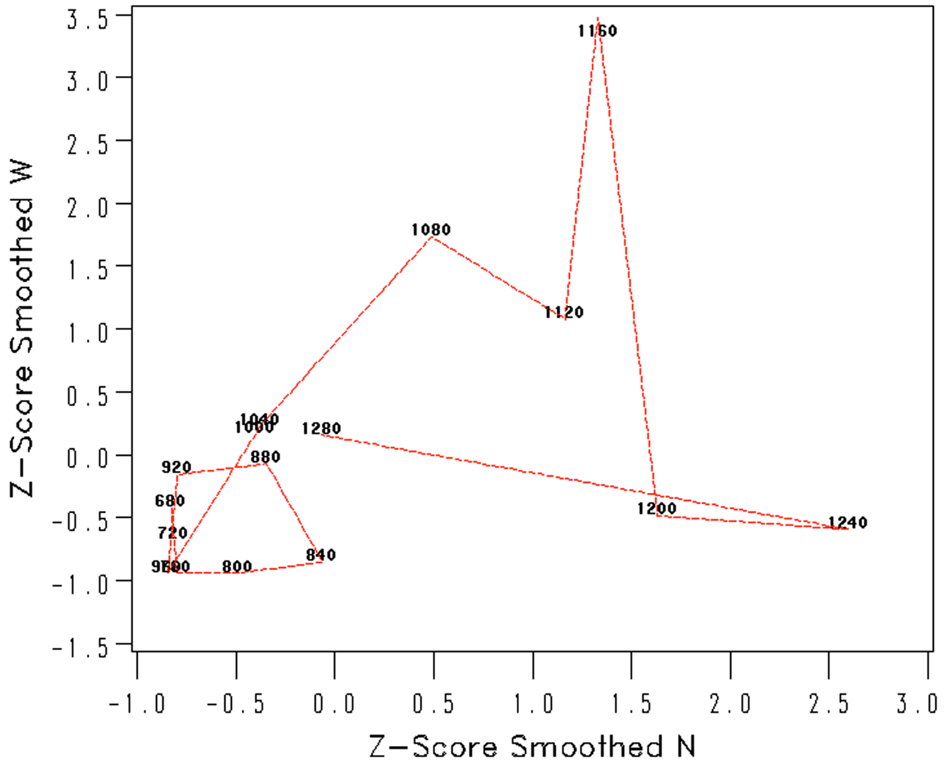

Figure 5. Phase plot of *N* and *W* (after smoothing) using data from Southwest Colorado.

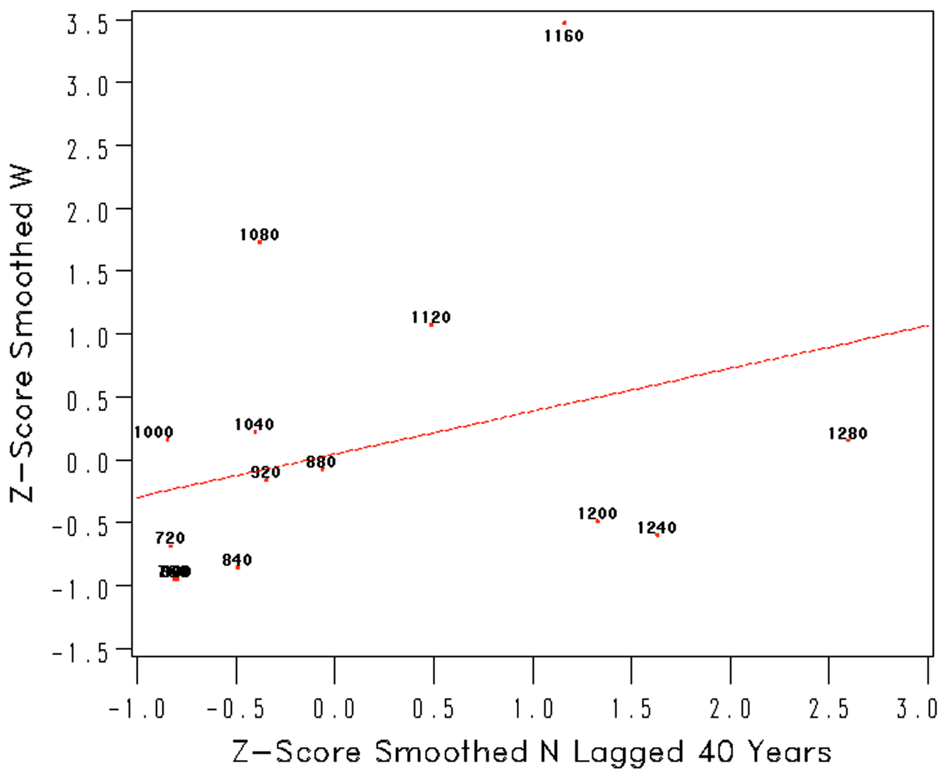

Figure 6. Regression of *W*[t] on *N*[t-1]: $r^2 = .09$, $p > F = 0.27$.

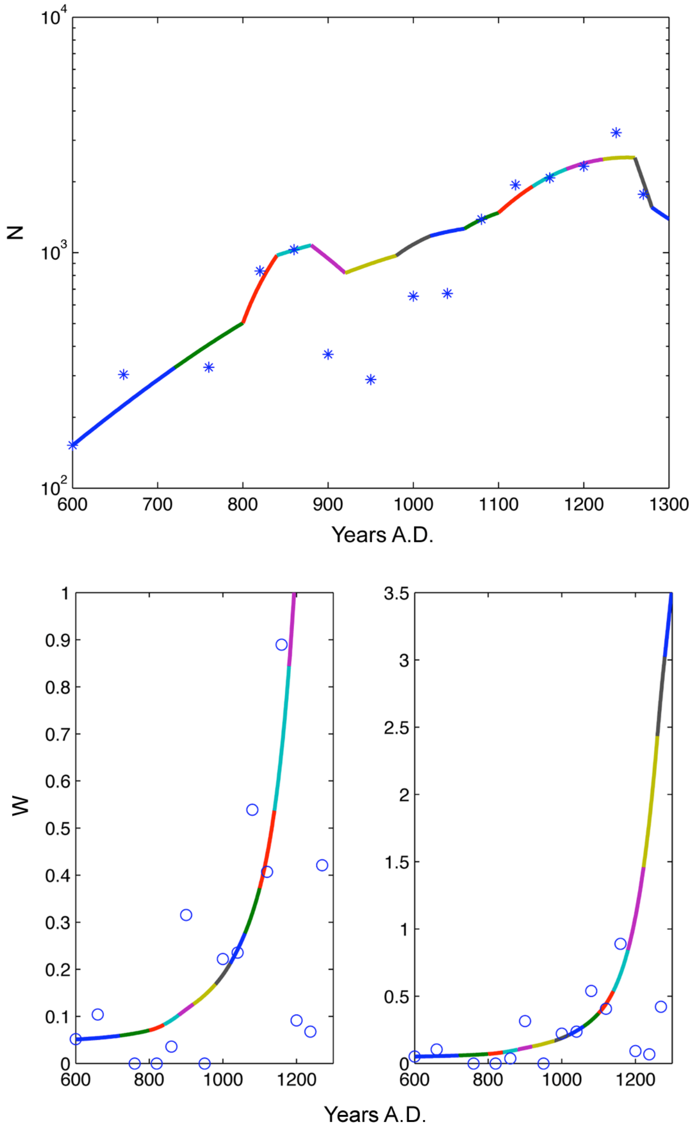

Figure 7. (top) *N* (note log scale) from data (blue asterisks) against best-fit model for equations 1 and 3 (colored line). (bottom) *W* from data (blue circles) against best-fit model for equations 1 and 3 (colored lines). (below) On the left we graph W in its possible range, from 0 – 1.0. On the right we graph the actual estimated values, which exceed 1 in the 1200s. Using *r* between .007 and 0.014, best-fit values for the unknown parameters *a*, *b*, and *c* are *a*= 0.00011, *b*=0.003, *c*=0.006, and the goodness-of-fit as measured by the residual ($\text{ESS}_{\log(N)}$ + ESS_{W}) is 2.98.

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[i] Keeley cannot accurately correct for varying carrying capacities in these estimates in such a way

that he could convert equivalent population densities into possibly very different “population

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pressures." In those limited cases where such corrections were possible (1996:119), he considers the data to show either a complex, or weak, relationship between population "pressure" and intensity of conflict.

[ii] This equation by itself can be considered a model for harvesting; in that case the WN term represents how many people can be "harvested" by war. This model has the interesting property, illustrated by Mooney and Swift (1999:274-277), that increasing values for W increase the total numbers of casualties up to a point, but when values of N become sufficiently depressed then further increases in W cause the total number of casualties to decrease (since the achieved population growth will be small because of the small N).